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Neural dynamics of sensorimotor decision making: the role of basal ganglia, motor cortex and prefrontal cortex

Irene Lacal [1], Pierre Boucher [2], David Thura [3], Manuel Molano [4]

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Discussant: Juan Gallego

Sensorimotor decision-making is a complex process that requires the integration of cognitive, motivational, and kinematic features for the translation of sensory information into motor output. This concept aligns with the observation of widespread decision signals in the brain, particularly in subcortical and frontal cortical areas known for their involvement in action selection and execution, such as the basal ganglia, the primary motor cortex (M1), the dorsal premotor cortex (PMd), and the dorsolateral prefrontal cortex (dlPFC).

What roles do the different brain regions play in the functional continuum from sensory evidence-based decision formation to the kinematics of the response movement? In this panel, we will address this question by focusing on neurophysiological evidence collected from these cortical and subcortical brain areas across multiple model organisms (rats, rhesus macaques and humans).

First, Manuel Molano will talk about how the accumulation of decision evidence shapes response trajectories in rats and humans performing an auditory discrimination task. He will show how prior expectations influence response behavior and vigor in both species and demonstrates that this dynamic can be modelled computationally. Single neuron activity in rat dorso-medial striatum is shown to closely track slow fluctuations of vigor across trials.

David Thura will then discuss the role of the basal ganglia and sensorimotor cortex in action selection and movement vigor. By testing monkeys performing visually-guided choices between reaching movements and a reaching-based foraging task, he demonstrates that basal ganglia are responsible for coordinating and invigorating decisions and actions, leaving the task of selection to the sensorimotor cortex.

To follow, Irene Lacal will talk about the role of M1, PMd and dlPFC in action selection and execution in unconstrained rhesus macaques engaging in a task that requires to choose one of two alternative targets while or before walking towards them. Population dynamics suggest that, when choosing while walking, M1 is engaged primarily in the stepping behavior, leaving the task of selecting between action goals to PMd and dlPFC.

Lastly, Pierre Boucher will discuss the differential role of PMd and dlPFC in decision making. By testing rhesus macaques on a visual discrimination task that decouples perceptual decisions from action choices, he shows that neural population dynamics suggests that dlPFC main task is to solve the perceptual decision, while PMd is mainly involved in action selection.

Taken together, these results suggest the basal ganglia to be involved in action vigor and urgency, dlPFC in solving the perceptual aspects of decisions and M1 and PMd in selecting and executing the behavioral response. This functional specialization and its implications for our understanding of the neural basis of sensorimotor decision-making will be addressed in the final discussion.

10:30 - 11:05 Early Career Award Presentation and Talk

Cognitive shaping of motor behavior

Sam McDougle, *Yale University*

The fields of motor neuroscience and cognitive psychology are too often siloed. But cognitive processes affect motor behavior in a range of ways, influencing the selection, planning, and learning of movements. In turn, how we move affects what we perceive, closing the loop between cognitive and motor systems. In this talk, I will discuss some recent projects from my lab that highlight the intersection of cognition and motor behavior. I will feature work on how cognitive stages of action planning shape implicit forms of motor learning, the dynamic flow of information from decision-making to movement selection systems, and neural computations that cut across action and visual cognition. Overall, I will try to make the case that studying motor behavior in a vacuum risks missing key stops along the road from thought to action.

11:05 – 13:05 Session 2, Panel II

Why and how does active control of muscle spindles shape movement?

Surabhi Simha [1], Alessandro Santuz [2], Lena Ting [1], Michael Dimitriou [3]
[1] Emory University and Georgia Institute of Technology, [2] Max Delbrück Center for Molecular Medicine, [3] Umeå University

Discussant: David Franklin

Understanding how higher-level control mechanisms integrate with our peripheral sensory systems is necessary to understand how we move. Muscle spindles are sensory organs integral to proprioception and equipped with their own neural drive from the gamma motor neurons that receive descending cortical input. However, due to experimental limitations, little is known about how neural drive to muscle spindles is modulated in movement. In this panel, we will present recent advances in theory, modeling, and experimental approaches to better understand proprioception, particularly muscle spindles. We will articulate a compelling argument that active tuning of the neural drive to muscle spindles alters sensory feedback that shapes the nervous system's ability to predict and adapt to a dynamic environment. We will use evidence from recent developments in in vivo and genetic manipulations in animals, predictive computational models, and microneurography studies in humans. We hope to promote further research into gamma motor neurons and their control of sensory feedback in adaptive proprioception and action.

Lena Ting will discuss different physiological structures of muscle spindle Ia, II, and Golgi tendon organ Ib proprioceptors, highlighting that they may together encode muscle state. She will discuss how the muscle spindle outputs can be modulated by neural control and the role of supraspinal systems in shaping muscle spindles output in humans, which in turn shapes cortical and subcortical control of balance.

Alessandro Santuz will discuss the current state of the field in quantifying the role of proprioceptive feedback during dynamic motor tasks in vertebrates. He will present data from in vivo behavioral experiments in humans and mice using a mixture of electrophysiology, computational neuroscience and mouse genetics. Such multidisciplinary frameworks can be used to dissect the contributions of neural pathways for proprioception in the generation of robust locomotor output.

Surabhi Simha will present a neuromechanical framework to understand how biophysical properties of muscles and muscle receptors shape muscle spindle output. Using predictions from a biophysical computational model that simulates the effect of gamma motor drive on muscle spindle output, she will show how gamma drive can sculpt the spindle output in a task-appropriate manner (e.g. posture vs locomotion) as well as dissociate self-generated and imposed forces.

Michael Dimitriou will argue that muscle spindles under fusimotor control are best thought of as signal-processing devices rather than stretch receptors, giving rise to flexible coordinate representations according to task characteristics and goals. He will present data from human microneurography experiments showing that spindle tuning enables the independent preparatory control of reflex muscle stiffness, selective extraction of information during motor adaptation, and segmental stretch reflexes to operate in joint space.

15:30 – 17:30 Session 4, Individual I

O1.1 - A differential influence of the pathophysiology of Parkinson's Disease on distinct phases of muscle recruitment during visually-guided reaching

Madeline Gilchrist [1], Rebecca Kozak [1], Margaret Prenger [2], Kathryne (Kasey) Van Hedger [2], Penny Macdonald [3], Brian Corneil [1], Mimma Anello [3]
[1] Western University, [2] University of Western Ontario, [3] Clinical Neurological Science, Western University
Presenting Author: Madeline Gilchrist

Parkinson's Disease (PD) is characterized by slowed and reduced voluntary movements caused by dopamine depletion in the dorsal striatum. However, recent evidence suggests that PD leaves reflexive, visually-guided movements intact. Such selective sparing in PD is seen in the persistence of express saccades mediated by the midbrain superior colliculus (SC) well into disease progression. PD patients mistakenly generate more express saccades in an anti-saccade task, indicating deficient contextual control. Recent work measuring upper limb muscle recruitment during visually-guided reaching has implicated the SC via the tecto-reticulo-spinal pathway in the earliest phase of upper limb muscle recruitment following visual stimulus onset. Like express saccades, such express visuomotor responses (EVRs) are extremely short-latency (80-120 ms in human) and tied to the time and location of visual stimulus onset. Unlike express saccades, muscle recruitment during visually-guided reaches plays out over hundreds of milliseconds and includes both rapid, stimulus-driven recruitment followed by later, volitional recruitment. Could the pathophysiology of PD selectively influence these different phases of recruitment? To address this we recorded upper-limb muscle activity in two experiments with patients with PD (n = 16, n = 18) and age-matched healthy controls (HC; n = 18, n = 17). Both experiments required participants to consolidate an instruction to reach either toward (pro-reach) or away from (anti-reach) a visual stimulus. Task difficulty was increased in Exp 2 by reducing the duration of the instruction so that it appeared only 1000 or 500 ms before stimulus presentation. In both experiments, we found that EVRs on pro-reaches were spared and of similar magnitude in patients with PD compared to HC. However, the ensuing phases of muscle recruitment, including the phase aligned to reach onset, were significantly reduced in patients with PD ($p = 0.049$), which related to the expected lower peak reach velocities ($p = 0.035$). We also examined the magnitude of EVRs on anti-reach trials and found that when compared to the magnitude of EVRs on pro-reach trials, patients with PD were less able to contextually dampen EVRs, particularly when the instruction time was shortened to 500 ms ($p = 0.045$). Our results are consistent with parallel-but-interacting subcortical and cortical pathways converging onto a common reticulospinal pathway. In PD, the earliest recruitment phase mediated by the subcortical SC is spared, but contextual control is compromised. This finding mirrors the hyper-reflexive eye movements in PD and is consistent with the role of the dorsal striatum in modulating habitual movement. Following this initial phase, subsequent phases of muscle recruitment are dampened, producing the expected bradykinesia. Thus, signatures of a differential influence of PD on stimulus- versus movement-aligned recruitment are observable even within a single trial.

O1.2 - Sound activates a dormant visual-motor pathway bypassing primary visual cortex

Tatiana Malevich [1], Ziad Hafed [2], Yue Yu [3], Matthias Baumann [3], Tong Zhang [3]
[1] University of Tuebingen, [2] Centre for Integrative Neuroscience, [3] Hertie Institute for Clinical Brain Research
Presenting Author: Tatiana Malevich

Like in other species, the primate visual system contains an anatomical retinal projection bypassing the geniculostriate pathway and innervating the midbrain (Cowey, 2010). However, unlike in some of these species, such as the mouse, the functional significance of this alternative visual pathway remains unknown: in fact, increasing evidence suggests that it may be completely dormant in primates. We first tested this idea by performing focal, reversible inactivation of the primary visual cortex (V1) and investigating a robust oculomotor phenomenon, called saccadic inhibition. This phenomenon, which is believed to rely on subcortical eye-movement control circuits, such as the superior colliculus (SC) and downstream pre-motor neurons (Buonocore and Hafed, 2023), is characterized by a short-latency cessation of saccade generation after visual stimulus onset, as well as by a concomitant saccade direction biasing, first towards and then away from stimulus location. We reversibly inactivated V1 via muscimol microinjection (1.5"2.5 Î¼L; 10 mg/mL), rendering two rhesus macaque monkeys cortically blind to a specific region of the visual field. When we then presented a visual stimulus within this localized cortical scotoma, saccadic inhibition was completely abolished, confirming a dominance of the geniculostriate pathway, even for such a reflex-like oculomotor phenomenon. Simultaneously recorded SC visual responses were also eliminated. However, why does the alternative visual pathway, directly targeting oculomotor control circuits, exist at all? We hypothesized that this pathway might still be functional, albeit in a gated manner. During V1 inactivation, we paired a visual onset in the blind field with a sound pulse (50 ms; 1 KHz; suprathreshold) that was presented binaurally and was completely uninformative about the visual stimulus location. Saccadic inhibition was now partially restored, and it was stronger and earlier than when the sound pulse occurred alone. Most importantly, there was a re-emergence of saccade direction biasing towards the visual stimulus location, even though the sound was not spatially informative. Guessed visually-guided, foveating saccades towards a target presented in the blind field were also mildly more accurate when visual stimuli were paired with the uninformative

sound. These results demonstrate that multi-sensory information can activate an otherwise dormant visual-motor pathway bypassing V1, for example, by gating readout of retinotectal visual signals arriving at the SC. Given the large differences in dominance of geniculostriate versus retinotectal visual pathways in different animal models used to study the neural control of movement, our findings underscore the importance of multi-species comparisons in understanding hierarchical sensorimotor processes, and they inform models of active visually-guided behavior invoking parallel sensory streams.

O1.3 - Cerebellar encoding of prior knowledge in sensorimotor timing

Julius Koppen [1], Ilse Klinkhamer [1], Marit Runge [1], Devika Narain [1]
[1] *Erasmus Medical Center*
Presenting Author: Julius Koppen

Behavior in the natural world is rife with feats of temporal precision but laboratory measurements of such behaviors reveal surprising biases in sensorimotor timing. Previous theoretical work attributes some of these biases to Bayesian inference processes that increase their reliance on prior knowledge of well-timed movements under uncertainty. We, however, know little about how neural circuits utilize prior knowledge required for precise temporal control of movements. Here we use theory, large-scale electrophysiology, machine learning, and optogenetics to investigate whether cerebellar circuits could provide a substrate for encoding prior knowledge of temporal statistics to generate precise movements. We train mice on a modified eyeblink conditioning task, where they learn associations between a visual cue (conditioned stimulus CS) and a periocular airpuff (unconditioned stimulus US). Unlike conventional eyeblink conditioning, the time intervals between the CS and US are drawn from discrete uniform probability distributions of different statistics, i.e., very narrow, narrow, and wide. After several pairings, the eyelid learns to close predictively and on test trials where the airpuff is omitted, we evaluate the statistics of the predictive (conditioned) eyelid closure for different prior distributions. We found that kinematic and temporal properties of the eyelid movement adapted to changes in the statistics of the stimuli. Neural activity profiles of cerebellar Purkinje cells and putative molecular layer interneurons recorded during behavior in lobules IV/V and Simplex of the cerebellar cortex concomitantly changed their statistics to accommodate the changing prior distributions. We used a recent deep learning technique, known as LFADS, to decode trial-by-trial activity from cerebellar cortical neurons and decode behavioral metrics to establish changing statistics. We also analyzed latent population dynamics for different prior distributions to conclude that neural population tuning changes its statistics when the prior distribution switches from narrow to wide. Calibrated optogenetic perturbations to cerebellar Purkinje cells within the duration of the temporal distribution caused a complete suppression of the prior-related response. Furthermore, we found prior-related signaling in cerebellar Purkinje cell complex spike activity that was time-locked to the onset of prior distributions. Finally, we propose a computational model of the cerebellar-olivary circuit that uses juxtaposed plasticity principles to explain how the cerebellar cortex encodes and leverages prior knowledge to generate precise eyelid control.

O1.4 - Is there more to sequence learning than better anticipation?

Mehrdad Kashefi [1], Joern Diedrichsen [1], J. Andrew Pruszynski [1]
[1] *Western University*
Presenting Author: Mehrdad Kashefi

For nearly fifty years, motor sequence learning has been studied using the Serial Reaction Time (SRT) paradigm. However, the utility of the SRT for motor sequence learning has been severely criticized: it is suggested that in SRT, the majority of the learned improvement is due to either implicit or explicit prediction of the upcoming actions in the sequence.

We addressed this pitfall of the SRT with a novel continuous-reaching task that manipulates how many future reach targets are shown on the screen (Horizon). In Experiment 1, participants (N=14, 6F) performed sequences of 14 reaches in a robotic exoskeleton. Within a session, 80% of trials were repetitions of a fixed sequence and 20% were random sequences to assess sequence-specific learning and general learning, respectively. Critically, we manipulated how many future targets participants could see at any given time. In the Horizon 1 case, we replicated the classic SRT results. With practice, subjects became faster due to anticipation of the next movement. Importantly, in the Horizon 4 condition, we still observed a robust speed-up, even though full explicit knowledge of the upcoming targets was provided.

We conducted a second experiment to rule out the possibility that faster movement was just a result of more vigor due to familiarity with the learned sequence. In the first block, participants (N=15, 4F) learned one sequence with the right hand and another sequence with the left hand simultaneously. Then, we instructed them to execute the sequence initially learned with their right hand with their left hand, and vice versa. We observed no transfer of learning between hands in the first few trials of the second block, suggesting that the original learning was effector-specific and unrelated to motivational factors.

In a third experiment, we asked what is the minimum fragment of the practiced sequence that can evoke the learned speed-up. Each participant (N=28, 12F) extensively practiced a sequence then they executed random sequences which shared one, two, and up to five consecutive targets of the practiced sequence. We observed a speed-up for reaches connecting the practiced targets, but not in the reaches entering or exiting the practiced set of targets. Our results show that any given reach will speed up if the start, end, and previous targets are part of a previously practiced sequence.

We simulated the same task in a modular recurrent neural network (RNN) that controlled an arm model. The network was first trained on random point-to-point reaches and then over-trained on one sequence. In many networks, we saw that learning-related changes mostly occurred in modules connected to task and vision, not in motor-related modules. Together, with the behavioral results and RNN simulations, we propose a model for sequence learning that relies on optimizing individual movement for the sequence, rather than generating a dedicated sequence representation at the motor level.

O1.5 - Evidence against replay-mediated offline learning during the first minutes of motor skill acquisition

Anwesha Das [1], Alexandros Karagiorgis [1], Joern Diedrichsen [2], Max-Philipp Stenner [3], Elena Azanon [1]
[1] University of Magdeburg, [2] Western University, [3] Otto-von-Guericke University Magdeburg and Leibniz Institute for Neurobiology Magdeburg
Presenting Author: Anwesha Das

How can humans learn motor skills efficiently? Learning of a novel motor skill is typically exhibited by fast improvements in performance during practice (online learning). Boenstrup et al. 2019 have suggested a rapid form of offline learning during the first few minutes of skill acquisition, evident in performance gains across periods of rest interspersed between practice periods (micro-offline gains, MOG). Buch et al. 2021 suggested that these gains were potentially driven by temporally compressed neural replay of the practised sequence. We trained healthy human participants to produce a sequence of five key presses as often as possible in 10s practice periods interleaved with 10s rest periods. We replicated MOGs across 10s rests, in a total of 6 experiments. We found similar performance improvements across rest periods whether subjects were truly resting (N=34), engaged in motor imagery (N=34), or distracted by a demanding cognitive task (N=33). We also ran a between-subject study (N=79) wherein one group of participants performed a fixed sequence in every practice period whereas another group performed sequences of finger movements which never repeated, neither within a given practice period, nor across the entire experiment. If the MOG is driven by replay, it should vanish when sequences are never repeated. Unexpectedly, we found similar performance improvements when subjects trained on sequences that never repeated, questioning a role of replay for the observed performance gains. Furthermore, if MOG indeed corresponds to an offline gain, i.e., additional learning, then training with 10s rest periods (spaced training) should result in overall more skill compared to training without rest periods (massed training). Our 2 in-lab (N=62 and N=85) and 1 online (N=358) experiments, tested whether interspersed rest periods result in a true learning benefit. One group was trained via interleaved practice and rest periods of 10s each, whereas the other group was trained in a single, continuous practice period without breaks, matched in training duration. We intended to disentangle true, offline learning from other potential mechanisms that might be at play during breaks, so both groups were allowed to rest for a longer break of 5 minutes, enabling washout of accumulated fatigue and unmasking of true, latent learning. We compared performance between groups across 20s test periods at different points throughout the experiment. Despite significant MOG in the spaced training group, we observed that both resulted in a similar number of correct keypresses after washout. Across 3 experiments, we found no overall learning benefit when humans trained with vs. without 10s breaks. Taken together, our data indicate that the interpretation of MOG should cautiously differentiate between apparent learning and true, offline consolidation. Our findings will help understand early skill acquisition and strategies to benefit skill learning in humans.

O1.6 - Balancing demands for stability and flexibility in the motor system of rats performing multiple motor sequences

Naama Kadmon Harpaz [1], Steffen B. E. Wolff [2], Kiah Hardcastle [1], Rudy Gelb-Bicknell [3], Theodore J. Zwang [3], Bence Olveczky [1]
[1] Harvard University, [2] University of Maryland School of Medicine, [3] Mass General Institute for Neurodegenerative Disease, Massachusetts General Hospital
Presenting Author: Naama Kadmon Harpaz

The mammalian brain can learn to generate a near infinite number of actions by sequencing movements in new and adaptive ways. While we rely on such behavioral flexibility to interact with an unpredictable world, some behaviors, such as our signature, are performed repeatedly in the same way, making their execution reliable and robust to demands for continual learning. How the brain manages the tradeoff between flexibility and robustness is a key question not only for neuroscience, but also for AI systems that struggle in this domain.

One way to manage this tradeoff is to use the high dimensionality of neural circuits and assign each skilled behavior a dedicated manifold in neural state-space, allowing learning to continue along other dimensions while keeping the dedicated sub-circuit stable. To examine this hypothesis, we studied the acquisition of multiple motor sequences in freely behaving rats, and probed the activity of the sensorimotor striatum the main input region to the basal ganglia that has been implicated in the learning and execution of skilled behavior. Specifically, animals were trained in a continual manner on two different lever-tap sequences that shared the first element, allowing us to compare the behavior and neural activity associated with the same action embedded in different sequences. With practice, animals mastered both sequences, developing smooth and stereotypical movement trajectories. Following previous findings that have demonstrated the necessity of the sensorimotor striatum in the execution of a single learned motor skill, we hypothesized that lesions to this region in expert animals would affect the ability to perform the learned sequences. Indeed, learned kinematics were impaired following lesions of the sensorimotor striatum, showing a revert to a variable halting behavior. When examining the neural activity of single units in the sensorimotor striatum of expert animals we found that the two motor sequences were associated with stable yet distinct neural activity patterns, implying that learning leads to dedicated and unique task-specific activations in neural state-space, possibly minimizing interference and allowing each behavior to remain stable and robust to new learning.

In current ongoing work, we study how repeated practice leads to the engagement of the sensorimotor striatum and the separation of neural activity patterns. To that end, we have been developing a new flexible probe for electrophysiology recordings that can be used to record the activity of multiple single neurons continuously over months in freely behaving animals. This new method will allow us to study how neural circuits evolve over training to support motor sequence learning in the mammalian general-purpose learner.

Wednesday, April 17, 2024

08:00 – 10:00 Session 5, Panel III

Closing the loop: the role of feedback in neural population dynamics

Jonathan Michaels [1], Britton Sauerbrei [2], Amy Orsborn [3], Laureline Logiaco [4]

[1] Western University, [2] Case Western Reserve University School of Medicine, [3] University of Washington, [4] Massachusetts Institute of Technology

Discussant: Mark Churchland

The dynamical systems view of neural population activity, in which populations of neurons interact over time to produce coordinated patterns of activity, has been very influential in motor control - notably for characterizing cortical activity. This framework has typically been used to understand how goals are represented in motor planning and how this activity is translated into the muscle patterns required for movement, with less emphasis on the online control of movement. In parallel, decades of research have characterized the online, closed-loop control of movement through the lens of feedback control. While these efforts have led to successes in modeling motor behavior and have inspired analyses of neural data, this approach has not converged on a cohesive explanation of neural implementation. In this panel, we will bridge this gap by presenting and discussing evidence from rodents, primates, and computational models detailing how elements of feedback control can be integrated into the dynamical systems framework to provide a cohesive model of closed-loop motor control.

First, Britton Sauerbrei will discuss the complementary role of spinal circuits, the cerebellum, and motor cortex in locomotion when mice need to adapt to changes in limb properties, specifically showing that while motor cortex is not necessary when adaptation is required, activity shifts dramatically, potentially supporting future changes in voluntary control exerted by motor cortex.

Laureline Logiaco will discuss how different regions of the mammalian brain (cerebellum, M1, integrative sensorimotor cortices) can synergize to tackle learned closed-loop sensorimotor tasks, using a modeling approach. Specifically, this framework explains several experimental results in a single working model and makes predictions about task contingencies that require the synergy of many regions or instead mostly rely on a sub-part of the circuit.

Jonathan Michaels will discuss how we can integrate information related to expected future sensory input into frameworks of motor control, specifically showing that sensory expectation signals are present in many cortical areas of macaques, allowing the motor system to react flexibly to unexpected external perturbations.

Finally, Amy Orsborn will discuss how sensory feedback contributes to motor learning in interfaces like brain-computer interfaces, specifically showing that differences in the dimensionality of sensory feedback and movement control space may shape learning dynamics.

The panel concludes with a discussion focused on integrating the results of the talks into a common framework for understanding how different brain regions participate in incorporating sensory feedback in motor commands.

10:30 – 12:30 Session 6, Individual II

O2.1 - Using a stochastic optimal control framework to model the control of complex human movement: Application to an aerial acrobatics

Eve Charbonneau [2], Friedl De Groote [1], Mickaël Begon [2]
[1] KU Leuven, [2] Université de Montréal
Presenting Author: Eve Charbonneau

Optimal control theory has been used by biomechanists for decades to generate human movement. Resulting optimal kinematics closely reproduce human movements but lack the motor variability presented by humans and neglect the perception-action coupling needed to execute complex motion. Optimal feedback control theory has been proposed to overcome these issues [1]. It was brilliantly introduced in a computational method allowing for solving biomechanical stochastic optimal control problems (SOCP) involving more complex musculoskeletal models. It was done by including Gaussian motor noise, a Gaussian distribution of states, and a feedback loop based on deviations from the motor plan grasped by noised sensory input [2]. The SOCP optimal control policies better reproduced some key characteristics of human motion like stabilization through muscle co-contraction, realistic kinematic response to perturbations, and task-dependant modulations of feedback. This implementation considers sensory noise to be constant, whereas the acuity of our senses is state-dependent and lacks online prospective adaptations of the motor plan. These assumptions are not met during complex human motion involving multiple sensory inputs such as aerial acrobatics. Indeed, it was shown that athletes make prospective adaptations of their ongoing acrobatics in a feedforward manner [3] and our vestibular acuity depends on the head velocity. Thus, to model the gymnasts' behavior, we introduce in the current study state-dependent motor and sensory noise (*e.g.* vestibular noise is smaller if the head velocity is reduced) and feedforward adaptation to the nominal motor plan based on the somersault angular velocity to the dynamics equation. Optimal control policies for executing a backward somersault were generated with a full-body torque-driven skeletal model composed of seven degrees of freedom. The objective was to reach the landing position as consistently as possible and to minimize the expected efforts (including feedback and feedforward components) required. For comparison, three types of problems were solved: *i)* a deterministic optimal control problem (DOCP), *ii)* a constant noise SOCP, and *iii)* our new approach involving noise modulation and feedforward adaptations (SOCP+). The optimal kinematics generated through the three methods differed from one another. The SOCP control policy leads to smoother kinematics than the DOCP policy; this more conservative technique would require less precision during execution. The addition of noise modulations introduced modifications of the neck kinematics between the SOCP and SOCP+ policies. The SOCP+ reproduced the sensory acquisition strategies used by gymnasts to reduce landing variability. The appearance of these sensory strategies highlights the potential of this SOCP+ framework. As it is generic, it could help us better understand the organization of other complex human movements.

[1] Todorov, 2004

[2] Van Wouwe, 2022

[3] Bardy, J., 1998

O2.2 - Spinal reflex representation in the primary motor cortex

Tatsuya Umeda [1], Osamu Yokoyama [2], Michiaki Suzuki [2], Miki Kaneshige [2], Tadashi Isa [1], Yukio Nishimura [2]
[1] Kyoto University, [2] Tokyo Metropolitan Institute of Medical Science
Presenting Author: Tatsuya Umeda

How supraspinal and spinal structures in the nested hierarchy control limb muscles is a fundamental question in the neural control of limb movements. Various theories, including the servo control hypothesis and internal model for motor control, have historically been proposed to incorporate the role of spinal reflexes into cortical control of limb movements. More recently, optimal feedback control theory and active inference have been developed further to deepen our understanding of neural control of limb movements. Despite these theoretical advancements, the precise neural mechanism by which the central nervous system, in concert with spinal reflexes, orchestrates motor control signals, especially concerning the flow of information coded in neural activities across sensorimotor circuits, remains elusive.

Here, we simultaneously recorded activities in motor-related cortical areas (MCx), afferent neurons, and forelimb muscles of monkeys performing reaching movements. We developed a linear model to explain the instantaneous muscle activity based on the activity of MCx and peripheral afferents. Decomposing the reconstructed muscle activity into subcomponents explained by MCx and afferents activity, we found that initial muscle activation for forelimb movement is driven by MCx output, followed by the activation of peripheral afferents through limb movement, which in turn modulates muscle activity via spinal reflex pathways. Based on the information flow, we found that MCx, primarily the primary motor cortex (M1), encodes subsequent afferent activities attributed to forelimb movements. M1 also encodes a subcomponent of muscle activity evoked by these afferent activities, corresponding to spinal reflexes. Furthermore, selective disruption of the afferent pathway specifically reduced this subcomponent of muscle activity, suggesting that M1 output drives muscle activity not only through direct descending pathways but also through the transafferent pathway composed of descending plus subsequent spinal reflex pathways. These findings suggest that M1 generates optimal motor output by employing an internal forward model, which prospectively computes future spinal reflexes.

O2.3 - Spinal networks act as a continuous attractor during pause of movement

Salif Komi [1], Jaspreet Kaur [1], Madelaine Bonfils [1], Jakob Sørensen [1], Nicolas Bertram [1], Rune Berg [1]
[1] *University of Copenhagen*
Presenting Author: Salif Komi

How does a cat gracefully walk and suddenly freeze its ongoing movement when spotting a mouse? The common wisdom attributes this ability to neural circuits within the spinal cord that are well-known for their ability to generate rhythmic movements, doing so in symphony with the brain. However, the mechanisms behind this generation remain unclear. While the prevailing view suggests the existence of specialized modules for distinct functions, recent observations, including rotational neural activity during rhythmic limb movement (Lind 2022), challenge this perspective. Furthermore, the precise means by which the neural circuitry achieves a pause in ongoing movement across any posture remains elusive.

To investigate how spinal neural networks execute locomotion that can be paused at any point, we utilized high-density electrophysiology in rat spinal cords during voluntary locomotion, coupled with optogenetic perturbation of the pedunculo-pontine nucleus, a known regulator of movement arrest (Goni-Erro 2023). We present compelling evidence supporting the existence of continuous network attractor properties within the spinal network. We find that during volitional locomotion, the neuronal manifold activity exhibits robust rotational patterns, whose topology is invariant at various speeds and across animals. Furthermore, this trajectory converges to a stable point-attractor precisely at the moment of motor arrest, and it persists in this specific configuration until the movement is continued on the initial trajectory. Through computational modeling, we argue that the network is analogous to a Continuous Attractor Network (CAN), which has been demonstrated in grid cells of the entorhinal cortex associated with memory storage and retrieval (Gardner 2022). We finally suggest specific structural mechanisms by which the network is physically implemented and controlled to transition between locomotion and pause.

In light of these observations, we propose the presence of a CAN-analogous spinal network with rotational properties as the mechanism behind generation as well as the arrest of ongoing movement.

O2.4 - Distinct contributions of feedback and feedforward control during longitudinal de novo learning

Chen Avraham [1], Firas Mawase [1]
[1] *Technion - Israel Institute of Technology*
Presenting Author: Chen Avraham

Learning a motor skill from scratch, known as de novo learning, involves establishing a new control system. Typically, real-world motor tasks, like bicycle riding, require using a combination of feedback and predictive control systems to produce smooth and accurate movements. Due to the inherent time delay of feedback control and its inability to reflect the body's current state, employing a feedforward model is crucial to produce quick and precise actions. The development of feedback and feedforward control systems during the acquisition of new motor skills is not yet fully understood.

In our study, ten right-handed participants (6 females, age 24.7±2.0 years) practiced a mirror reversal continuous tracking task during 5 consecutive days. The target moved in a pseudo-random trajectory, shaped by a sum-of-sinusoids, across a frequency range of 0.1 to 2.15 Hz. We aimed to discern whether participants learned this task primarily through feedforward control, feedback control, or a combination of both. We assessed this by (1) checking for the presence of after-effects, which are indicative of feedforward control, and (2) introducing probe trials where the cursor made unpredictable translocations, prompting a feedback response.

Our findings showed a gradual learning, with participants achieving an average learning level of 54.37±0.08% by Day 5 (100% representing complete learning). Analysis of responses to cursor jumps on day 5 revealed a close alignment with ideal feedback responses (regression slope of 0.87±0.03), suggesting that continuous learning was mostly achieved using feedback control. Intriguingly, a small yet significant after-effect (15.29±0.11%) was also observed post-learning ($t(9)=3.47$, $p=0.0032$), indicating a contribution of feedforward control to the overall learning process.

However, the predominance of slower frequencies in overall learning could inadvertently obscure the actual impact of the feedforward controller. To verify this, we conducted a linear systems analysis, using the discrete Fourier transform, offering a more granular view than trajectory-alignment analysis. This analysis revealed rapid learning at lower frequencies and slower learning at higher frequencies. Interestingly, higher frequencies were associated with greater after-effects, suggesting a more pronounced role of feedforward control at these frequencies ($t(9)=2.55$, $p=0.031$).

These results provide new insights into how humans acquire de novo motor skills. The properties of de novo learning can potentially be explained by the existence of two distinct control pathways: Firstly, corrective feedback responses operate at low frequencies, acting early on learning and improve with practice. Secondly, at high frequencies, the target's speed may surpass the capacity for feedback control, resulting in predominantly inadequate feedforward responses during early learning. However, this feedforward controller is flexible and develops gradually with practice.

O2.5 - Decision uncertainty as a context for motor memory

Nobuhiro Hagura [1], Kisho Ogasa [1], Atsushi Yokoi [2], Gouki Okazawa [3], Masaya Hirashima [4]
[1] NICT, [2] National Institute of Information and Communications Technology, [3] Institute of Neuroscience, Chinese Academy of Sciences, [4] Center for Information and Neural Networks, National Institute of Information and Communications Technology
Presenting Author: Nobuhiro Hagura

In a penalty shoot-out of a football (soccer) game, one may decide to kick the ball to the right corner confidently, seeing that the goalkeeper is moving to the other side, or decide to make the same kick while being unsure about the goalkeeper's movement. Because both actions are apparently identical, we tend to believe that the same motor memory (i.e., a motor program for kicking the ball to the right) is retrieved and executed for both cases regardless of the quality of the preceding decision.

Indeed, previous perceptual decision-making studies have treated uncertainty as a factor for modulating the evidence accumulation process for decisions, implicitly assuming that an identical motor program is triggered once the evidence level reaches a bound (Ratcliff & MacKoon, 2008, Gold & Shadlen, 2007). The current theory of motor learning posits that the brain flexibly forms and switches between multiple motor memories through contextual inference process, relying on external sensory cues linked to action (Heald et al., 2021). In this framework, again, uncertainty of cues is treated as a variable which leads to uncertainty of the associated contexts, not the cue to directly specify the context for the motor memory.

Opposing to the dominant views in both decision-making and motor learning literatures, we show that uncertainty of the decision cues for action execution, by itself, acts as a significant contextual cue for motor memory. Participants judged the direction (left or right) of a visual motion (random-dot motion) presented on the screen. They were asked to reach towards the target of the perceived motion direction by moving a manipulandum with their right hand. The reaching movement following the decision was performed under a velocity-dependent force-field. We manipulated the uncertainty level of the decision by changing the coherence level of dots motion.

We showed that actions learned following certain (uncertain) decisions only partially transfer to actions following uncertain (certain) decisions. Participants were able to learn two different force-fields if each perturbation was preceded by a different decision uncertainty level. Crucially, such contextual effect generalized to novel stimuli with matched uncertainty levels. Finally, we demonstrated that participants could differentiate the force-field contexts based on the decision uncertainty at the deliberation/planning stage of action, before performing the decided action.

Taken all together, our findings broaden our understanding of contextual inference for motor memory, emphasizing that it extends beyond physical stimuli to encompass the internal inferential state of the environment.

O2.6 - Striatal and cerebellar involvement in reinforcement learning in the human infant brain

Juliana Trach [1], Tristan Yates [1], Sheri Dawoon Choi [1], Lillian Behm [1], Cameron Ellis [2], Samuel McDougle [1], Nicholas Turk-Browne [1]
[1] Yale University, [2] Stanford University
Presenting Author: Juliana Trach

The ability to learn from positive and negative feedback is an essential cognitive capacity throughout life but perhaps especially when first learning to make sense of and interact with the world during early development. Behavioral work suggests that even very young human infants can use reward feedback to guide their actions toward maximizing rewards they receive from their environment. However, it is unknown how the infant brain learns from and processes rewards, nor what the time course of maturation is for the relevant neural systems. Prior work with adults and adolescents has highlighted canonical regions of the striatum in reinforcement learning (RL; Bartra et al., 2013; Fouragnan et al., 2018). More recently, there has been growing interest in the role that the cerebellum might play in this crucial learning capacity (e.g., Wagner & Luo, 2020). While the cerebellum has historically been associated with motor control and error-based motor learning, work with nonhuman primates and rodents has yielded evidence of neural processing of rewards and reward predictions in the cerebellum, providing one example of a nonmotor function of the region (Heffley & Hull, 2019; Kostadinov & Hausser, 2022; Sendhilnathan et al., 2020; Wagner et al., 2017). Still, it is unclear whether part or all of this RL system is mature in infancy or whether cerebellar processing changes as infants gain more motor capacities. Furthermore, methodological challenges have limited the study of subcortical structures - like the cerebellum - in infants, which cannot be easily studied with traditional infant neuroimaging techniques such as EEG and NIRS. Recent advances have made it possible to conduct fMRI studies in awake and behaving infants (Ellis et al., 2020). We used fMRI to measure whole-brain activity during an infant-friendly Pavlovian RL paradigm. Infants were presented with two shapes, one associated with a high reward probability (80%) and the other with a low reward probability (20%). One shape was randomly selected on each trial, and then it revealed either a rewarding stimulus (a dynamic smiley face) or no outcome. Our model-based fMRI analyses focused on core components of RL: reward prediction (i.e., Q-value), reward feedback, and both signed and unsigned reward prediction error. Our results revealed widespread processing of all of these signals, including the striatum, insula, anterior cingulate cortex, and thalamus. Moreover, we found evidence for infant cerebellar responses that correlated with both reward prediction and reward feedback. Overall, this work marks a promising step in our understanding of RL in the infant brain and the role of the cerebellum in cognitive functions.

15:00 – 17:00 Session 8, Panel IV

The underlying mechanisms of motor impairments after stroke

Lior Shmuelof [1], Inbar Avni [1], Stuart Baker [2], Alkis Hadjiosif [3], Jennifer Mak [4]
[1] Ben Gurion University of the Negev, [2] Newcastle University, [3] Harvard University, [4] Bioengineering Department, University of Pittsburgh

Stroke is the leading cause of long-term disability in the western world. Disability after stroke can be driven by a combination of underlying impairments, such as control deficits, loss of dexterity, weakness, spasticity, and pathological synergies. The extent and time-course of recovery may differ across impairments, highlighting the importance of phenotyping for the prognosis of stroke recovery.

The overarching goal of this panel is to review recent approaches towards phenotyping motor impairments after stroke and their underlying mechanisms. A suggested conceptual approach to phenotyping motor impairments is through the direct and indirect effects of the lesion on motor pathways. Negative signs, such as loss of control and weakness are proposed to be associated with damage to the corticospinal tract (CST), whereas positive signs, such as spasticity and pathological synergies, are suggested to be driven by hyper-activation of the reticulospinal tract (RST).

Avni et al. will present a longitudinal kinematic study of subjects with stroke that shows that weakness and pathological synergies appear together in the early sub-acute stage but show a differential recovery time course, pointing to their dissociable origin. Baker et al., will present a lesion study in monkeys that aims to characterize the origin of positive signs in the primary motor cortex, concluding that positive signs may be associated with a significant loss of CST input to sub-cortical circuits. To further characterize the contribution of cortical areas to motor impairments, Mak et al. will present the results of an rTMS stimulation study in stroke subjects, showing indications of altered non-primary motor area involvement in the control of movement after small, subcortical strokes. Finally, Hadjiosif et al. will take a different approach by studying the consistency between deficits during holding still, hypothesized to reflect RST function, and reaching, which is thought to be dominated by CST function. The reported lack of interaction between holding deficits and reaching deficits provides further support for the dissociable origin of negative and positive signs.

We show that disability after stroke can be conceived as an outcome of a combination of negative and positive signs that may be associated with distinct motor pathways. Moreover, some of the results highlight a causal association between loss of CST input and the hyper-activation of RST and call for a systematic examination of the causes of emergence and recovery of positive signs. The motor pathway account for motor deficits after stroke and the potential dependence between CST and RST may be fundamental for the understanding of general principles in motor control.

Thursday, April 18, 2024

08:00 – 10:00 Session 9, Panel V

Feedforward and feedback mechanisms of neural control: theory and applications

Frederic Crevecoeur [1], Friedl De Groote [2], Etienne Burdet [3], David Franklin [4], Janneke Schwaner [5]
[1] University of Louvain, [2] KU Leuven, [3] Imperial College London, [4] Technical University of Munich, [5] University of California, Irvine

Discussant: Friedl de Groote

The principles of control theory have advanced but also shaped our understanding of how the brain controls movements, while the combination of computational and experimental results has guided research into the neural correlates of sensorimotor functions. For example, the early introduction of optimal control assumed an open-loop controller capable of selecting efficient trajectories and mapping them to motor commands. Subsequent studies have highlighted the importance of feedback control, which has challenged the nature of trajectory representation in the brain by showing that for some tasks, goal-directed control does not necessarily require a feedforward controller. More recently, feedforward and feedback control mechanisms have been associated with different time frames, the former referring to the gradual acquisition of motor patterns through development and learning, while the latter was prevalent for execution of movement and responses to disturbances. At the interface between these time frames, several studies have demonstrated behavioral and neurophysiological correlations between adaptive motor patterns and responses to perturbations when humans are exposed to changes in limb dynamics. This research required dissecting the neuroanatomy of feedback pathways, leading to a precise description of how the visual and proprioceptive systems engage various feedback loops. The current observations concluded that feedforward and feedback pathways may not be completely separable from functional and behavioral perspectives. The impact of interpreting neural data associated with movement control is enormous, since the sensorimotor pathways involved in feedback control and adaptation must therefore overlap.

In this session, we propose to present recent advances based on similar principles, applied to a wide variety of systems, tasks and populations. More precisely, the success of theoretical control models quickly comes up against the complexity of the human body, which is particularly challenging to describe for locomotion tasks. Modeling the physics of locomotion to understand and evaluate the neural control of gait is a subject that will be addressed (J. Schwaner). The interaction between feedforward and feedback control mechanisms has been exploited to study the multimodal properties of neural control in adaptation tasks including multiple effectors, goals and environments (D. Franklin), interactions between individuals, including typically developing children (E. Burdet), and in response to dynamic changes in the environment (F. Crevecoeur).

As these contributions highlight, we are currently witnessing a paradigmatic shift towards complex tasks, more representative of daily activities. We will discuss how interpreting behavioral data through the lens of a control theoretical approach can shed light on the nature of the underlying neural controller, potential dysfunctions, as well as the limits of our current understanding.

10:30 – 12:30 Session 10, Panel VI

Neural control of speech: What did we miss in the last 20 years?

Elvira Pirondini [1], Sergey Stavisky [2], Ludo Max [3], Marc Slutzky [4], Nicholas Card [2]
[1] University of Pittsburgh, [2] University of California, Davis, [3] University of Washington, [4] Northwestern University

Planning and executing motor behaviors requires orchestrating neural activity among multiple cortical and subcortical regions. Interestingly, the coordination between these brain areas underlying movement and speech generation appear to share similarities. The field of speech neural control has recognized this affinity by leveraging knowledge and technologies developed for limb movements to investigate speech production and promote functional recovery in patients with neurological injury. However, these explorations have so far remained marginal in the community of Neural Control of Movement. We believe that sharing recent progress in studying the neural control of speech could now close the loop by benefiting researchers working on upper and lower-limb motor control. For this, Dr. Ludo Max will open the panel by discussing recent behavioral studies that focus on sensorimotor interactions in the context of orofacial speech movements in neurologically healthy individuals with an emphasis on similarities and differences with paradigms for limb sensorimotor learning. Dr. Marc Slutzky will then continue along this line showing how the cortical encoding of speech production has homologous hierarchical organization with that of upper-limb movements and how non-frontal cortices may contribute to speech production. Dr. Nicholas Card will then steer the panel towards novel advances in neurotechnology for speech motor deficits. He will show that brain-computer interfaces (BCIs), which have until recently been primarily developed for limb restoration applications, have now reached a level of performance in the speech BCI domain suitable for clinical deployment for restoring rapid communication to people living with severe dysarthria. In particular, he will show a novel accurate and rapidly-calibrating method that could benefit other BCI applications. Dr. Elvira Pirondini will continue in this direction showing her recent results on the use of deep brain stimulation to improve hand motor control and how these results translate to restore natural speech. Finally, Dr. Sergey Stavisky will drive the discussion around an important question: what did we miss in the last 20 years in the field of speech neural control that could now be leveraged for advancing our knowledge in speech and limb motor control and restoration of volitional functions?

Friday, April 19, 2024

08:00 – 10:00 Session 12, Panel VII

Spinal cord and brainstem control of upper limb movements. Is it time to revisit our cortically-centered view of hand motor control and learning?

Shahab Vahdat [1], Julien Doyon [2], Sho Sugawara [3], Veronique Marchand-Pauvert [4]
[1] University of Florida, [2] McGill University, [3] Tokyo Metropolitan Institute of Medical Science, [4] Inserm, Sorbonne Université

Our classical view of neural control of movement states that the execution of goal-directed upper limb movements mainly relies on the activation of cortical motor areas, such as primary motor and premotor cortices. On the other hand, postural and balance control heavily relies on the activation of brainstem motor nuclei, such as the reticular formation. Growing evidence from animal work is starting to challenge this view by demonstrating active involvement of multiple brainstem and intersegmental spinal cord circuits in the execution of goal-directed forelimb movements, including the medullary reticular formation and the propriospinal neurons at C3-C4 cervical levels. What is the relationship between the activities of brainstem and intersegmental spinal cord centers and cortical motor areas in upper limb motor control? Do these findings extend to humans with a more developed corticospinal pathway? Are they also involved in motor planning and motor learning? In this panel, we will explore these questions across multiple levels of the central nervous system (cortical, brainstem, spinal cord), in various behavioral paradigms and processes involving upper limb movements (planning, execution, learning), and across multiple model organisms (humans, mice). First, Shahab Vahdat will discuss the contribution of brainstem and spinal cord activity in hand/forepaw force control, using innovative fMRI protocols enabling assessment of task-related brain and spinal cord connectivity in humans and mice. Shahab will discuss the modular organization of functional connectivity between medullary reticular formation, C3-C4 propriospinal system, and cortical motor areas involved in hand force control. Second, Sho Sugawara will detail the structural features of brain-spinal cord pathways to clarify the anatomical basis for voluntary motor control. Sho will further discuss premovement activity in brain-spinal cord pathways using simultaneous brain-spinal cord fMRI. Sho's work delineates how premovement spinal cord activation may contribute to motor planning in humans. Third, Veronique Marchand-Pauvert will discuss the functional role of propriospinal neurons in hand motor control. Veronique will discuss the origins of cortical inputs to the C3-C4 propriospinal neurons using a combination of TMS and peripheral nerve stimulation. Her work suggests a direct descending control of propriospinal transmission from premotor cortex in humans. Lastly, Julien Doyon will discuss a comprehensive view on neural substrates of motor sequence learning in humans, in which spinal cord local circuits play an active role in this process. Using simultaneous spinal cord-brain fMRI, Julien will discuss several lines of evidence showing learning-induced changes in the spinal cord circuits across various stages of learning, and how they relate to cortical and subcortical activations. The panel will conclude with a discussion focusing on the themes emerging across the talks led by Leonardo Cohen.

10:30 – 12:30 Session 13, Individual III

O3.1 - Differential roles of the cerebellum and basal ganglia in decision making

Sabrina Abram [1], Jonathan Tsay [2], Tianhe Wang [1], Samuel McDougle [3], Richard Ivry [4]

[1] *University of California, Berkeley,* [2] *University of Cambridge,* [3] *Yale University,* [4] *University of California*
Presenting Author: Sabrina Abram

The outcome of a choice depends on which action we select as well as how we execute this action. Consider playing the slot machines in a casino versus a claw machine in an arcade. In the casino, we need to select which slot machine to play, hoping to have chosen the one ready to pay off a jackpot. In contrast, with a claw machine, we not only need to select our desired toy but also maneuver the claw to successfully grasp it. The latter affords a sense of agency. Decisions made with a sense of agency (action selection with action execution) involve different strategies than those made without a sense of agency (action selection alone).

Do these two scenarios also differentially engage neural systems associated with decision making and motor control? Dopaminergic circuits within the basal ganglia are central to models of reward learning and motor control, and recent studies involving rodents and non-human primates have also implicated the cerebellum in reward processing and learning. Here, we tested individuals with neurodegenerative disorders affecting the basal ganglia (Parkinson's disease, PD) or cerebellum (cerebellar degeneration, CD) on decision-making tasks, comparing their performance to older controls (OC). We used a 2x2x3 design, manipulating the learning environment (model-free vs model-based), sense of agency (without-agency vs with-agency), and group (CD, PD, OC). In the model-free condition, participants selected and reached to one of two targets, each associated with reward probabilities that varied over time. In the model-based condition, they selected one of two options, each associated with transition probabilities that caused a specific target to appear, and then reached to this target to earn rewards. In the without-agency condition, we told participants that the outcome was determined by a lottery. In the with-agency condition, we told them that they were rewarded if they accurately reached to the target, giving the illusion of control.

Performance in the without-agency condition was strikingly similar for CD participants and controls (CD n=21, OC n=15). In contrast, CD participants performed worse than controls in the with-agency condition (CD n=16, OC n=15). We observed this same pattern for both model-free and model-based learning. We fit a reinforcement learning model to choice behavior and found that, for the with-agency CD group, differences in performance could be explained by deficits in decision noise for model-free learning and deficits in learning rate for model-based learning. Our preliminary results for the PD group point towards the opposite pattern: trending deficits without-agency (n=8) while intact performance with-agency (n=8) for model-free and model-based learning.

In summary, these results provide evidence for the differential involvement of the cerebellum and basal ganglia in decision making, with the cerebellar contribution limited to situations where the outcomes of our decisions depend on action execution.

O3.2 - The hand outperforms the eyes at localizing somatosensory targets

Marion Naffrechoux [1], Eric Koun [2], Alessandro Farnè [2], Alice Catherine Roy [3], Denis Pélisson [2]
[1] *Lyon Neuroscience Research Center (IMPACT Team),* [2] *Lyon Neuroscience Research Center (CRNL), IMPACT Team,* [3] *Dynamique Du Langage Laboratory*
Presenting Author: Marion Naffrechoux

Neural representations of our body state are critical to generate and monitor our interactions with the environment. Among such body representations (BR), the body state estimate is necessary to plan, execute and correct on-line the motor command of goal-directed movements. Despite their crucial contribution to motor behavior, BR are nonetheless distorted even in healthy participants according to several studies testing the localization performance of unseen body parts (proprioceptive or proprio-tactile targets). However, these BR distortions were mostly studied with the contralateral upper limb as a probe. Thus, to determine whether the observed mislocalizations result from a true representational distortion, comparison with another effector, such as the eyes, is required. Such comparison is particularly interesting because the eye and hand motor control systems have distinct properties and rely on partly separate neural substrates.

In the present study, we aimed to assess the accuracy of two effectors (eye and hand) to localize somatosensory targets. Twenty-six healthy participants performed two localization tasks. For the proprioceptive task, they had to localize the index fingertip of their unseen dominant hand positioned passively, at random, at one of two possible forearm positions (10° and 30° of elbow flexion from the initial -horizontal- position). For the tactile task, they localized the vibrotactile stimulus applied to the index finger or to the thumb of their unseen dominant hand (fixed forearm position at 30° of elbow flexion from horizontal). In each task, the localization response consisted of an ocular saccade or a manual pointing with the opposite hand, each response type alternating between saccade and manual blocks of trials. Linear mixed models were applied separately to the horizontal and vertical localization errors to analyse the effect of effector (eye vs hand) and target position (10° vs 30° or finger vs thumb).

Target position affected the localization performance, which generally was more accurate for the 30° proprioceptive target and for the thumb tactile target. Note that, in agreement with previous work, localization responses to proprioceptive targets erred toward the body, as if arm length was underestimated. Also confirming previous studies is the finding that the thumb was less affected by distortions than the index finger. Moreover, the effector affected the localization performance in both tasks: horizontal errors were larger for the ocular responses than for the manual responses. Noteworthy, despite this difference in accuracy, eye and hand effectors led to positively correlated errors, suggesting that they similarly track somatosensory defined positions on one’s arm. This last observation opens the possibility to use the eyes as probes to assess body distortions in populations with upper limb motor disorder (such as Developmental Coordination Disorder or after stroke).

O3.3 - Cerebellar input and output circuits for dexterous movement

Eiman Azim [1], Ayesha Thanawalla [1], Oren Wilcox [1], Kee Wui Huang [1], Elischa Sanders [1]
[1] Salk Institute for Biological Studies
Presenting Author: Eiman Azim

A critical challenge for the sensorimotor system is managing the intricate coordination of dozens of limb muscles to interact with the world with speed and dexterity. Despite the importance of sensory feedback, delays in the transmission of peripheral signals imply an additional more rapid internal feedback mechanism. A prominent theory posits that outgoing motor commands are copied to the cerebellum, where they are used to generate predictions of impending movement outcomes that can be used to compensate for sensory delays and rapidly update motor output. Yet how putative copy signals are functionally organized as they enter the cerebellum and how cerebellar output rapidly refines motor output remain poorly understood.

In a first project, we explore the lateral reticular nucleus (LRN), a brainstem structure that conveys copy signals from the spinal cord to the cerebellum. We find diverse molecular, anatomical, and electrophysiological properties of LRN neurons, suggesting distinct subclasses process different movement related features. Perturbation of LRN neurons disrupts forelimb movements, as revealed by machine learning-based approaches designed to identify kinematic phenotypes. In a second complementary project, we focus on output pathways in the cerebellar nuclei (CN) that impact limb movement through diverse motor targets. We show that anatomically distinct subsets of CN neurons have discrete contributions to forelimb motor control, with separate subclasses capable of eliciting rapid changes in motor neuron activity, muscle recruitment, and movement kinematics. Together, these findings reveal a functional logic to cerebellar input and output pathways that facilitate rapid refinement to enable dexterity.

O3.4 - Kinematic and kinetic signals in monkey and human motor cortex

Elizaveta Okorokova [1], John Downey [1], Charles Greenspon [1], Sliman Bensmaia [1], Anton Sobinov [1]
[1] *University of Chicago*
Presenting Author: Elizaveta Okorokova

Object manipulation requires control over various behavioral variables: kinematic, describing posture and movement of the hand, and kinetic, describing forces. Humans excel at this behavior - the hand conforms to the object's shape and size during reaching, and fingers apply precise forces to hold and move the object after grasping. Previous studies have suggested a more robust encoding of hand postures compared to grasp force in the motor cortical responses of both humans and non-human primates. However, those conclusions were drawn based on the classification of a low number of grasping postures and discreet forces, neglecting the continuous nature of hand movements and changes in applied force. To understand the interaction between posture and force signals in the motor cortex during naturalistic behaviors, we conducted a parallel set of experiments with healthy non-human primates and humans with tetraplegia. In the first set of experiments, we trained non-human primates to grasp sensorized objects with an instructed force level. The object changed size and orientation to evoke different movements. Throughout the experiment, we recorded hand kinematics across 28 degrees of freedom together with the manual forces applied to the object. In the second set of experiments, a human participant was instructed to attempt grasping objects of varied sizes and orientations in a virtual environment with different levels of force. In both experiments, we recorded corresponding neural responses from the motor cortex using chronically implanted Utah electrode arrays. We first characterized the tuning of individual neurons in monkey and human motor cortices to object shape and target force. We have found that individual neurons were modulated to the time course of the task and that the representations of object and force were intermixed. We then built linear and non-linear decoders of continuous kinematic and kinetic traces. Surprisingly, our findings demonstrated that the motor cortex exhibits a robust representation of grasp force, comparable to the representation of the individual components of movement, such as hand orientation, or aperture. Moreover, our investigation into the relationship between neural representations of force and kinematics revealed only weak linear dependence between grasp force and hand posture. These results carry significant implications for our understanding of manual motor control and the creation of the next generation of decoders for brain-controlled bionic hands that can permit dexterous object manipulation.

O3.5 - Leveraging preparatory activity from the human motor cortex for high performance brain-computer interface control

Mattia Rigotti-Thompson [1], Yahia Ali [1], Samuel Nason-Tomaszewski [1], Claire Nicolas [2], Nick Hahn [3], Donald Avansino [3], Domenick Mifsud [1], Kaitlyn Tung [4], Shane Allcroft [5], Jaimie Henderson [3], Leigh Hochberg [6], Nicholas Au Yong [1], Chethan Pandarinath [1]

[1] Emory University and Georgia Institute of Technology, [2] Massachusetts General Hospital, [3] Stanford University, [4] Georgia Institute of Technology, [5] Brown University, [6] Brown University & Massachusetts General Hospital

Presenting Author: Mattia Rigotti-Thompson

Preparatory activity that precedes movement execution is a well-known property of neural activity within the motor cortex. Non-human primate studies have demonstrated that preparatory activity encodes several properties of upcoming movements, such as direction, distance, and speed. However, this wealth of information is usually ignored in intracortical brain-computer interface (iBCI) applications, where control is driven by instantaneous readouts from neural activity during intended movement. In this work, we studied preparatory activity from the motor cortex of human participants with the goal of harnessing it to improve BCI control. We recorded intracortical spiking activity from the precentral gyrus of participants T11 and T5 enrolled in the BrainGate2 clinical trial while they performed 2D cursor control tasks. We first designed a cursor following task where participants were instructed to prepare and attempt movements to a randomly cued peripheral target following a variable but known delay. Consistent with previous studies, we identified a neural trigger signal aligned to the cued movement initiation time at the end of the delay (T11: $r = 0.81$, 147 trials; T5: $r = 0.89$, 167 trials). We also identified preparatory activity that preceded this signal, which showed tuning to the direction of the upcoming movement (decoding $R^2 > 0.40$ for over 250 ms before trigger when delay ≥ 0.6 s, for both participants). As a proof of concept for iBCI use, T11 performed a variant of the task where both movement initiation and intended direction were decoded online from preparatory activity. This allowed T11 to achieve self-paced, rapid control of an on-screen cursor to fixed-distance targets (400 ms movement time, median angular error < 18 degrees, 91 trials). We next characterized preparatory activity for attempted movements that were less-constrained to better resemble practical iBCI control. Participants used an iBCI-controlled cursor to acquire targets in a 2D spatial grid (19 targets) without enforced delays or a fixed start position. We evaluated the decoding accuracy of the intended movement endpoint from neural activity, and found that both endpoint direction and distance could be decoded during the first 400 ms after target presentation (T11: dir. $R^2 > 0.85$, dist. $R^2 > 0.20$, 554 trials, 5-fold cross-val.; T5: dir. $R^2 > 0.80$, dist. $R^2 > 0.30$, 788 trials, 5-fold cross-val.). This demonstrates that neural trajectories are tuned to the direction and distance of the endpoint around the time of movement initiation. Overall, this work is one of the first to characterize the encoding properties of preparatory activity recorded from the human motor cortex and shows the potential of leveraging this activity for high performance brain-computer interface control.

O3.6 - Vestibular stabilization drives gaze control strategies in primate locomotion

Oliver Stanley [1], Ruihan Wei [1], Kathleen Cullen [1]

[1] Johns Hopkins University

Presenting Author: Oliver Stanley

Stable and accurate control of gaze - the sum of the head's position and orientation in space with the eyes' orientation in the head - is integral to activities of daily living, particularly for guiding locomotion. The vestibular system makes critical contributions to both components of gaze control (i.e., head stabilization and visual stabilization). Specifically, the vestibulo-collic and vestibulo-spinal reflexes help keep the head steady in space during locomotion and to counteract unexpected postural perturbations, while the vestibulo-ocular reflex keeps the retinas on-target by driving eye movements to counteract head movement. To better understand the contributions of the vestibular system to behavioral stabilization during locomotion, we assessed gait and the gaze control of two normal rhesus macaques and one with long-term complete bilateral vestibular loss during walking both on a treadmill at varied speeds and during repeated passages of a linear walkway.

We recorded single-eye video-oculography using a head-mounted camera and used a head-mounted 6D inertial measurement unit and retroreflective markers to capture head movement & orientation. Animals' gait was captured in 3D via markerless feature tracking using synchronized cameras set around the behavioral apparatus. As expected, we identified systematic differences in gait and head movement kinematics between normal and vestibular-loss animals.

The macaque with chronic vestibular loss exhibited lower gaze stability and higher variability in limb and head movements, a trend which was exacerbated at higher locomotion speeds. In all animals, gaze shift occupied approximately one quarter of each step cycle on average, and showed modulation with the step cycle during treadmill locomotion. The strength of this modulation was reduced during overground walking. In comparing the frequency and magnitude of gaze shifts during treadmill versus overground locomotion, we found that healthy animals increased the frequency of gaze shifts while the vestibular-loss animal increased the magnitude of those shifts. We speculate that, for animals with vestibular loss, a gaze control strategy using a smaller number of large gaze-correcting shifts may be more efficient than making many small shifts that would be quickly washed out by the gaze instability resulting from the absence of vestibular reflexes. Taken together, these findings establish that the vestibular system provides a foundation of postural and gaze stability that enables more effective motor control strategies during locomotion.

15:00 – 17:00 Session 15, Panel VIII

Current debates on the integration of touch and movement

Tobias Heed [1], Konstantina Kilteni [2], Matej Hoffmann [3], Katja Fiehler [4]

[1] University of Salzburg, [2] Donders Institute for Brain, Cognition and Behaviour, Radboud University, [3] Czech Technical University in Prague, [4] University of Giessen

Discussant: Kathleen Cullen

Sensorimotor research has had a strong focus on visual and proprioceptive information for movement planning and execution. Touch has received much less attention in motor control research, even though movements are often directed towards tactile events, such as an itch or a tap on the shoulder, and every movement evokes tactile sensory input, such as contact with an object (hands) or the ground (feet), hitting an obstacle, or movement of clothing on the skin.

Tactile processing has received more attention in other areas of (cognitive) neuroscience, for instance in the domain of multisensory processing, in which movement is, however, often not taken into account. Yet, research has begun to grow together across domains over the last decade, and there are now a number of ongoing debates on the processing of touch in the context of movement. Our symposium turns to two such debated tactile-motor topics: (1) the attenuation, or suppression, of tactile input when movement is planned or executed; and (2) the spatial coding of tactile events. Our aim is to show how seemingly "clear and logical" ideas have turned out to be incorrect, and to give an outlook on the currently debated, possible alternative explanations.

Regarding (1), human participants are often less sensitive to tactile input when they plan or perform a movement than in non-movement contexts. Current debates revolve around the question whether tactile sensitivity reduction involves predictions of forward models, or whether touch is generally reduced by default during movement. Our talks will highlight different approaches to this question, both in the context of movement towards the own body “ that is, sensitivity reduction for the touch one produces oneself as opposed to the touch one receives without planning “ and movement to other objects “ that is, when touch is "collateral", rather than related to the movement goal per se.

Regarding (2), the focus on visuo-motor paradigms in motor research has stimulated theories about visuo-motor and tactile-motor processing as being analogous. A key tenet of tactile-spatial processing emerging from this approach has been that touch is transformed into a "3D-like, visual" spatial code, and that this 3D spatial code is the basis for planning movement towards touch. On the one hand, findings from neuroimaging seem to fit well with this idea. On the other hand, recent findings from both multisensory decision making and infant tactile-motor development call this idea into question, suggesting that tactile processing may not involve recoding into 3D space and, thus, refuting the idea that visuo- and tactile-motor processing are analogous.

In sum, our symposium focuses on two areas of tactile-motor processing to sketch out the positions of the respective debates, highlight emerging theories and approaches, and point out potential (non-) analogies to visuo-motor theories.

17:00 – 18:00 Distinguished Career Award Presentation and Talk

On the “Neural Control of Movement”

Eberhard Fetz, *University of Washington*

Assuming that the neural control of movement poses answerable questions, we have investigated the relations between primate motor cortex cells and muscles using diverse approaches. First, we trained monkeys to activate motor cortex cells, hoping to reveal their “muscle fields”; this quickly proved to be untenable because monkeys could make many different movements (or none) to fire any cell. Moreover, even consistently correlated cells and muscles could be readily dissociated by operant conditioning. Focusing next on those cells whose spikes causally facilitate muscles (probably via monosynaptic corticomotoneuronal connections) we discovered a variety of relationships in their relative firing patterns. Remarkably, monkeys could even dissociate the activity of CM cells from their target muscles, in both directions (still unpublished), showing that the relative activation of these directly connected elements is surprisingly flexible. The explicit coding of movement parameters by populations of cortical cells turns out to be slippery as well: many different parameters can be extracted from the same population of cells with simple linear decoders. Trajectories of population activity in multidimensional neural space have led to the concept of lower-dimensional manifolds constraining dynamics, suggesting that explanations of movement control are better sought in the properties of manifolds than the roles of individual neurons. Such descriptive exercises are conceptually seductive but evade the harder details about how neural computation in the brain causally generates volitional movements. Toward that end, experiments combining operant conditioning with multiunit recording and neural network modeling could provide further insights.

Satellite Meeting

8:45 – 9:30 Scientific Keynote

Next generation neural interfaces at Neuralink

Joseph O'Doherty leads the Next Gen team at Neuralink. His interests include bidirectional neural interfaces with the nervous system for the restoration of movement and sensation.

9:30-11:00 Session 1: Restoration

Potentiation of cortico-spinal output via targeted electrical stimulation of the motor thalamus
Elvira Pirondini, University of Pittsburgh

Cerebral white matter lesions prevent cortico-spinal descending inputs from effectively activating spinal motoneurons, leading to loss of motor control. However, in most cases, the damage to cortico-spinal axons is incomplete offering a potential target for new therapies aimed at improving volitional muscle activation. In this talk, I will show that by engaging direct excitatory connections to cortico-spinal motoneurons, stimulation of the motor thalamus could facilitate activation of surviving cortico-spinal fibers thereby potentiating motor output and improving voluntary grip force control in monkeys and human subjects.

Restoring touch through a brain interface: local geometric features encoded via patterned microstimulation of human somatosensory cortex
Giacomo Valle, University of Chicago

Intracortical microstimulation (ICMS) of somatosensory cortex (S1) evokes vivid touch sensations, the properties of which can by systematically manipulated by varying the parameters of stimulation. However, natural touch conveys much richer information about objects and our interactions with them, which supports dexterous manipulation. We seek to expand the repertoire of ICMS-based artificial touch, by judiciously designing spatiotemporal patterns of ICMS inspired by our understanding of tactile coding in S1, and thus to confer greater dexterity to brain-controlled bionic hands.

Therapies orchestrated by patients’ own rhythms
Hayriye Cagnon, Imperial College London

One in six people live with a neurological condition, which poses an enormous burden on patients, carers, and the healthcare system. Bioelectronics, in particular stimulation-based therapies, provide an exciting therapeutic alternative due to their focal and reversible nature. However, current approaches almost universally face limits of side-effects, loss of efficacy over time and effectiveness being restricted to a small subset of the patient population. I will present our work on developing and testing stimulation-based therapies, which aim to overcome these challenges.

11:30-13:00 Session 2: Augmentation

Assistive, augmentative and adaptive: Considerations for designing the future body
Dani Clode, Cambridge University

Can you effectively control a robotic thumb with your toes? Can the human brain adapt to the integration of an *extra* limb? And, what implications arise when a traditional prosthetic is replaced with a robotic tentacle? Through a multidisciplinary lens, designer Dani Clode's work not only seeks answers to these questions, but also pushes the boundaries of what we perceive as the future of the human body in the realm of augmentation and prosthetics.

Augmenting Mobility and Motor Performance: Soft Wearable Exosuits in Wellness, Rehabilitation and the Workplace
Lorenzo Masia, Heidelberg University

- *Overcoming Limitations of Rigid Exoskeletons: The Rise of Soft Wearable Exosuits*
- *Restoring Movement and augmenting Human Performance: Advanced Control Strategies in Neurological Rehabilitation and Wellness.*
- *Enhancing the Symbiosis between Man and Exosuits: Machine Learning in Wearable Robotics*

A wrist-based surface EMG neuromotor interface for human computer interaction that works across a population
Abby Russo, Meta Reality Labs

We describe the development of a noninvasive neuromotor interface that allows for computer input using surface electromyography (sEMG). We developed a highly-sensitive and robust hardware platform that is easily donned/doffed to sense sEMG at the wrist and transform intentional neuromotor commands into computer input. We paired this device with an infrastructure optimized to collect training data from thousands of consenting participants. This allowed us to develop generic sEMG neural network decoding models with performant out-of-the-box generalization across people (median performance for test users on a continuous navigation task: 0.5 target acquisitions/second; discrete gesture detection task: 0.9 gestures / second; handwriting task: 19.6 words per minute).

14:00-15:30 Session 3: Future Horizons

Biomagnetic sensing: A high-performance approach to building non-invasive neural interfaces
Nishita Deka, Sonera

Magnetomyography (MMG), or the recording of magnetic fields generated by muscle activity, offers a high-fidelity and robust approach to non-invasively recording motor signals, but has not been well studied due to limitations of existing magnetometers. In this talk, I'll show results from characterization of MMG using a variety of sensors and comparisons to surface electromyography (sEMG). I'll then discuss information content and classification accuracy for a gesture or handwriting task to show how

MMG can be leveraged to develop new inputs for human-computer interfaces. Finally, I'll outline a path to making MMG widely available with our proprietary sensing technology and how this unlocks new use cases in research, consumer electronics and diagnostics.

Next-generation neurotechnology for decoding and regulation of brain states – Virtual talk
Maryam Shanechi, University of Southern California

I will describe our work at the intersection of AI and control theory to enable closed-loop brain-machine interface systems that can not only decode but also control neural activity patterns.

Towards a clinically viable speech neuroprosthesis
Francis Willett, Stanford University

Recent demonstrations of speech BCIs have shown real promise for restoring fluent conversation to people with paralysis. Here, I will discuss our work on high-performance neural decoding of speech using Utah arrys and the outstanding issues that remain. I will also discuss our recent findings on the representation of speech in the brain - although Broca's area does not appear to represent speech, we have identified two separate areas in motor cortex that are specialized for speech and are promising targets for speech BCIs.

16:30-17:10 Non-technical Keynote

The training-technology nexus for neurorestoration and neuroprosthetics
John Krakauer, Johns Hopkins University

The nervous system is experience dependent - it responds to training. Data from animal models to humans shows that behavioral improvement in the setting of a neurological condition is a function of the dose and intensity of training. Neurotechnology can either augment the efficacy of training for neurorestorative effects or training can improve the ability of a patient to use a neuroprosthetic. These interactions between behavior and technology will be explored.

Satellite Poster Abstracts

PS - 1 - Virtual and physical active tool-use training do not change time perception in peripersonal or far space

Jahanian Najafabadi Amir [1], Christoph Kayser [1]
[1] *Bielefeld University*

Previous work has suggested that our perception of time is plastic and dependent on the distance of the stimulus to our body. For example, Annelli et al (2015) showed that stimuli presented in peri-personal and far space are judged differently and that this distance-effect on time perception can be shaped by training participants with a tool that effectively extends the reachable space. These studies indicate that the perception of time can be remapped in an action- and effector-dependent manner. We here aimed to replicate and extend these results using a paradigm in which we tested time perception at multiple distances from the body prior to and following active tool-use training. In two independent studies, we probed 60 participants on three temporal tasks (visual bisection, visual categorization and auditory categorization) for stimuli presented at three distances from the body (60 cm, 120 cm and 240 cm) presented in physical and virtual reality environments. In between testing blocks, participants performed blocks of active tool-use training whereby they used a physical or a virtual mechanical grabber to move coins at a distance of 120 cm from the body. For each task we tested for an effect of spatial distance, tool-use training and their interaction. Our data suggest that in both virtual and real environments, time perception is not affected by the distance of the stimulus to the body and is not shaped by extension of the action-related body by tool-use training. Hence they call into question to what degree and how robustly time perception is shaped by the distance of the probe to the body and how malleable this is by extension of the peripersonal space by tool-use training.

PS - 2 - Neural mechanisms underlying self-regulation of corticospinal excitability; a transcranial magnetic stimulation - evoked potential (TEP) pilot study

Helene Arnold [1], Kathy Ruddy [2], Colin Simon [1]
[1] *Trinity College Dublin,* [2] *Queen's University Belfast*

Corticospinal excitability describes the responsiveness of corticospinal tract pathways to stimulation. While previous studies have shown that corticospinal excitability can be self-regulated with the use of motor imagery strategies, the neural mechanisms underlying this process are not yet fully understood. This study builds upon preliminary findings uncovering how sensorimotor circuits are altered by motor imagery to facilitate or suppress motor output by investigating a relatively new measure of brain activity: transcranial magnetic stimulation-evoked potentials (TEPs). In an operant conditioning paradigm, individuals were trained to increase and decrease corticospinal excitability by receiving feedback on the size of their motor-evoked potentials (MEPs) in response to transcranial magnetic stimulation (TMS). Concurrent electroencephalographic (EEG) recordings enabled the visualization of brain states associated with resting, upregulated, and downregulated corticospinal excitability and the analysis of TEP characteristical differences. Statistical comparisons revealed that the N45 component of TEPs was significantly reduced in the upregulated corticospinal excitability state compared to rest (p<0.05). This is particularly relevant for stroke rehabilitation research, as a comprehensive understanding of the brain state desirable for enhanced motor performance could allow individuals to self-induce a brain state conducive to neuroplasticity as a precursor for accelerated and more pronounced functional recovery.

PS - 3 - Top-down processing activates deprived sensory brainstem nuclei following tetraplegia

Paige Howell [1], Finn Rabe [1], Simon Schading-Sassenhausen [2], Sarah Meissner [1], Patrick Freund [2], Nicole Wenderoth [1], Sanne Kikkert [1]
[1] ETH Zürich, [2] University Hospital Zürich

While the major relay nuclei of the somatosensory stream classically rely on bottom-up input, research in cats and non-human primates has indicated that they are also subject to descending cortical modulation. Whether similar processing exists in humans remains unknown. However, tetraplegic spinal cord injury patients, experiencing partial or complete interruption of ascending sensory input, offer a potential model to explore whether top-down processing might activate subcortical somatosensory nuclei in humans. Here, we investigated whether attempted hand movements in complete tetraplegic patients and partial hand movements in incomplete patients would result in preserved activation within the ventroposterior lateral (VPL) nuclei of the thalamus and the cuneate nuclei of the brainstem. Furthermore, we explored whether the amount of activation correlates with clinical measures of hand function. We found that the canonical pattern of hand activation was preserved in both complete and incomplete tetraplegics despite the absence or only partially intact transmission of bottom-up sensory input. Notably, the amount of preserved activity in patients did not correlate with retained sensorimotor hand function, time since injury, and the amount of preserved spinal cord fibres. Together, these findings suggest, for the first time, that mere cortical processing can preserve activation within the VPL and cuneate nuclei in humans.

PS - 4 - Motor learning mechanisms are not modified by feedback manipulations in a real-world task

Federico Nardi [1], Shlomi Haar [1], Aldo Faisal [1]
[1] Imperial College London

Error and reward feedback are the primary drivers of motor learning and are thought to be processed by two distinct mechanisms: error-based learning and reward-based learning. In lab-based tasks, they are often isolated, while in real-world scenarios it is not easy to separate them. We established pool billiards as a motor learning paradigm (Haar, van Assel, & Faisal, 2020) and showed that individuals use different contributions of error and reward during real-world learning (Haar & Faisal, 2020). Then, to allow for perturbations and visual manipulations, we integrated it into an embodied Virtual Reality (EVR) environment (Haar, Sundar, & Faisal, 2021). In the EVR setup, the VR headset provides visual feedback as the participant plays pool with a physical cue stick and table. Here, we introduced visuomotor rotations and delivered exclusively error or reward feedback to explore the impact of forcing the use of a specific learning mechanism.

32 participants completed two sessions, learning one rotation with error feedback and another with reward, which was in the object's behaviour and not the world coordinates. The sample was counterbalanced in terms of rotation direction and feedback order. While the error feedback displayed

the cue ball trajectory until the ball collision but no pocketing, the reward feedback consisted of a fixed trajectory with ball pocketing for every successful trial. Following previous works in lab-based tasks (Therrien, Wolpert, & Bastian, 2016), a success zone was defined based on improvement from previous trials.

Our behavioural results showed differences between the learning curves with the two feedback. Participants managed to correct the entire rotation with the error feedback but only part of it with reward (Nardi, Haar, & Faisal, 2023 ICORR). Analysing several measures known to behave differently while learning with different mechanisms, such as lag-1 autocorrelation and inter-trial variability decay, we found no difference between the two sessions, indicating that the visual feedback provided in EVR was not enough to force the participants to learn only from specific mechanisms.

We further quantified the brain activity pattern of the two learning sessions, looking at the trend of post-movement beta rebound (PMBR). Previous studies showed PMBR increase during error-based learning and decrease over reward-based learning, even though not in the same task and with the same participants, as done here. While our data suggest different trends with a clear PMBR decrease with the reward feedback, there was no PMBR trend during the error session, suggesting again that while the reward feedback was eliminated in this condition, participants kept using reward-based learning.

These findings underscore the distinction between lab-based tasks and real-world situations, emphasising that while the former are valuable, they may not fully capture the intricacies of how humans learn movement in complex scenarios.

PS - 5 - Neuroplasticity of finger representations induced by a TMS-based BCI-neurofeedback approach

Ingrid Odermatt [1], Sanne Kikkert [1], Manuel Schulthess-Lutz [1], Ernest Mihelj [1], Paige Howell [1], Caroline Heimhofer [1], Roisin McMackin [2], Patrick Freund [3], Nicole Wenderoth [1]
[1] ETH Zürich, [2] Trinity College Dublin, [3] University Hospital Zürich

Brain computer interfaces (BCIs) based on neurofeedback (NF) and motor imagery (MI) can be used in neurorehabilitation to train motor functions without overt movements. However, the neuroplastic changes induced by BCI-NF training remain largely unknown. Here we used finger individuation, i.e., the selective facilitation of single finger muscles, as a model to study neuroplasticity induced by BCI-NF training.

A NF group (N=16) underwent four sessions of TMS-based NF training. Participants were instructed to perform MI of a target finger (thumb, index, or little) to selectively upregulate corticospinal excitability, while downregulating excitability of the other, non-target fingers. TMS-induced motor evoked potentials were used to provide visual feedback about participants finger-specific corticospinal excitability. As expected, the NF group improved finger-selective MEP modulation after TMS-NF training. We did not see improvements in a control group (N=16) without TMS-NF training. Using fMRI and representational similarity analysis, we found that finger MI representations became more dissimilar after training compared to the control group. Further, we observed a finger-specific release of short intracortical inhibition in the target versus non-target MI condition.

Together, these findings show that TMS-NF learning induces neural changes that might be driven by neuroplasticity. Our results pave the way to apply TMS-NF in neurorehabilitation to aid recovery of fine motor functions.

PS - 6 - Task-related changes in connectivity between parietal and parieto-occipital areas in chronic left hemisphere stroke

Elisabeth Rounis [1]
[1] *University of Cambridge*

Introduction:

Limb apraxia, a disorder of skilled action not consequent on primary motor or sensory deficits, has traditionally been defined according to errors patients make on neuropsychological tasks. Recent lesion symptom mapping studies suggest extrastriate visual areas may be important in mediating them. This would suggest that perceptual deficits may account for some subtypes of apraxia. In this study we investigated the possibility of diaschisis affecting perceptual areas in the brain following left hemisphere stroke; and whether this related to patients' apraxia deficits.

Methods:

We conducted a visual-perceptual localizer task involving 29 patients with left hemisphere stroke, comparing their performance to that of 17 age-matched healthy volunteers. Employing a standard block-design localizer task, participants were tasked with observing static colour photographs depicting familiar tools, headless bodies, non-tool objects, and scrambled versions of these stimuli (Valyear and Culham, 2010). Simultaneously, they engaged in a 1-back task. To pinpoint brain regions selectively engaged in tool-related visual processing, we conducted one-sample t-tests ($p<0.05$, FWE corrected) in each subject, seeking areas exhibiting heightened activation for tools in comparison to headless bodies, non-tool objects, and scrambled stimuli. Subsequently, we identified body-selective regions by contrasting activity for bodies against tools, non-tool objects, and scrambled stimuli. Psychophysical interactions were carried out to identify areas of diaschisis between these in patients, comparing them to healthy volunteers.

Results & Conclusion:

Our analyses consistently identified heightened activity for tools compared to other stimuli and bodies compared to other stimuli, respectively. These included pMTG (LOC) region and an anterior region along the IPS for tools and the extrastriate body area (EBA), known to selectively respond to human bodies and body parts when compared to objects and other control stimuli (Downing et al., 2001). The LOC region was consistently positioned laterally, ventrally, and anteriorly to EBA, in line with findings by Valyear and Culham (2010). There was no significant change in activation in any of these regions between healthy controls.

However, PPI analyses to unravel areas of functional disconnection (diaschisis) identified that the left IPS showed increased connectivity with Left LOC in patients versus controls in the tools contrast; conversely, the left LOC and EBA regions appeared disconnected in the bodies task. The study did not involve many patients and therefore we could not identify a reliable effect of praxis errors on these specific functional disconnections.

PS - 7 - EMG control of a hand augmentation technology

Julien Russ [1], Kitty Goodridge [1], Francesco Cenciarelli [1], Hristo Dimitrov [1], Dani Clode [1], Tamar Makin [1]
[1] *University of Cambridge*

Wearable augmentation technologies hold a promise for improving motor control, not only in their functionality but also in their integration into daily life. The diverse applications, from enhanced productivity to improved healthcare outcomes, underscore the potential transformative impact of these technologies on human capabilities. Yet, one key bottleneck in the realization of these technologies is the control mechanism. Since augmentation technologies are designed to enhance motor abilities beyond the biological body, it is unclear how to best output motor control for precise and continuous use, without disrupting the biological body's motor abilities.

Electromyography (EMG) interprets muscles-generated electrical signals ancould offer a direct link between user intent and device response. The potential for seamless non-invasive integration with the human body places EMG as an intuitive and efficient control mechanism, paving the way for a more natural user experience. Nevertheless, EMG also presents challenges for device control. Specifically, the signal can be noisy even after processing, potentially impacting proportional control.

We aimed to evaluate the viability of EMG as a control method for augmentation technologies, using the Third Thumb (Dani Clode design) as a model. Currently, the Thumb is controlled through force sensitive resistors (FSRs) placed under the toes (one per DoF). We compared this validated control system against bipolar EMG surface electrodes. Participants performed a battery of tests, designed to probe Thumb motor control, emphasizing dexterity, cognitive load, proportional control and learning. To probe motor synergy between the Thumb and hand control, the tasks required either individuation, coordination, or collaboration between the Thumb and the biological hand. This series of tests was repeated twice, using the two different control methods: Toe-control FSR and Calf control EMG. For each run of the paradigm, the participants were not informed of the control method they are currently using. This allows an unbiased comparison of motor execution and learning between the two control methods. Further work will aim at isolating two degrees of freedom from the non-augmented arm to control the Thumb as an alternative means for EMG Thumb control using the same motor control paradigm.

Our results will allow us to determine whether EMG control provides a comparable level of motor dexterity and training to learn how to operate the Thumb at the level of traditional FSR control. This will not only exemplify the potential of EMG in enhancing user control but also highlights its potential challenges as an input method for hand augmentation. Overall, we aim to show how EMG-driven control aligns with the broader trajectory of wearable technologies, offering users a tangible extension of their physical abilities.

PS - 8 - The developing homunculus: sensory body maps in children with and without upper limb differences

Raffaele Tucciarelli [1], Laura-Ashleigh Bird [2], Malgorzata Szymanska [1], Mathew Kollamkulam [3], Harshal

Arun Sonar [4], Jamie Paik [4], Tessa Dekker [5], Dani Clode [1], Dorothy Cowie [6], Tamar Makin [1]
[1] University of Cambridge, [2] Durham University, [3] University of Oxford, [4] École Polytechnique Fédérale de Lausanne, [5] UCL Institute of Ophthalmology, [6] University of Durham

The aim of this study was to compare primary somatosensory cortex (S1) topography and activity in the missing hand hemisphere of congenital one-handed children (1h) and adults, relative to typically developed 2-handed (2h) children and adults. Congenital hand loss leads to large-scale neural adaptations in S1 that are not yet fully understood. Recent research in 1h adults indicates that the S1 territory corresponding to the missing hand shows increased activation (relative to 2h adults) when moving various body parts (Hahamy et al., 2017; 2019). It has been suggested that this remapping is facilitated by compensatory strategies - using other body parts to substitute the missing hand function could harness the freed-up hand resources. However, this theory has not yet been empirically validated. Within this theoretical framework, a key prediction is that the sensory representation of the body in one-handers is shaped by the compensatory use of multiple body parts during childhood. The developmental stages of childhood offer a favourable environment for use-dependent plasticity, as during this period, brain organisation is particularly sensitive to activity and experiences. Alternatively, these neural adaptations might be predetermined and thus already present from the onset of development.

We used fMRI to measure somatosensory activity in 1h and 2h children (5-8 years old) and adults (18-65 years old). We stimulated multiple body parts along the body ipsilateral to the missing hand, as well as the intact hand. We also measured compensatory behaviour by having the participants manipulate a controlled series of everyday objects (e.g. opening a book bag, using a toy screwdriver and putting on a glove), with a focus on body-part engagement during the different tasks.

Behavioural results suggest that one-handed children use their legs, torso and face more than both 2h children and 1h adults. Preliminary fMRI univariate results revealed somatosensory remapping of the residual arm representation in the deprived hand area in children as young as 6 years old. Qualitatively, both 1h adults and children show greater activity than two-handed adults and children, specifically in the deprived cortex. One-handed adults show larger responses and more distinct peaks, as do one-handed children. However, the deprived cortex contains less information about alternative body parts in children than in older one-handers. Taken together, the results could suggest continual development of the somatosensory homunculus in later childhood. This in line with the protracted development of manual motor skills. Multivariate representational similarity analysis suggests information about body parts is present in the deprived hand area, especially for the face. Further analysis and modelling will attempt to determine the relative contributions of different body parts based on the developmental period, and links with compensatory behaviour.

PS - 9 - Spatial transformations underlying saccadic eye movements to tactile and visual target stimuli

Celia Foster [1], Maxime Gaudet-Trafit [2], Valentin Marcon [2], Franck Lamberton [3], Wei-An Sheng [2], Suliann Ben Hamed [4], Tobias Heed [5]
[1] University of Cambridge, [2] University of Lyon, [3] CERMEP-Imagerie du Vivant, [4] Institut des Sciences Cognitives Marc Jeannerod, [5] University of Salzburg

Different spatial transformations are required to make saccadic eye movements to tactile and visual stimuli on our body. When we feel a touch, our brain must combine the location of the touch on our skin with our body's current posture to determine the saccade target location in external space. In contrast, when we see a visual stimulus on our body, our brain can prepare the saccade based on just the retinotopic location of the visual stimulus. Nevertheless, some studies suggest that visual stimuli are encoded relative to the body position in frontoparietal brain regions. In the present study, we directly compared the brain networks involved in tactile and visual sensorimotor transformation to determine whether there is shared, multisensory coding of these sensory stimuli in anatomical or external-spatial reference frames, and/or a common coding of the saccade target location regardless of the sensory modality.

Participants made eye movements to visual and tactile stimuli presented on their hands, while we recorded their brain activity using fMRI. Participants were positioned with their arms in uncrossed and crossed postures, such that the right hand was positioned in the left side of space when the arms were crossed. This allowed us to distinguish between coding of sensory stimuli in an anatomical reference frame (relative to the hands) and an external-spatial reference frame (relative to the position in external-space). We further distinguished brain responses involved with sensory processing and saccade planning using a delayed anti-saccade paradigm, where participants only learned the final saccade target location (towards or away from the sensory stimulus) after a delay.

We could decode the anatomical location of tactile stimuli (left vs right hand, regardless of side of space) from bilateral somatosensory, motor and insular cortex, and right interior frontal cortex. We could not decode visual stimuli relative to the hands from any regions. External-spatial tactile location (left vs right side of space, regardless of stimulated hand) could be decoded from a medial region extending from posterior parietal to occipital cortex, and from bilateral lateral occipital cortical regions. External-spatial visual stimulus location could also be decoded from these regions, and classifiers trained to decode external-spatial tactile location could generalise to external-spatial visual location, and vice versa, suggesting a shared multisensory coding. Once the saccade movement goal was specified, a broad network of occipital, parietal and frontal brain regions encoded the saccade target location, in a common coding regardless of whether the movement target was tactually or visually defined.

Altogether, our results demonstrate that both tactile and visual stimulus locations are recoded by parietal cortex into common, modality-independent saccade movement goal locations.

PS - 10 - Explainable deep learning for localizing cortical physiomarkers from deep brain stimulation

Nicolas Calvo Peiro [1], Mathias Haugland [1], Yen Foung Tai [1], Anastasia Borovykh [1], Shlomi Haar [1]
[1] *Imperial College London*

Deep Brain Stimulation (DBS) is a common procedure in people with severe movement disorders - such as Parkinson's Disease (PD), Essential Tremor (ET) and Dystonic Tremor (DT) - once symptoms are no longer manageable with medications. DBS consists in stimulating specific areas of the patient's brain through an implanted electrode. However, stimulation approaches are still rudimentary. Reliable physiomarkers for discriminating neural response from the stimulation are needed to enable a closed-loop adaptive DBS system for personalised therapy.

Here, a deep learning model for agnostic physiomarker search in EEG recordings is presented. Our Convolutional Neural Network (CNN) is based on the EEGNet structure, and our proof-of-concept work of classifying EEG activity during DBS. Our Siamese CNN was created for the EEG-based distinction of different DBS settings (same vs different) within a patient. In addition, an explainability method based on ablation studies is proposed for identifying the spectral location of the features utilized by the model, which can be used as physiomarkers. All the work presented here was done on a mixed cohort of DT and PD patients performing their monopolar review. Due to the nature of the dataset, analysis of different DBS settings was only done for the change in amplitude and contact of both electrodes.

We found that our models could learn to discriminate between DBS settings regardless of the patient's condition. Our models achieved better accuracies when discriminating between contact point rather than stimulation amplitude, suggesting a more pronounced brain response in the former case. Furthermore, we obtained better results when only one hemisphere's electrode was active at a time. This can be simply justified by the fact that, when stimulating with both electrodes, the combined effect of both leads is perceived and therefore changing parameters in a single lead will have a smaller impact in the EEG response, resulting in a lower classification performance. The theta band extraction was attributed to the patients' tremor and the NBG extraction was identified as a potential direct physiomarker for DBS response in EEG data. The channel-wise ablation studies revealed that, as expected, different channels were used for the classification task for the different DBS leads (left vs right), and overall, it showed that accurate classification of the stimulation can be achieved with a single EEG channel, providing it's the right one.

Overall, we have here provided a proof-of-concept of EEG-based DBS setting discrimination and have reaffirmed the recent shift in research from beta band (13-30Hz) physiomarkers to physiomarkers in the NBG range. Our future works will focus on further improving the explainability of the model and on expanding these methods for inter-patient classification.

PS - 11 - Investigating the propagation of beta bursts across the corticospinal tract in Parkinson's disease

Cosima Graef [1], Alejandro Pascual Valdunciel [1], Dario Farina [1], Ravi Vaidyanathan [1], Yen Foung Tai [1], Shlomi Haar [1]

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Increased cortical and subcortical beta band activity (12-30 Hz) and beta bursts are robustly reported neural activity characteristics of Parkinson's disease (PD). Multiple studies suggest their potential as neurophysiological measures for assessing therapeutic efficacy, particularly for closed-loop deep brain stimulation (DBS). While ongoing clinical trials of closed-loop DBS utilise beta power as a physiomarker to adjust stimulation, uncertainties persist regarding how beta power and characteristics of beta bursts respond to stimulation and different symptomatic scenarios. To address these uncertainties, high-density surface electromyography (HDsEMG) emerges as a promising non-invasive neural signal to explore beta activity and bursts' underlying mechanisms along the corticospinal tract.

HDsEMG records muscle activity with high spatial and temporal resolution, enabling a comprehensive electrophysiological assessment. Recent research shows that beta activity occurs in bursting patterns at both cortical and motor unit levels during isometric contractions of the tibialis anterior muscle (Bracklein et al. 2022 JNeurosci). This demonstrates that peripherally measured beta bursts result from cortical projections. Expanding on this, our study replicates these findings using smaller upper limb muscles, and showcases its sensitivity to DBS settings.

We conducted recordings in 15 healthy participants to track beta burst characteristics (e.g. duration, amplitude, rate) at the peripheral and cortical levels. Motor cortex activity was recorded using a 19-electrode electroencephalography (EEG) headset, while forearm muscle activity was monitored using 256-electrode HDsEMG, targeting the extensor carpi radialis (ECR) and ulnaris (ECU). Torque measurements were recorded during a trapezoidal force tracking task during isometric wrist extension, involving various percentages (10%, 20%, and 30%) of maximum voluntary contraction (MVC).

Our analysis involved decomposing a substantial number of motor units for each muscle (up to 21). Exploration into variations in beta burst features showed correlations between HDsEMG and EEG beta bursts, suggesting a degree of coherence between beta bursts occurring within the motor cortex and those in the peripheral regions.

We then ran the paradigm on PD patients who receive DBS therapy, adjusting the amplitude of their DBS during the experiment, to examine HDsEMG signal sensitivity to changes induced by alterations in DBS parameters. Our preliminary results show high sensitivity of the peripheral beta burst features to the changes in the DBS settings.

In summary, we demonstrated the ability to track beta bursts across the corticospinal tract, highlighting its generalisability and sensitivity to DBS settings. This integrated approach holds promise for understanding dynamic changes in the brain during neuromodulation interventions and symptoms fluctuations.

PS - 12 - Neurophysiology vs Neuroanatomy of deep brain stimulation in Parkinson's disease

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Parkinson's Disease (PD) is a progressive movement disorder, where motor symptoms in the advanced stages of which are typically managed using deep brain stimulation (DBS). DBS parameters are determined by trained clinicians though extensive open-loop programming sessions. Those parameters change the neuroanatomical target of the stimulation by changing the overlap of the volume of tissue activated (VTA) by the stimulation with target nuclei. Neural recording during DBS (LFP recordings from the DBS electrode and EEG recordings) have shown the sensitivity of neural oscillations, in the cortex and in the Basal Ganglia, to the change in stimulation. Specifically, activity in the beta band (12-35Hz) was shown to be enhanced in PD patients and decreased by DBS. While both neuroanatomical and neurophysiological aspects of DBS were studied intensively, they were not being studied in conjunction hence there is a limited understanding of their relationships and interactions. Exploring these relationships can improve our understanding of the network effects of DBS and increase the accuracy of DBS optimization. The aim of this study was to determine the role of active electrode location, and corresponding overlap of the VTA with target nuclei, on cortical oscillatory activity during changes in DBS settings in Parkinsonâ€™s disease patients.

Cortical recordings were obtained with mobile EEG during routine DBS parameter adjustment visits in the clinic. Arm tasks were used by the clinician to determine the efficacy of the DBS settings. From these task periods, aperiodic and periodic spectral features, as well as band-related bursting features (amplitude, duration, and rate), were extrapolated for the beta band. To obtain the volume of overlap corresponding to the DBS settings, leads were localised by merging pre-operative MRI and post-operative CT scans in LEAD-DBS (Horn & Kuhn 2015 NeuroImage). The location of the active electrodes was identified and VTA overlap was calculated with the corresponding nucleus. Following the extraction of these physiomarkers, the delta between them for each pair of DBS settings was calculated.

Typically, active contacts were found either near the subthalamic nucleus (STN) or the globus pallidus interna (GPi). While stimulating the STN, increase in overlap correlated with a decrease in beta burst amplitude and duration which was in line with expectations. This was incongruent with GPi stimulation, where increase in overlap was associated with increase in beta burst amplitude. Moreover, relationships between periodic and aperiodic features were investigated and showed different trends depending on stimulation location. We further demonstrate how neurophysiological response to DBS changes when small changes in the location of the active electrode change the nucleus being primarily stimulated.

PS - 13 - Intracortical local field potentials as stable signals for across-user brain-computer interface control

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Accurate decoding of user intent is central to many augmentation and assistive technologies, including brain-computer interfaces (BCIs) that allow individuals to control a computer cursor or a robot with their thoughts, and neuroprostheses that translate thought into action via electrical stimulation of sensorimotor pathways.

Current approaches typically map the activity of hundreds of simultaneously recorded neurons into control signals. Albeit successful, these approaches are limited by the current lifetime of intracortical electrodes for recording neural spiking activity, for which the number of recorded units decreases over time (and fluctuates over days). Interestingly, intracortical local field potentials (LFPs) that capture synaptic processes in the proximity of a recording electrode can be usually monitored even after detection of neural spiking has become impossible (Tomislav Milekovic et al *J Neurophysiol 2018*). Combined with their good predictive power (Flint et al *J Neurophysiol* 2015; Stavisky et a *J Neural Eng* 2015), LFPs may be an attractive alternative as control signals for BCIs and neuroprostheses.

However, the use of intracortical LFPs as control signals still faces at least two major challenges. First, micromovements inside the brain or encapsulation processes lead to changes in the recorded signals that can translate into decoder accuracy degrading over time. Second, in contrast to everyday tech products, LFP decoders still need to be computed on a subject-by-subject basis.

Here, we combined a series of studies from our group to overcome both challenges. We have shown that, in the sensorimotor cortices, specific LFP bands exhibit a robust similarity with the latent dynamics that capture the coordinated spiking activity of a neural population (Gallego-Carracedo et al *eLife* 2022). In another series of studies, we were able to show that latent dynamics, which we recovered from different populations of spiking neurons, allow stable decoding of movement kinematics for up to two years of experiments (Gallego, Perich et al *Nature Neurosci* 2020). Besides, these latent dynamics are preserved across individuals engaged in the same task, which enables transferring decoders across subjects (Safaie, Chang et al *Nature* 2023). As predicted from these results, we could align specific LFP bands to achieve both stable decoding across sessions within an individual, and decoder generalisation across individuals. In all cases, decoder performance for the most predictive bands was virtually identical to an upper bound derived using within-session decoders trained on spiking activity.

Thus, decoders based on intracortical LFPs could be readily deployed for accurate, stable control across individuals. Thanks to the current availability of devices that record LFP signals, such an approach may accelerate the deployment of systems for robust closed-loop control of neuromodulation therapies or assistive and augmentation technologies.

PS - 14 - Stochastic Dynamic Operator (SDO) descriptions of neurons can flexibly scale from single-unit to population-level analysis

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In the spinalized bullfrog, the hindlimb wiping reflex is a model spinal motor behavior. During wipe, we record populations of spinal interneurons, single motor units from muscles, and intramuscular EMG activity across the major muscles of the hindlimb. The spike-triggered average (STA) is -ubiquitous to identify the connectivity and effects of spinal interneuron spikes on motor behavior. However, STA does not include spinal state (e.g., locomotor or wiping phase). We find both interneurons and single motor units show strong state-dependent effects. To unify our observations, we use the *Stochastic Dynamic Operator* (SDO) framework to test state-dependent and probabilistic relationships in the data. SDOs describe the predicted *change* in probability distribution of state given an initial state distribution, connected to spiking events. Spike-triggered SDOs from individual interneurons and motor units show significant, state-dependent, relationships across subsets of EMG channels, consistent with synergy. The SDO matches or improves performance over the STA for predicting signal behavior near spiking events during reflexive wipe. SDOs can also be generated from applied stimuli, such as intraspinal microstimulation (ISMS). Using SDOs, the response of a population to stimulus or perturbation is modeled as the superposition of the stimulus-triggered SDOs of component neurons. SDOs may be used as a basis for stochastic controllers recruited by gain schedules. If gain schedules are regulated by cyclical processes, SDO controllers capture rhythmic or oscillatory phenomena (e.g. locomotion). SDOs bridge the state-dependent modulation by individual neurons with the evolution of the spiking population, and the associated motor output. The SDO may thus be a useful tool spanning characterization of neurons as both single units and network components, and their neuromodulation.

PS - 15 - Yoga as a natural model for motor learning in a null space

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Learning how to coordinate muscles across the body to achieve a specific pose often converges around a narrow set of common solutions despite the multitude of possible configurations. This convergence reflects skill learning, which aims to reduce effort and variability. Experts may develop multiple effective solutions within a null space, aligned with their physical capabilities, as long as critical task elements are maintained. This study uses yoga as a rich model for motor control due to its demands for precise muscular engagement, breath, flexibility and coordination. During practice, natural motor redundancy and practice variations enable multiple executions of a pose, often appearing outwardly correct. However, such variations may conceal risks due to compensatory mechanisms employed to achieve aesthetic alignment. As such, whether experts develop more robust or more versatile pose signatures might offer a unique insight to contrast with lab-based skill learning.

We recorded muscle activations during yoga using surface electromyography (EMG) in 10 yoga experts and 10 intermediate practitioners across two sessions in an ecological environment. EMG data from eight muscle groups during 13 yoga poses (eight rounds of repetition) were analysed to extract "pose signatures" and compare them within and between sessions, participants, and expertise levels.

We hypothesized that experts exhibit more consistent muscle activation across sessions than novices due to refined motor skills. Intermediates, in comparison, who are still developing a consistent strategy within the redundant skill space, will show more variability within and across sessions. However, considering the inherent variability in achieving a pose, we anticipate observing more inter-individual variations within the expert group relative to the intermediate group. This is because experts develop unique motor solutions for each pose, while intermediates will demonstrate more versatile strategies with greater overlap across practitioners.

Preliminary findings reveal a high degree of within-session consistency in both groups across repetitions. However, variability across participants remains substantial, indicating multiple viable strategies for pose execution. Further analysis aims to investigate across session results and elucidate temporal dependencies within sessions and assess energy expenditure based on muscle engagement percentages.

This research aims to deepen our understanding of the mechanisms used to reduce the solution space within the complex motor control environment of yoga. By observing the natural variability of practitioners, we seek to explore the complex motor skill learning dynamics between effort and variability minimization outside the imposed constraints of controlled lab environments. Moreover, the techniques developed here for pose signature determination hold promise for enhancing training safety and efficacy across various sports and skill levels.

PS - 16 - Closed-loop model-based optogenetic neuromodulation enables high-fidelity fatigue-resistant muscle control

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Closed-loop neuroprostheses show promise in restoring motion in individuals with neurological conditions. However, conventional strategies based on functional electrical stimulation (FES) fail to accurately modulate muscle force and exhibit rapid fatigue because of its unphysiological recruitment mechanism. Here we present a closed-loop control framework that leverages physiological force modulation under functional optogenetic stimulation (FOS) to enable high-fidelity muscle control for extended periods of time (>60 minutes) *in vivo*. We first uncovered the force modulation mechanism of FOS, showing more physiological recruitment and significantly higher modulation ranges (>320 percent) compared to FES. Second, we developed a neuromuscular model that accurately describes the highly non-linear dynamics of optogenetically-stimulated muscle. Third, based on the optogenetic model, we demonstrate real-time control of muscle force with improved performance and fatigue resistance compared to FES. This work lays the foundation for fatigue-resistant neuroprostheses.

PS - 17 - Multifunctional, adaptive and interactive AI system for acting in multiple contexts

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Future prosthetic and assistive devices will be much more proactive than current human-machine interfaces, exploiting brain signals and other currently unconventional means of communication, such as gaze and gestures, to perceive human intentions and convey feedback. Such a rich bidirectional communication will require AI-based decoding where both the device and the assisted person will likely need to learn and adapt to each other. The complexity of the interactions and their importance to the assisted activities will require particular attention on trust in the communication, as well as more general trustworthiness in the AI interface and assistive devices. We aim to enact this vision by developing techniques for AI-based decoding of motor intentions with bidirectional feedback between the user and the AI devices that supports mutual learning and trust building. The proposed intentions decoder takes input from neural (posterior parietal and motor cortices) as well as behavioral (kinematics and gaze) signals and applies predictive coding techniques to learn to infer the desired human intentions. A lighter non-invasive version of the interface is built around intuitive and natural communication by gaze movements that typically precede any manual or bodily action. Identified targets of the intended actions are highlighted upon a gaze shift on the target. Oculomotor reactions to this signaling are used by the user as a means to convey to the decoder a mismatch and therefore improve the decoding. A testbed scenario is navigation on a wheelchair and reaching objects with a robotic arm.

PS - 18 - Ventral motor cortex activity supports neural cursor control by a person with paralysis

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Intracortical brain-computer interfaces (iBCIs) offer the potential to restore communication for people with paralysis due to neurological disease or injury such as ALS or stroke. Typically, hand-based iBCIs for cursor control are driven by electrodes in dorsal precentral gyrus (dPCG), whereas iBCIs for speech decoding use electrodes in ventral precentral gyrus (vPCG). It was unknown whether an iBCI can enable both cursor and speech functionality if all the electrodes were implanted in vPCG (to maximize speech decoding accuracy).

In this study, we demonstrate for the first time cursor and click control driven by neural activity recorded from microelectrodes (four 64-electrode Utah arrays) in vPCG. This cursor iBCI was used by participant T15, a 45-year old man with ALS enrolled in the BrainGate2 clinical trial. T15 achieved a bitrate as high as 1.83 bits per second (average 1.68 bps) in a target grid selection task. This result suggests that iBCI users may be able to have arrays placed only in vPCG in order to operate both a cursor and speech iBCI, offering the flexibility of a multimodal iBCI without compromising on speech decoding accuracy.

In a simultaneous cursor and speech task, vPCG-driven cursor control was more susceptible to interference from attempted speech than in prior studies of dPCG-driven cursor control. Exploring and addressing this, perhaps through finding orthogonal cursor and speech neural subspaces in vPCG, warrants future study.

PS - 19 - Anisotropy of temporal resolution on the hand dorsum

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Spatial perception of touch on the hand dorsum has been shown to be distorted, depending on the orientation axis of the delivered stimulus. Here, we show that temporal perception of touch follows a pattern similar to spatial perception, where the mediolateral and proximodistal axes have different temporal resolutions.

Twenty participants underwent a temporal order judgment task (TOJ), where they judged the order of two stimuli successively delivered on the hand dorsum. The experiment was designed in a 2-by-2 factorial design. One factor was the skin axis; whether the two stimuli were aligned with the mediolateral axis or aligned with the proximodistal axis. Another factor was the posture, where the participant's hand orientation was either extended (fingers pointing ahead) or flexed (90Â°rotated relative to the body). The latter factor was to examine the skin-space dependency, thus the tactile RF dependency, of the effect.

We found that the temporal resolution, measured as just noticeable difference (JND) of TOJ, was higher (smaller JND) for the mediolateral axis compared to the proximodistal axis, irrespective of the hand posture (main effect of skin axis; $p<0.05$).

Due to the anisotropy of the receptive field shape on the hand dorsum, stimuli on the mediolateral axis have a higher probability of crossing more RFs than the proximodistal axis, which can enhance the temporal segregation of the tactile inputs. Therefore, our result suggests that the anisotropy of the tactile receptive field may not merely affect the spatial processing, but also shapes the temporal processing of touch.

PS - 20 - Precise cortical contributions to sensorimotor feedback control during reactive balance in aging and Parkinson's disease

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The cortex's role in shaping motor output during balance remains poorly understood. Balance is largely mediated by subcortical circuits with the cortex becoming engaged as needed. We hypothesize that subcortical and cortical sensorimotor feedback loops contribute to balance correction, with cortical contributions increasing with balance difficulty, aging, and Parkinson's disease. We recorded whole-body kinematics, electromyography, and electroencephalography during balance recovery to examine relationships between hierarchical circuits and their engagement across balance tasks of varying difficulty in older adults and people with Parkinson's disease.
We use a neuromechanical model to reconstruct balance-correcting muscle based on a quantitative relationship to sensory information encoding balance error. In young adults, we showed that balance correction is primarily subcortically mediated at low levels of difficulty. As balance difficulty increases, additional muscle activity appears that follows similar relationships to balance error at a latency consistent with transcortical sensorimotor feedback and cortical responses to perturbation. Here we show that people with Parkinson's disease exhibited increased cortically-mediated antagonist muscles a than older adults without Parkinsonâ€™s disease, indicating disease-related impairments hinder the efficacy of cortical contributions to balance.

PS - 21 - Open-source solutions for accurate hand markerless kinematics measurement using web cameras

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We present a novel markerless tracking pipeline for 3D kinematics using web cameras and standard computing resources. Leveraging Google's MediaPipe for robust 2D tracking and Anipose for model alterations, camera calibration, and triangulation, our setup captures detailed hand and body movements without specialized equipment. The pipeline further offers hand shape and orientation metrices, aimed at intuitive motor and postural measurements.

Our system's reliability was tested with five participants over ten hours of recordings. Using a simple setup of three cameras and a desktop computer, synchronized with a red LED light, participants performed actions involving three seconds movement and grasping of various objects. Videos were trimmed (using the LED indicator), 2D marker positions were then obtained via MediaPipe, and 3D triangulation and joint angle calculations were obtained via Anipose. Furthermore, we computed circular medians of joint angles and hand shape/orientation estimates for comparison. Marker detection failure rates, frame-to-frame consistency, temporal smoothness, and a classification analysis were conducted to evaluate pipeline reliability, robustness, and capability.

The kinematic measurements results demonstrate high consistency, with low coefficient of variation and high intraclass correlation coefficients. Low overall failure rate due to occlusion or rapid movement, but frame-to-frame cross-correlation and temporal smoothness were notably high, given the complexity of the problem. Furthermore, using the computed features and a simple classifier, we obtained high gesture classification demonstrating ability to identify differences even within similar hand movements. Processing on a standard laptop (Intel Core i5-8300H, Nvidia GeForce GTX 1060, 16GB RAM) was under 10s with moderate CPU/GPU utilization.

Further aspect the integration of Anipose into our pipeline is its option for model re-training and alterations via its DeepLabCut integration. It enables tracking of tools, prostheses, or augmentation devices like artificial body parts. This adaptability enhances the technology's applicability in diverse research, allowing tracking of interactions between humans and artificial elements, marking a significant advancement compared to other approaches. This is something that we will be investigating further in future developments of the pipeline.

This research underscores the advancements in open-source software for markerless tracking and contributes to the democratization of motion analysis technology, bridging the gap between high-end, cost-prohibitive systems and accessible solutions. By simplifying the acquisition and analysis of kinematic data, we hope to enable a broader spectrum of users to explore and benefit from detailed motion analysis. Our ongoing efforts are focused on refining this pipeline to further its accuracy and applicability in multiple lines of research.

PS - 22 - Enhancing balance in the older adults: a tailored approach integrating postural training and proprioceptive stimulation

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This study investigates the impact of an 8-week balance training program, with and without superimposed proprioceptive stimulation, on balance and gait performance of older adults. Proprioceptive stimulation was applied through muscle vibration, transcutaneous electrical nerve stimulation or their combination, those stimulation modalities being known to target Ia afferent fibers from muscle spindles, crucial for sensorimotor integration. A total of 49 healthy elderly participants (80 years Â± 4) were randomly assigned into different groups: training (n=8), training + local vibration (n=10), training + transcutaneous electrical nerve stimulation (n=14), and training + local vibration and transcutaneous electrical stimulation (n = 17). All participants followed an 8-week intervention period, with two 1-hour sessions per week. The training sessions involved tailored postural exercises with and without proprioceptive stimulation targeting the triceps surae and tibialis anterior muscles. Outcome measures included the Berg Balance Scale, 6-minute walking test, 10-meter walking test, Time-Up and Go test, and Center of Pressure variables during static postural tasks. Our results suggest that tailored balance training effectively improves balance but does not significantly impact gait performance in older adults. Moreover, combining tailored balance training with proprioceptive stimulation did not potentiate the observed benefits.

PS - 23 - Generalisation of motor skill learning with a hand augmentation device

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The integration of robotic augmentation devices represents a frontier in enhancing human motor abilities. We investigated the behavioural aspects of motor learning, adaptability and resource allocation trade-offs in motor integration of a toe-controlled extra robotic thumb (the Third Thumb, Dani Clode Design) in hand skill. Over seven days, 30 individuals were trained in laboratory and at-home sessions to use the Thumb in tasks requiring both independent and collaborative movements with their natural fingers. Changes in augmented-hand motor skills, generalisation and alteration of lower limb abilities for these augmentation participants were evaluated against two control groups: an active control group (n=20) engaged in one-hand piano training to develop hand-toe coordination without using the Thumb, and a passive control group (n=18) that received no training.

Augmentation participants demonstrated clear improvements in motor skills, underscoring their ability to acquire novel motor skills using the Third Thumb and advocating for the success of at-home training. We also observed broad training-driven generalisation, where augmentation participants demonstrated the ability to transfer acquired motor skills to untrained tasks, even when using different body parts to control and wear the Thumb, and to untrained body postures, suggesting that the learning process involved might encompass aspects beyond traditional motor learning mechanisms.

We next examined whether this diverse new set of motor skill come with bodily costs. Therefore, we explored the effects of using the toe-controlled Thumb on balance, finding a modest but significant decrease in balance performance when participants used or wore the device, with no difference in impact between passive wearing and active control, and regardless of training. We also investigated the after-effects of Thumb use on participants' balance capabilities when not using the device. In this context, there appeared to be a tendency for a reduction in the ability to balance freely after Thumb training, while the Thumb was not being worn. Despite these preliminary evidences being not entirely conclusive yet, they underscore the need to understand the potential lasting effects of using augmentation devices on existing motor skills.

Overall, our results revealed the possibility of acquiring robotic augmentation specific motor skills, which resulted broadly generalisable beyond trained tasks and settings. However, they also highlighted potential trade-offs with regards to natural abilities of controlling toes. This highlights the complexity of integrating augmentation devices with the motor control of the human body, suggesting a need for further research on impacts and long-term effects on the biological body.

PS - 24 - Comparison of pathways for sensory feedback for wearable devices

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Our motor system relies on somatosensory feedback to inform about the current state of our limbs and their interactions with the external environment. Accordingly, great resources have been devoted to creating artificial somatosensory feedback for wearable robotics (such as prosthetics and body augmentation technology). However, the natural tactile feedback received from where such devices are worn on and controlled by the body has been crucially overlooked. This intrinsic sensory feedback may be harnessed to inform about device somatosensation, and may even be more easily integrated and less cognitively demanding than artificial feedback.

This study aims to consider the utility and limitations of intrinsic feedback compared to its artificial counterparts. We created three sensory feedback systems for use with the Third Thumb (Dani Clode Design), a supernumerary robotic finger worn on the hand. The first had no artificial feedback, and just utilised the intrinsic feedback naturally received on the side of the hand during Thumb usage. We then developed a vibrotactile feedback system where vibration produced by objects engaging with the tip of the Third Thumb elicited an equivalent level of vibration delivered via a ring on the user's ring finger. Lastly, we developed a skin stretch feedback system where deformation received on the tip of the Third Thumb produced a proportional amount of linear skin stretch on the user's inner wrist.

We first considered a series of perceptual tasks, where participants received sensory feedback without actively using the Third Thumb. This informs us about whether participants can extract meaningful information from the feedback. Participants (*N*=20) performed a texture discrimination task and a material density discrimination task with each feedback system. We predicted that the vibrotactile feedback would excel at the texture task whilst the skin stretch feedback would excel at the material task. Our results successfully demonstrate this pattern when the feedback is compared to the respective other artificial feedback system. However, we found that the intrinsic feedback performed comparably to each of the artificial systems on their preferred task. This demonstrates that interpretable sensory information can be extracted from this natural feedback, and artificial sensory feedback may not provide additional value.

We then compared performance differences when these feedback systems are used in an active motor task (*n*=20 per feedback group). In this ongoing study, participants complete a fragile egg task aimed at assessing proportional control abilities before and after training on a series of Third Thumb-biological thumb collaboration tasks. Preliminary findings demonstrate that all participants can perform the task. The outcomes will inform us whether artificial feedback provides helpful information during active object interactions, or conversely negatively impacts smooth motor control and learning.

PS - 25 - Can the somatosensory cortex integrate a tactile representation of an extra robotic body part?

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Motor augmentation technologies, such as the use of an extra robotic finger, present novel sensory and motor challenges that probe the adaptability of our body representation. This study investigates the primary somatosensory cortex's (S1) role in integrating a new robotic limb, the Third Thumb (Dani Clode Design), by examining changes in somatosensory processing and motor skill acquisition over a seven-day period. We assessed changes to the tactile hand representation before and after a week of altered finger-synchronisation motor training: either due to extended Third Thumb training (*n=30*), or training to play the keyboard (*n*=20), with an additional passive control group that receive no training (*n=20*). We used fMRI to study the representational similarity patterns across the biological fingers and Third Thumb (via intrinsic touch) before and after training.

During the training, participants engaged with the Third Thumb in a range of tasks, with most of the training achieved during an unsupervised, at-home, training regimen. Participants achieved significant improvements not only in tasks they directly trained but also in untrained tasks, showcasing a broad learning effect, underscoring the capacity for flexible motor learning to achieve versatile skills. The active control group also demonstrated significant improvement in keyboard playing tasks.

Next, we examined whether the brain is able to use tactile input arising as a natural by-product of wearing the Third Thumb (intrinsic feedback) to support motor learning, and how this information is integrated with that of the biological fingers. At baseline we observed that S1 processes vibrotactile feedback from the Third Thumb in a topographically appropriate alignment to the biological fingers, but distinctly from that of the skin where it is attached. Following training, the representational similarity between the intrinsic feedback of the Third Thumb and the biological fingers and palm has increased, hinting at an integrative adaptation to the augmentation device.

In addition, both the Thumb and the keyboard training groups showed a reduction in the biological inter-finger information content. This suggests that the effect may be at least partially due to the abrupt changes in the finger synchronisation patterns these active training paradigms induces.

Overall, our preliminary findings suggest that successful Third Thumb training triggers adaptive changes to the representation of the Thumb in relation to our body, above and beyond an alternative finger skill learning. While training-induced changes to the biological hand representation may be tied to the alterations in finger synchronisation patterns over the week of training, we also find early evidence of further Third Thumb specific changes. We tentatively conclude that the primary somatosensory cortex is able to change the representation of the biological body to account for the use of an additional limb.

PS - 26 - Decoding hand movements with optomyography

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Muscle contractions are often used as control signals to wearable assistive devices such as prostheses and exoskeletons. Non-invasive myography is of particular interest for such applications because of its ease of implementation and the possibility of individual adjustments. Electromyography has been widely used for sensing muscle activity. Yet, electromyography recordings have limitations, including changes in skin-electrode contact, mechanical artifacts, interference from power supply and interference from other muscles. To overcome these problems, new types of myography have been proposed, particularly optomyography which utilizes optical sensors placed on the skin to measure displacement and tension in the underlying tissue. In optomyography, optical data are collected using an infrared light that passes through the skin. Here we introduced an optomyography-based approach for decoding hand movements. Optomyographic signals were recorded in five participants performing hand movements. The data were classified to extract hand configuration, angle and movement direction. We suggest that this approach could enrich the control of wearable devices.

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PS - 27 - Enhanced prosthetic hand control through AI and VR integration for intuitive and natural finger movements

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Introduction: Surface electromyography (sEMG) is a widely used method for prosthetic control. Unfortunately, most applications are not intuitive and only allow users to perform a limited set of gestures, using movement classification or switching between gestures with several base commands.

Methods: We created a system using virtual reality (VR) to collect data on precise hand movements. The system included aggregation of sEMG data from the forearm to develop a control system for prosthetics. We developed an AI model to decode continuous movements from the muscle activity. This approach allows for intuitive control of a prosthetic hand, enabling natural movements for individuals with amputations and congenital hand underdevelopments.

Results: We collected a 50 hours dataset of hand movements paired with sEMG signals, and trained an AI model to accurately predict intended movements in real-time for individuals with hand disabilities. Our system demonstrated high accuracy in identifying continuous, precise finger movements and wrist rotations in amputees, enabling intuitive and natural control of a hand in VR.

Conclusions: Our research emphasizes the significant potential of sEMG in improving prosthetic hand control. It points towards a future where individuals with amputations can experience enhanced motor control through such technologies.

PS - 28 - Perception of weight and effort with an upper limb soft exoskeleton

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Lightweight soft upper limb exoskeletons (exosuits) offer flexible support for anti-gravity tasks, without restricting natural movements. By reducing muscle effort and delaying fatigue, they show promise in both industrial settings and assisting people with motor impairments. Previous studies have primarily focused on biomechanics and subjective user experience. However, the success of this technology relies on its ability to reduce perceived effort without impairing weight perception. Understanding how these devices impact user's perception and action is therefore crucial.

We addressed three questions 1) How does wearing an exosuit affect individual's ability estimate weight? 2) What influence does repeated experience with an exosuit have on motor adaptation and learning? 3) How is individual's perception of effort altered when using an exosuit?

Participants are involved in two sessions (exosuit on and exosuit off). Surface electromyography (EMG) is used to track differences in muscle activity within and across both sessions. In Task 1, based on the seize-weight illusion, participants consecutively lifted two boxes for weight estimation and confidence rating. We predicted a dissociation between perceptual and sensorimotor expectations over time, which will be exacerbated by the exosuit. Preliminary analysis indicates exosuit users initially display reduced illusion effects and confidence levels, aligning with controls over time, suggesting an improvement in sensory discrimination after repeated experience.

Task 2 involves a reinforcement learning paradigm in a volatile environment. Two boxes labelled A and B were used. Participants are informed that, typically, one of the boxes is predominantly heavier while the other is predominantly lighter. However, these weight contingencies may change at some point, and participants do not have prior knowledge of such alterations. Participants are presented with either box and are required to guess whether the presented box is heavier or lighter. Subsequently, they are instructed to lift the box. We hypothesise that wearing an exosuit may reduce the learning rates.

Task 3 involves an effort-reward decision-making task. Participants are asked to choose and lift either a low-effort, fixed-low-reward box or a high-effort box with rewards ranging from Â£3 to Â£7. Depending on their choices, participants receive an additional monetary bonus. We hypothesise that with the exosuit on, perceived effort will decrease, leading to a preference for the high-reward box.

Our findings will allow us to comprehend how wearing an exosuit impacts motor learning, weight estimation and perceived effort. In a world where wearable robotic devices are rapidly evolving and being commercialised, understanding the effect that this technology has on people's ability to interact with the environment is vital.

PS - 29 - Auditory noise improves postural control in children with and without autism spectrum disorder: A pilot study

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Recent studies have reported improved postural stability with auditory noise in healthy adults. To understand the neural underpinnings of augmented auditory stimulation, assessing whether the effect can be generalized to individuals with sensory challenges like autistic children is of importance. We examined the effectiveness of environmental auditory noise in autistic (ASD) and typically developing (TD) children.

To test the hypothesis that both ASD and TD children improve postural stability with auditory stimulation, 27 children (ages 6-12, 16 ASD and 11 TD) performed tandem stance while hearing environmental sounds resembling 1/f noise at 75-80dB (NOISE condition) and 43-47dB (NORMAL condition). We assessed postural stability using center of pressure (CoP) velocity. To identify the relationship between sensory and motor features, their sensory difficulties were characterized using the Sensory Processing Measures, a parental survey. Results showed that postural stability improved in the NOISE condition for both ASD and TD groups. We also found that those with severe auditory difficulties exhibited reduced postural stability in the NOISE condition.

In sum, our results demonstrate the positive influence of sensory augmentation on postural control even in autistic children. The findings provide insights into the role of stochastic resonance in the auditory domain that enhances vestibular function. Future studies are warranted to further elucidate the underlying neural mechanisms regarding sensorimotor augmentation.

PS - 30 - Investigating the modulation of muscular null space for the control of supernumerary degrees of freedom

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Prior research has demonstrated the potential of muscular null space modulation for robotic augmentation, where the muscular null space, defined as muscle activation patterns not directly related to task-relevant forces, could be utilized to control supernumerary degrees of freedom. This approach would enable simultaneous control of both natural limbs and a supernumerary end-effector. In a previous study (Gurgone et al. 2022) we computed the null space from the matrix that approximates the mapping of EMG activations over 15 muscles onto isometric force, estimated by linear regression from EMGs and forces for multiple target directions. In this study, we aim to compare this method with a direct approach in which participants are instructed to activate specific muscles while minimizing the isometric force production. We compared these two approaches using the same EMG recording setup or a simpler configuration that only included data from six muscles, two of which used high-density electrode arrays. To compute the EMG-to-force matrix, participants performed a task where they had to reach and hold a cursor at various planar targets by generating forces on the horizontal plane. Participants were then asked to increase the EMG amplitude of targeted muscles while minimizing isometric force production. We then extracted a few components explaining most of the variation of the EMG patterns during the modulation of EMG amplitude for all muscles. We assessed the dimensionality of these components and their relationship with the null space obtained from the EMG-to-force matrix. The overall objective is to reveal the crucial parameters to optimise the setup for practical use and improve the identification of controllable null space dimensions.

PS - 31 - Integrating visual perception in assistive robotics for human augmentation

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Human locomotion is a complex interplay of sensory inputs, with vision playing a crucial role in adapting to varying terrains and obstacles. Emphasizing parallels between the role of visual cues in humans in navigating the environment, this study delves into the integration of visual perception in a robotic assistive hip exosuit to augment human movements during walking.

Our approach leverages *geometric modelling-based computer vision* to dynamically adjust assistance levels during tasks involving stairs and level walking. The algorithm assesses scene components captured by an RGB-D camera by considering plane orientations, interconnections, dimensions, and composition. Unlike prevalent machine learning-based methods, our control framework operates without the burden of training constraints and computational overload, ensuring real-time adaptability to changing environments. This paradigm shift opens avenues for more efficient and responsive assistive technologies, catering to individual needs and preferences.

Evaluation with six subjects yielded promising results, with a classification accuracy of 93.0 Â± 1.1%.

Notably, assistance guided by artificial visual cues significantly adjusted assistive torque during stair ascent (+33.95 Â± 8.80%) and reduced it during descent (-17.38 Â± 6.02%) compared to conditions without visual input ($p < 0.05$). This modulation of assistive torque closely mimics the natural modulation of human biological torques during such tasks, reflecting the seamless integration of visual perception into the control framework.

Additionally, our study revealed a significant reduction in metabolic cost of transport with the vision-based assistance algorithm. Specifically, during stair ascent, there was an average reduction of -18.93 Â± 4.08%, which was statistically higher ($p < 0.05$) with respect to a condition without assistance modulation by visual inputs and with respect to an unassisted condition.

In conclusion, this research demonstrates the effectiveness of integrating visual perception into assistive robotics, offering promising avenues for the development of personalized and adaptive assistive technologies aimed at empowering individuals with enhanced movement capabilities. The seamless integration of visual perception not only enhances the adaptability and responsiveness of assistive devices but also contributes to optimizing energy expenditure and improving overall movement economy.

PS - 32 - Epidural stimulation with viral BDNF therapy improves recovery of function after SCI, delays onset of viral side effects, and maintains observed hindlimb muscle synergies and motor modularity

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Some interneuronal circuits in the spinal cord that project directly onto motoneurons may be organized for modular muscle control, as synergy groups, rather than individually. EMG recordings reflect the premotor network drives, and potential modular network structures, allowing inferences of modular spinal circuit changes after spinal cord injury (SCI) and rehabilitation. Using dimensionality reduction techniques (ICA) on hindlimb EMG, our lab has presented modular spinal circuit structures in neonatal, adult, injured and uninjured rats. Here, we employed ICA to study changes in spinal circuits throughout rehab using combination therapies for SCI in rats. Although each therapy modality, rehab robotics training, biological (viral BDNF), and epidural stimulation (ES), improves function individually, we understand little about their synergistic interactions functionally. We also have limited knowledge of the effects of such combination therapies on muscle activation patterns and their underlying neuronal circuits. These might reflect different neuronal control strategies for motor coordination applied through recovery. Our lab has demonstrated enhanced locomotor outcomes in rats with complete T9/10 SCI after combining robot training with viral BDNF and ES. Prior work revealed a potential critical period during the initial two weeks of training, where ES likely attenuates hyperreflexia development that can be an effect of the BDNF treatment on motor function. Hyperreflexia can result in the eventual collapse of gained motor function in ~40% of rats. Broad-current spread ES centered at L2 and S1 prevented collapse over 6 weeks when combined with viral BDNF and robot rehab. Here, we tested if combined therapies with ES can prevent collapse beyond 6 weeks and if more selective ES can further improve locomotion. We hypothesized that the combined treatment using localized ES would more selectively target the central pattern generators at L2 and S1, resulting in improved stepping. We also hypothesized modularity analysis of the hindlimb muscles would reveal spinal circuit reorganization and alteration or preservation of spatial synergy structure across the different rehab treatments and outcomes. Our data show that suprathreshold ES extends the therapeutic window of BDNF to significantly improve assisted locomotion. The increasing prevalence of clonic movements after 6 weeks suggests that ES delays hyperreflexive collapse caused by sustained overexpression of BDNF. ICA of the hindlimb EMGs supports a conserved modular control of locomotion after SCI. We here observe high post-SCI correlation values of the weighting matrices and synergy matching in all groups. This suggests preservation of spatial synergies after SCI and rehab, and regardless of collapse outcome. Future analysis will explore the differences in the temporal activation patterns and drives across these outcomes to better understand the progression of collapse and its prevention or delay by ES.

PS - 33 - An accurate and rapidly calibrating speech neuroprosthesis

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Brain-computer interfaces (BCIs) can provide a rapid, intuitive way for people with paralysis to communicate by transforming the cortical activity associated with attempted speech into text. Despite recent advances, communication with BCIs has been restricted by requiring many weeks of training data, and by inadequate decoding accuracy. Here we report a speech BCI that decodes neural activity from 256 microelectrodes in the left precentral gyrus of a person with ALS and severe dysarthria. This system achieves daily word error rates as low as 1% (2.66% average; 9 times fewer errors than previous state-of-the-art speech BCIs) using a comprehensive 125,000-word vocabulary. On the first day of system use, following only 30 minutes of attempted speech training data, the BCI achieved 99.6% word accuracy with a 50 word vocabulary. On the second day of use, we increased the vocabulary size to 125,000 words and after an additional 1.4 hours of training data, the BCI achieved 90.2% word accuracy. At the beginning of subsequent days of use, the BCI reliably achieved 95% word accuracy, and adaptive online fine-tuning continuously improved this accuracy throughout the day. Our participant used the speech BCI in self-paced conversation for over 32 hours to communicate with friends, family, and colleagues (both in-person and over video chat). These results indicate that speech BCIs have reached a level of performance suitable to restore naturalistic communication to people living with severe dysarthria.

PS - 34 - Human subjects can utilize tactile feedback delivered via contactors sliding on their forearm skin to detect finger postures with a task-dependent feedback channel dominance

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Tactile and proprioceptive senses from our limbs are crucial for motor planning and execution as well as the sense of embodiment. Sensory substitution offers a promising avenue to address impaired senses by conveying pertinent information through intact sensory pathways. In this study, we initially explored whether healthy subjects could accurately estimate the angle of a single joint solely based on the tactile feedback provided by a probe sliding along their forearm. Subsequently, we expanded our study by incorporating three probes to relay feedback about the positions of the thumb, index, and middle

fingers, facilitating gesture detection and object size discrimination tasks. Actuated by linear servo motors, the tactile probes moved based on the postures of the corresponding fingers, while control signals were generated through either a program or a sensorized glove worn by an experimenter across different sessions. Our findings revealed that while subjects exhibited improved joint angle detection with tactile feedback compared to no feedback conditions, performance did not reach parity with visual feedback. Moreover, subjects effectively utilized tactile feedback for hand gesture recognition and object size differentiation. Modeling analyses underscored the collective contributions of all three tactile probes to user responses in all tasks, with the index finger assuming particular significance in size discrimination tasks. These results underscore the potential of sensory substitution to enrich sensory experiences and augment motor control among individuals with motorized prostheses, highlighting the necessity of comprehending user preferences and task-specific requirements in the development of such systems.

PS - 35 - Similar oscillatory mechanisms map touch on hands and tools

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Numerous studies have found evidence that tools become incorporated into a plastic neural representation of our body, suggesting that our brain re-uses body-based neural processing when we use tools. However, little is known about how this is implemented at the neural level. Here we used the ability to localize touch on both tools and body parts as a case study to fill this gap. Neural oscillations in the alpha (8-13 Hz) and beta (15-25 Hz) frequency bands are involved in mapping touch on the body in distinct reference frames. Alpha activity reflects the mapping of touch in external coordinates, whereas beta activity reflects the mapping of touch in skin-centered coordinates. Here, we aimed at pinpointing the role of these oscillations during tool-extended sensing.

To this aim, we recorded participants’ oscillatory activity while tactile stimuli were applied to either hands or the tips of hand-held rods. Posture of the hands/tool-tips was uncrossed or crossed at participantsâ€™ body midline in order for us to disentangle brain responses related to different coordinate systems. We found that the scalp distributions of alpha and beta modulation were nearly identical when touch was on the body or on a tool. Only alpha oscillations were modulated by posture, suggesting that they are related to tactile processing in external spatial coordinates. Furthermore, source reconstruction of this space-related alpha modulation revealed a similar bilateral network of parieto-occipital regions involved in mapping touch on tools and on hands.

In conclusion, we found that the brain uses similar oscillatory mechanisms for mapping touch on a hand-held tool and on the body. These results support the idea that neural processes devoted to body-related information are being re-used for tool-use. Furthermore, since alpha-band modulation followed the position of touch into external space, this is the first neural evidence that tactile localization on a hand-held tool involves the use of external spatial coordinates.

PS - 36 - Sensory peripheral electrical stimulation decreases intermuscular coherence and phase difference between the wrist flexors and extensors in essential tremor patients

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Sensory peripheral electrical stimulation is a promising intervention to suppress upper-limb tremors in Essential tremor. Open-loop sensory and closed-loop stimulation strategies are reported to provide short-term tremor suppression using accelerometer. However, the impact of these strategies on the muscle activity is unknown. We examined the change in intermuscular coherence and the phase difference in the muscle activity of the wrist flexor and extensor following open-loop (OLS), closed-loop (CLS), and compared to a control (CON; no stimulation) condition in four Essential tremor patients. Patients held two postures (arms stretched and flexed close to chest), for 30 seconds each, before and after each intervention. EMG signals from the flexor carpi radialis and extensor carpi radialis were measured for both arms during the postural holds. Change in peak intermuscular coherence and mean delays (phase difference) between the wrist flexor and extensor muscles in the tremor band were computed for both arms. Linear mixed effect models with factors of Condition (OLS, CLS & CON) were used for statistical comparisons. Change in peak coherence was significantly lower with CLS ($p < 0.001$). Similarly, the shift in phase was significantly larger with CLS ($p < 0.001$). No statistical difference were observed for the other two conditions. Results suggest that closed-loop stimulation strategy had significantly larger changes in the neuromechanics of the wrist extensor and flexor muscles.

PS - 37 - The myokinetic control and stimulation interface: a robotic platform to study kinesthesia in humans

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Significant efforts have been devoted to providing sensory feedback for upper limb amputees, primarily concentrating on tactile sensation restoration, leaving challenges related to proprioceptive feedback relatively unaddressed. *Magnetomicrometry* introduces a novel approach exploiting implanted magnets for wireless tracking of muscle tissue, thereby offering a direct assessment of their physical contraction to facilitate control of prosthetic or assistive devices. Additionally, implanted magnets present an unprecedented opportunity to stimulate musculotendon proprioceptors (muscle spindles and Golgi tendon organs) through untethered selective vibrations (**Figure 1**). This study tackles the challenge of simultaneously tracking multiple moving magnets, such as those associated with muscle contractions, while subjecting them to controlled vibrations generated by external coils. Validation of the system's feasibility in precisely vibrating moving magnets was conducted using 4x2 mm NdFeB disk magnets affixed rigidly to a viscoelastic substrate simulating the stiffness of muscular tissue. Physical oscillations of the magnets were analysed via video assessment with a high frame rate camera (1000 fps), and a comprehensive evaluation of tracking accuracy and precision during vibration delivery was performed for both single and multiple magnets (up to four) in presence and absence of the actuating magnetic fields. The results demonstrate the capability of a real-time system to simultaneously track and vibrate multiple moving magnets within a forearm-sized workspace (99th percentile male). Furthermore, highly selective torsional vibrations within the frequency range known to elicit the tendon illusion (70, 80, and 90 Hz) were achieved on two moving magnets, with over 80% of spectral power (Î³) concentrated at the desired frequency (**Figure 2**). Moreover, vibration frequency remained coherent during the entire magnet motion, exhibiting a nearly constant spectrogram over time. On the other hand, tracking accuracy and precision remained robust against the influence of the coil magnetic field, with median position errors below 1.2 mm and median displacement errors, e_D, below 0.95 mm under multiple testing conditions (involving different vibration directions, *x* and *z*, and torque amplitudes, 40 and 80 Î¼Nm) (**Figure 3**), thus below the expected excursions of magnet following muscle contractions (around 5-6 mm). This study marks a significant advancement in the field of sensorimotor restoration and augmentation, toward the establishment of a bench system for studying proprioception, and in particular kinesthesia, in humans. This innovative device offers a distinctive approach that holds promise for future clinical trials involving magnetomicrometry, enabling the study of sensations arising from the targeted activation of muscle-based kinesthesia while minimizing interference from skin mechanosensory receptors.

PS - 38 - Using multimodal neuroimaging to guide implantation of brain-computer interfaces

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Invasive brain-computer interfaces (BCIs) have the potential to restore, and even augment, our motor and sensory abilities. A critical step towards the complete realization of this vision is deciding where in the brain to implant devices that can provide rich enough, task-relevant neural signals to meet the unique demands of the BCI (e.g., operating a robotic arm, providing artificial sensory feedback). To guide BCI implantation, rather than relying solely on neuroanatomical landmarks, which have an inherent degree of person-to-person variability, one solution is using functional neuroimaging techniques (fMRI, MEG) to map brain activity to localize potential BCI implantation sites. While several groups have found neuroimaging to be helpful in this regard[1â€“3], we still do not know whether neuroimaging functional activity accurately predicts the content of the recorded neural signals and location of sensations evoked by the implanted device. Understanding the similarities and differences between these datasets is essential for guiding future BCI implantation. In the present study, we directly compared predicted pre-implant neuroimaging sensorimotor maps to observed post-implant neural recordings and stimulation-evoked percept locations. We tested five individuals with tetraplegia as part of an ongoing BCI clinical trial. Prior to implantation, participants underwent multimodal neuroimaging (fMRI, MEG or both) while attempting to move individual body-parts (e.g., fingers, arm, lips) to define pre-implant sensorimotor maps. Using these maps to guide implantation, participants were implanted with four intracortical microelectrode arrays with stimulating capabilities [two in primary motor cortex (M1); two in primary somatosensory cortex (S1)]. From the pre-implant neuroimaging data, we identified clear somatotopic organization of the body across sensorimotor cortices for all participants. When comparing the location of the anatomical hand knob to peak functional hand activity in M1 or S1, we observed significant variability across participants, suggesting that anatomical landmarks alone are not sufficient for localizing optimal somatotopic sites. After implantation, we observed that intracortical microstimulation of the S1 arrays evoked sensations of the fingers and palm in all participants. Additionally, intracortical neural recordings from the M1 arrays during attempted movements showed some somatotopic organization. Qualitatively, the predicted pre-implant neuroimaging maps were highly similar to the observed body maps captured from the intracortical neural recordings in M1 and the stimulation evoked sensations in S1. While we demonstrate that neuroimaging activity is a good predictor of intracortical recordings and stimulation evoked sensation locations, we highlight the similarities and differences between these datasets that will impact BCI implantation. Overall, the present study provides a roadmap for navigating BCI implantation.

PS - 39 - Examining asymmetric activation of mirror neuron networks in stroke EEG during motor imagery

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In recent years, the integration of motor imagery into rehabilitation strategies has enhanced stroke prognosis. Traditional protocols for motor imagery in stroke therapy have typically involved simple, unilateral movements focused on a single upper limb, limiting the full potential for rehabilitation. In this study, we introduce and evaluate a novel motor imagery protocol based on the breaststroke swimming style, which engages both upper limbs simultaneously. We investigate the impact incorporating this unified functional motor imagery protocol has to increase neuroadaptation and enhanced functional connectivity across brain regions, particularly within the delta and alpha EEG frequency ranges. We assess the effectiveness of this innovative motor imagery approach and establish correlations between task-specific EEG measures, such as the delta-alpha ratio, and clinical outcomes measured by the Fugl-Meyer Assessment. This allows us to derive a clinical diagnostic measure reflecting the activation of the human mirror neuron system from scalp EEG signals obtained from a cohort of 30 subjects, including 18 hemiparetic stroke patients and 12 healthy controls. Our analysis reveals a simultaneous suppression of the EEG mu frequency band and acute alterations in the pairwise delta to alpha EEG frequency band ratio during both the planning and execution phases of the motor imagery protocol. Specifically, we observe changes in EEG power that indicate asymmetry across brain regions in chronic stroke survivors, particularly during the execution phase compared to the planning and resting phases. Furthermore, our study links these EEG power asymmetries, particularly in the delta, alpha, and mu frequency bands, to the Fugl-Meyer motor assessment scores. This highlights the significance of these frequency bands in representing brain circuit dynamics and underscores their potential as biomarkers for stroke rehabilitation. Overall, our findings offer neurobiological evidence supporting the efficacy of a bilateral unified functional motor imagery protocol in stroke rehabilitation. Moreover, they identify distinct brain circuit dynamics as a potential clinical feature and biomarker of stroke recovery.

PS - 40 - Wearable myoelectric interface for neurorehabilitation (MINT) conditioning reduces abnormal co-activation and improves arm function in chronic stroke

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Arm impairment from stroke is due not only to weakness, but also to abnormal muscle co-activation (abnormal synergies). Our previous studies showed that in-lab training with a myoelectric computer interface (MyoCI) designed to counteract this abnormal co-activation can reduce this co-activation and may improve arm function (Seo et al, 2022). The MyoCI training maps EMGs in the co-activating muscles to orthogonal components of cursor movement, providing intuitive feedback that enables stroke survivors to reduce co-activation. Here, we present results from a randomized controlled trial investigating the efficacy of a wearable version of MyoCI called the myoelectric interface for neurorehabilitation (MINT). MINT conditioning is gamified and performed at home, which increases motivation and enables a high training dosage.

Chronic stroke survivors were randomly assigned to train with 3 different MINT variations (providing feedback about 2 or 3 muscles simultaneously) or a sham control group (providing feedback on one muscle at a time to control for a non-use effect). All groups engaged in 90-minute daily sessions, 6 days per week for 6 weeks; muscle sets were changed every 2-3 weeks. Fifty-nine participants completed the training. Participants in all experimental groups improved by a mean of 4 s in the primary outcome, the Wolf Motor Function Test, after 6 weeks compared to baseline (p=0.0007), exceeding the minimal clinically important difference of 1.5 s. Participants who trained 3 muscles simultaneously improved by 6.8 s compared to baseline (p=0.006), while the sham group did not significantly change from baseline (p=0.28). Further, the 3-muscle group improved at 6 weeks by significantly more than the sham group (p=0.02) and continued to improve 4 weeks after ending therapy (9.4 s vs. 3.4 s, p=0.02). Notably, even individuals with severe impairment improved significantly. Experimental groups also improved their reaching range of motion, while the sham group did not; thus, improvement was in the affected arm itself, not compensatory.

We used nonnegative matrix factorization to perform muscle synergy analysis on EMGs from 9 muscles during reaching. MINT conditioning did not change the number or composition of synergies overall. However, the disparity index (DI), a measure of within-synergy co-activation between the trained muscle pair, increased in the first two muscle pairs trained with MINT, indicating reduced co-activation was specific to these two muscle pairs and did not affect other muscles in the synergy. Further, reduced co-activation, particularly in the first muscle pair trained (which was also the most abnormally co-activating pair), correlated with improved arm function. These results provide evidence that abnormal co-activation causes impaired arm function after stroke. They further indicate that home-based, wearable MINT conditioning can improve arm function in chronic stroke survivors with moderate to severe impairment.

PS - 41 - Limits of neural stimulation for prosthetic control: tactile afferents cannot follow high rates of electrical stimulation

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Background:

Sensory feedback for prostheses improves use and embodiment, with rejection often being due to lack of sensory feedback [1]. Sensory feedback for natural touch arises from patterns of tactile afferent firing involving rates of up to several hundred spikes per second (Hz). Most prosthetic feedback systems attempt to replicate these patterns through electrical or mechanical stimulation of peripheral nerves where it is generally assumed that high-frequency electrical stimulation generates a 1:1 response between stimulus pulse and afferent spiking. However, human upper-limb amputees with intraneural electrodes are unable to distinguish electrical frequencies above 50 Hz [2], whereas healthy subjects can discriminate mechanical frequencies over 200 Hz. To explore this discrepancy, we investigated responses of individual low-threshold tactile afferents to both stimulation modalities, in humans (median nerve microneurography) and rats (teased sciatic nerve).

Methods:

Single-unit recordings were performed in both species. Afferents were classified as fast- or slowly-adapting based on response to indentation. Following classification, electrical (gel surface electrodes) or pulsatile mechanical (shaker and probe) stimulation was delivered at 50, 100 and 150 Hz.

Results:

While some units (including slowly-adapting afferents) could maintain a 1:1 response to mechanical stimulation up to 150 Hz for at least 1 second, they were largely unable to do so for electrical stimulation above 50 Hz.

Significance:

We directly observed neurophysiological evidence of tactile afferent inability to follow high-frequency electrical stimulation. This introduces considerations in stimulation for prosthetic limb control and builds on psychophysical findings described by Bensmaia's group.

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PS - 42 - Neural basis of manual coordination in human motor cortex

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Manual interactions with objects involve coordinated movement of many joints of the hand, from the wrist to the tips of the fingers, an ability critically dependent on motor cortex (MC). Thus far, nearly all of our insights into the neural mechanisms behind manual dexterity have come from work with monkeys, the closest animal model to humans. However, there are anatomical differences in both the musculoskeletal and nervous systems of monkeys and humans, and monkeys cannot easily be instructed to produce repeated, complex hand movements. Here, we investigate human hand movement control, ranging from isolated single digits to coordinated movement of the fingers and wrist, leveraging a clinical trial with 5 participants implanted with electrodes in MC. We found that single digit flexion and extension movements were represented along different axes in neural state space, likely associated with the different actuating muscles. We discovered that MC decoders of attempted finger movement depended on the participant's imagined wrist posture. Although a given decoder performed well within a condition, its ability to generalize between postures was limited, the representations in MC of wrist and fingers intertwined, potentially the result of extrinsic hand muscles that span the wrist. We investigated the coordinated control of multiple digits by having the participants attempt to shape their hands into several different postures. We found that the neural responses in MC did not simply reflect a superposition of the MC responses of the constituent isolated digit movements. Together, these results provide a detailed characterization of the neural basis of coordinated manual behavior in humans and a foundation for decoding manual behavior from MC.

PS - 44 - Manipulating task-relevant artificially evoked somatosensory feedback in a bidirectional brain-controlled guitar playing game

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Intracortical microstimulation (ICMS) of the somatosensory cortex can restore spatially explicit touch sensations in a person's paralyzed hand[1,2] and improve the performance of a brain-controlled prosthetic arm[3]. This novel source of sensory information has been shown to evoke electrode-dependent responses in the motor cortex when the participant is at rest[4]. However, whether and how these artificial sensations modulate motor cortex activity during task-performance remains unclear. If ICMS is processed similar to natural touch, one would expect a motor cortex response that depends on the ongoing motor task and informativeness of the incoming sensory signal. In this study, we investigate the neural communication of ICMS via implanted microelectrode arrays (Blackrock Microsystems, Inc.) in the somatosensory and motor cortices of three participants with tetraplegia during a bidirectional brain-controlled guitar playing game. During this task, participants not only play the strings via imagined finger movements, but also feel what string they play via ICMS. Occasionally, the sensation was evoked on a finger incongruent with the ongoing motor task. Participants reached a motor performance (total match between the timing and type of instructed and decoded finger movements) of 70-78% in absence of stimulation. These finger-specific neural responses persisted during ICMS, as classifier performance remained stable in presence of congruent ICMS. If the observed electrode-specific neural responses are more than straightforward electrical propagation due to inserted charge, we expect them to differ with respect to the imagined (in)congruent finger. This would show that ICMS-evoked sensations can become a meaningful part of the sensorimotor loop.

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PS - 45 - Neural Data Transformer 3: a foundation model for motor decoding

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For decades, intracortical motor decoding has used bespoke models per experiment to adjust for changes in the observed data. However, motor data also conserves statistical structure across time, behavioral tasks, and even subjects. This fact motivates decoders that exploit prior data to efficiently decode in new settings. In particular, deep neural networks (DNNs) directly trained on data from prior days can then rapidly adapt to new days. This example suggests a simple strategy to dissociate further factors of variability that frustrate robust decoding, such as somatosensory or cognitive state: fit a DNN across broad variability to decode robustly under it. This principle has been validated in the extreme in recent natural language and computer vision models, trained at internet scale to yield models of proportionally foundational utility.

We propose a foundation model for intracortical motor decoding, trained on 2000 hours of paired primate neural population activity and motor covariates, called Neural Data Transformer 3 (NDT3). NDT3 adapts with minimal data to decode arbitrary kinematic dimensions or EMG signals at a level that matches or exceeds specialist models prepared on the target datasets. We demonstrate scaling of model performance with both dataset and model parameter count in offline decoding analysis. These properties suggest NDT3 may be a prime candidate for the first widely available, large scale deep network to improve motor decoding from intracortical data.

PS - 46 - A modular architecture for trial-by-trial learning of redundant motor commands

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During movement planning and execution, the central nervous system needs to coordinate the activity of a large and redundant set of muscles acting on multiple joints. Although an ample body of evidence suggests the existence of muscle synergies that simplify the problem of coordinating the multiple degrees-of-freedom of the human body, the mechanisms governing changes at the muscular level during de novo learning tasks (which likely involve both changes to synergy recruitment and synergy structure) are still poorly understood. In this study, we present a computational model for the generation of redundant muscle activity patterns during isometric force-reaching tasks where explicitly defined modules, implemented as spatial muscle synergies, can be updated together with their recruitment coefficients. This update is performed by the backpropagation of the force error through a forward model of the isometric task. This internal model can in turn be updated, reflecting learned changes in the task environment. Our model can predict how muscle synergies structures, their recruitment, and the force error correction change over multiple days of practice with de novo learning tasks. Such a computational model may improve the understanding of neural mechanisms through which the different components of a modular architecture are adapted trial-by-trial in the presence of

visual errors and may be useful in the development of novel motor rehabilitation and augmentation technologies.

PS - 47 - Neural avalanches to design innovative sensorimotor-based brain-computer interface

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Most of Brain-Computer Interface studies rely on local measurements disregarding the interconnected nature of brain functioning. Here, we proposed an original marker: the neuronal avalanches, propagating cascades of bursts of activity among brain regions. We used electroencephalography signals from 20 subjects during resting state and motor imagery tasks. To track the probability that an avalanche would spread across any two channels/region we built an avalanche transition matrix.

Within the use of Support Vector Machine classifiers, we compared the performance resulting from avalanche transition matrix to a baseline approach, Common Spatial Patterns. In both sensor and source-space our pipeline yielded significantly higher classification accuracy than current golden standard approach in the most of subjects and a smaller inter-subject variability.

We investigated the interpretability of these findings by comparing the selected features and the set of edges where a significant condition effect was observed in most of the subjects, â€œreliableâ€� edges. We observed that a large correspondence between these them conducted to an improved classification performance. Consistent patterns were observed across electrodes over motor areas connected to parietal and occipital areas, suggesting the involvement of multiple cognitive processes during a motor imagery task.

Our results suggest that integrating periodic and aperiodic features could pave the way to innovative neurotechnology designs.

Poster Sessions

Poster Session 1

Tuesday April 16, 2024

A – Adaptation & Plasticity in Motor Control

1-A-1 - Role of contextual cues on the expression of competing motor memories

Adarsh Kumar [1], **Neeraj Kumar** [2]

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Details

Learning two competing sensorimotor perturbations can be achieved when each perturbation is associated with a distinct contextual condition, encompassing both physical parameters and underlying neural dynamics. However, the understanding of mechanisms underlying the expression of these competing motor memories is not very clear. This study investigates the role of contextual cues on the formation and retrieval of competing motor memories, focusing on the phenomenon of interference. Interference occurs when some memories hinder the acquisition and retrieval of others. We hypothesized that contextual cues play a crucial role in guiding memory formation amidst interference and that the expression of competing motor memories depends on the amount of training, congruency of contextual cue and memory recency. Using a visuomotor rotation task, participants made a planner movement between start and target circles in a virtual realty setup where hand was occluded and hand-position was provided by a cursor feedback. The task involved two competing adaptations: a 30-degree clockwise rotation (Task A) and a 30-degree counterclockwise rotation (Task B). Each task was associated with a different secondary target, with feedback clamped to zero-error for reaches to this target. This secondary target predicted the rotation type, serving as a contextual cue for the motor plan. We conducted three experiments to examine the role of context in memory expression. Experiment 1 involved learning Task A for 160 trials, Task B for 20 trials, followed by null clamp trials (Task N) providing zero-error feedback under different contexts. Context-dependent memory expression was observed, with Task A memory expressed in Context A and Task B memory in Context B. In the absence of context, Task B memory briefly appeared but quickly decayed back to baseline behavior. Experiment 2, with equal exposure to both tasks (160 trials each), demonstrated dominant Task B memory expression in contexts B and no context, while Context A led to Task A memory expression. This suggests that with sufficient practice, the latest motor memory tends to prevail, even without contextual cues. Experiment 3 involved interleaved Task A and B trials. Similar dominance of Task A and Task B memories in specific contexts was observed. However, in the absence of context, behavior returned to baseline, emphasizing the importance of context in memory formation and retrieval. These findings highlight the critical role of contextual cues in the expression of competing motor memories, supporting the idea that contextual information is essential for guiding memory formation, retrieval, and expression amidst interference. Understanding how the brain deals with interference and enables spontaneous recovery enhances our knowledge of motor learning. This has implications for designing rehabilitation protocols and learning strategies that optimize motor memory retrieval and adaptation by leveraging the power of context.

1-A-2 - Neck muscle vibration in SCNP leads to differential changes in neurophysiological measures in response to visuomotor tracing task

Alexandre Kalogerakis [1], **Paul Yielder** [1], **Hailey Tabbert** [1], **Ushani Ambalavanar** [1], **Bernadette Murphy** [1]

[1] Ontario Tech University

Details

Individuals with subclinical neck pain (SCNP) exhibit altered sensorimotor integration (SMI), presenting as impaired proprioceptive awareness and decreased ability to acquire a novel visuomotor tracing task. Past work found that neck muscle vibration in healthy adults impaired upper limb proprioception and motor skill acquisition, while those with neck pain showed immediate improvements in neck and elbow joint position sense. It is likely that vibration-induced changes in muscle spindle discharge improved SMI in SCNP participants, but it is unknown whether vibration improves the ability of those with SCNP to acquire a visuomotor tracing task, and impact somatosensory-evoked potentials (SEP) peaks related to SMI, which this study addresses.

Eleven right-handed SCNP participants aged 21.8 ±1.7 were randomly allocated to vibration (V, n=4, 2F) or no vibration (NV, n=7, 6F) groups. Both groups had vibrators affixed over the right sternocleidomastoid and left cervical extensor muscles. Short-latency SEPs were elicited via right median nerve stimulation at 2.47 Hz and 4.98 Hz and collected via a 64 channel EEG cap (ANT Neuro) before and after acquisition of a motor tracing task (MTT). Following the pre-acquisition phase, the V group received 10-minutes of 60 Hz vibration, while the NV group had 10-minutes of rest, with vibrators in place but turned off. Participants then completed the acquisition and post-acquisition phases. Retention was assessed 24 hours later.

The V group showed greater increases than NV in the following SEP peaks: N13 (38% vs 10), N20 (33% vs 7%), P25 (28% vs 4%). The N11 increased by 23% vs a 10% decrease for NV, while the N18 increased by 33% vs an 18% decrease in NV. In contrast, the N24 decreased by 5% in V compared to a 20% increase for NV. The N30 increased by 6% for V vs 14% for NV. The NV group showed greater improvements in normalized error from pre- to post-acquisition (NV:22%, V:15%) and from post-acquisition to retention (NV:31%, V:25%)

These preliminary results suggest differential changes in SEP peaks associated with somatosensory processing at the level of the spinal cord (N11), primary somatosensory cortex (N20 and P25), olivary-cerebellar pathway (N18), and cerebellar-somatosensory pathway (N24). Both groups showed small increases in early SMI (N30). The smaller improvement in motor performance for the V group alongside differences in several SEP peaks related to SMI (N30), cerebellar processing (N18 and N24) and somatosensory processing (N20 and P25) suggests that the transient alterations in muscle spindle discharge induced by vibration, may have impacted early somatosensory processing, which in turn impacted the ability to learn the MTT. Given that past work has shown that neck vibration on its own does change SEP peak amplitudes, it is likely an interactive effect of vibration on the MTT that is responsible for the differential SEP peak alterations. Further work is needed to confirm these results.

1-A-3 - Long-term development of a motor memory

David Franklin [1], **Pascal Nietschmann** [1], **Thalia Papadopoulou** [1], **Sae Franklin** [1]

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Details

Humans exhibit remarkable abilities in learning motor skills. While motor performance continues to improve, even after years of practice, most studies examine the learning of novel dynamics over hundreds of trials. That is, most of our understanding of the parameters and characteristics of motor learning rely on studies examining only the early adaptation processes. While some studies of complex task adaptation have examined thousands of trials, the adaptation to a single velocity-dependent force field is usually considered to be complete within a few hundred movements. Here we investigate motor adaptation to a single novel force field with over seven thousand trials and multiple weeks of training, to uncover the process of human motor learning. Ten right-handed participants performed training sessions once every week for eight consecutive weeks, with a follow-up session fifteen weeks later to assess retention. Participants performed forward reaching movements with their right hand using a robotic manipulandum in a velocity dependent curl force field. Throughout the sessions we probed the adaptation process by measuring the decay, spontaneous recovery, retention, angular generalization, and transfer of the motor memory to the opposite limb. Participants adapted quickly to the dynamics, showing a fast reduction in kinematic error and a rapid increase in predictive force compensation within the first session. Importantly, we find continuous adaptation over the subsequent sessions. Moreover, there is strong retention of the predictive forces between sessions, increasing gradually until the fifth session. We observe a strong increase in spontaneous recovery between the first and seventh session, indicating a stronger motor memory, but little change in the decay rates over the training weeks. Despite extensive training we found no evidence of transfer to the left hand. However, while generalization to adjacent reaching directions was stable across training, we did find a narrowing of the Gaussian-like angular generalization with practice, suggesting a fine tuning of the spatial properties of the motor memory. Finally, even after fifteen weeks without practice, participants immediately exhibited similar levels of predictive adaptation to the dynamics. Our results show that learning continuously progressed over time, creating a stable motor memory that is retained for prolonged periods without task exposure. Notably, while predictive adaptation developed over time, other aspects, such as the decay rate, remained relatively unaffected during our training period. Our research highlights motor memory formation and durability and could inform training strategies aimed at developing motor skills or advancing rehabilitation.

1-A-4 - A novel robotic thumb proprioception assessment reveals surprising aspects of proprioceptive adaptation in unimpaired and stroke participants

David Reinkensmeyer [1], **Luis Garcia-Fernandez** [2], **Andria Farrens** [1], **Chris Johnson** [1], **Vicky Chan** [1], **Joel Perry** [3], **Erich Wolbrecht** [3]

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Details

Thumb movement is critical for human hand function and is often impaired by stroke. Despite this, there are few assessments for evaluating thumb proprioception. Here we leveraged a recently-developed

thumb robot to develop a novel assessment for thumb localization accuracy. In the Circle Jump game, the FINGER rehabilitation robot moves the visually-hidden thumb in a circle. Participants press a button at the moment they believe their thumb aligns with a target on a screen, causing a ball to be shown and subsequently jump to the target. We examined 1) how assessment parameters affected proprioceptive error of neurotypical participants, and 2) how error evolved in response to 3 weeks of robotic hand therapy with stroke participants. In the first experiment, 26 neurotypical participants attempted 20 jumps per Circle Jump game, and we varied circle diameter, speed, the employed finger (thumb or index), and rotation direction across games. We observed several surprising results. Participants had an average error of 31.6 deg across all games, equivalent to 1.5 cm bias at the thumb tip. Thus, we don't know very accurately where our thumbs are. Making the game more challenging by halving the circle diameter had little effect on error, but doubling thumb rotation speed decreased error by 14.2 deg, suggesting that thumb localization relies on integration of velocity signals. Playing the game with the index finger reduced error, counter to expectations from cortical representation sizes. Most interestingly, switching rotation direction suddenly degraded accuracy, revealing a novel form of sensory adaptation with error dynamics reminiscent of internal model formation in motor adaptation. Just after we reversed rotation direction at the start of a new game, error doubled, similar to a direct effect. Error then decreased over the next 20 jumps, indicating significant adaptation. When we then reverted the rotation direction, error increased again in an after effect that gradually washed out. This suggests that the human proprioceptive system continuously adapts a thumb localization model based on the history of movement velocity it experiences. In the second experiment with 17 chronic stroke participants, mean thumb proprioception errors were approximately double those of the neurotypical population. Thumb errors remained stable across robotic hand training, while finger proprioception errors (quantified with a different assessment) decreased. This suggests that there is specificity of plasticity in hand proprioception training. We conclude that the Circle Jump assessment is a valuable new tool for quantifying thumb proprioception. With it, we identified surprising features of thumb localization, a novel form of sensory adaptation, that stroke impairs thumb localization, and that robotic hand therapy improved finger but not thumb proprioception.

1-A-5 - Optimization of modularity during development to simplify walking control across multiple steps

Elodie Hinnekens [1], **Bastien Berret** [2], **Estelle Morard** [2], **Manh-Cuong Do** [2], **Marianne Barbu-Roth** [3], **Caroline Teulier** [2]

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Details

Walking in human adults seems to rely on a small number of modules that reduce the number of degrees of freedom that are effectively regulated by the central nervous system. In toddlers who just started to walk, producing a single step of walking involves a similarly small set of modules, but whether this small set is sufficient to generate several steps remains unclear. Toddlers indeed produce a high amount of variability across strides, which is believed to have both a central origin for motor exploration, and a peripheral origin due to the need of regulating balance constraints. Here we investigated whether the variability of toddlers' data across strides could originate from a small set of motor modules as in adults. We also estimated the effect of balance constraints on this variability by repeating the analysis while supporting the toddlers.

We recorded the electromyographic activity of 10 bilateral (lower limbs) muscles in adults (n=12) and toddlers (n=12) during 8 gait cycles. Toddlers were recorded while walking overground independently and while being supported by an adult over a treadmill. This allowed to assess whether motor variability would persist with reduced balance constraints, suggesting that it would not fully originate from peripheral regulations. For each condition and age group, we computed kinematic parameters as well as an index of EMG variability. We used the Space-by-Time Decomposition method to model the underlying modular command, with or without averaging data, and compared different aspects of the resulting modular organizations.

The EMG activity of toddlers was significantly more variable than in adults (p<.001). To account for this greater stride-by-stride variability, more modules were required in toddlers (p<.001). Using the space-by-time factorization analysis uncovered that activations of these modules varied more across strides (p<.001) and were less parsimonious compared to adults (p<.001). Interestingly, every result was similar when diminishing balance constraints, suggesting that peripheral regulations are not fully responsible for the increased plasticity observed when modeling toddlers' modular organization.

These findings suggest that the modular control of locomotion evolves as the organism develops and practices. While adults seem to be able to handle several strides of walking with few modules, toddlers could require more modules and use them with more variability. However, the high number of modules and lack of selectivity in toddlers' modular organization could also indicate the absence of modularity. Overall, this study highlights the important plasticity that underlies the locomotor system around walking onset, and suggests that new walkers have the possibility of flexibly activating their motor command to produce a broader range of possible actions, though distinguishing between modular and non-modular inputs remains challenging.

1-A-6 - Evoked motor responses induced by subdural stimulation of motor, premotor, and parietal cortex using novel conducting polymer electrodes in a non-human primate stroke model

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Details

Neuromodulation therapies utilizing electrical stimulation of the cortex have shown considerable promise for improving motor function after brain injuries such as stroke. The use of stimulation electrodes placed directly on the cortex surface allows for much higher spatial resolution than non-invasive approaches such as TMS, and avoids damage to the underlying tissue that inevitably occurs with more invasive approaches such as deep brain stimulation. New conducting polymers show great potential as flexible neural stimulation materials, with very low impedance and high charge delivery capacity compared to rigid conventional implantable surface electrode arrays made from metals. These properties enable safe and effective stimulation with high spatial resolution, especially when combined with ultra-thin substrates that conform to the surface of the brain.

Here, we have developed small sub-mm flexible surface electrodes using the conducting polymer Poly(3,4-ethylenedioxythiophene)(PEDOT) for subdural cortex stimulation to promote recovery after stroke. We tested the efficacy of these electrodes to evoke motor responses in two anesthetized macaques, one of which had previously undergone a medial cerebral artery occlusion stroke. We stimulated the leg and hand representation areas of the primary motor cortex (M1), as well as the hand area of the dorsal premotor cortex (PMd) and parietal Area 5. We recorded the electromyographic (EMG) activity of several distal muscles of the arm and leg during stimulation. We compared the motor thresholds and EMG responses evoked with standard (1mm) and micro (300 µm) surface electrodes, using monopolar and bipolar stimulation. We compared evoked motor responses from surface stimulation with those evoked with intracortical microstimulation (ICMS) trains delivered to layer V as commonly done in motor mapping studies.

Our surface electrodes were able to evoke motor responses in all areas studied, with the lowest thresholds in the M1 hand area, and the highest in PMd. Overall, the 300 µm electrodes showed similar performance to the larger 1mm electrodes, while allowing for greater spatial resolution. Whereas surface stimulation of M1 or PMd showed a greater preference for distal extension muscles, Area 5 was highly specific to thumb and digit responses. Interestingly, whereas evoked motor responses from surface and layer V stimulation were very similar in hand M1, this was less true for the other areas studied. Notably, the same exact movement was never observed by both forms of stimulation in parietal Area 5.

In conclusion, our results demonstrate that our cortical surface electrodes can deliver effective subdural stimulation with high spatial precision at sub-mm sizes in a non-human primate stroke model.

1-A-7 - Online interference of declarative memory in force field adaptation

Judith Rudolph [1], **Luc Selen** [1], **W. Pieter Medendorp** [2]

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Details

We continuously adapt our movements to changes in our motor system and in the environment. Dual-rate state-space models describe adaptation in terms of a fast process that learns and forgets rapidly and a slow process that learns more slowly but retains longer. Recent studies suggest that the fast process relies on resources of the declarative memory system, despite the common belief that motor adaptation is a form of procedural learning. However, in these studies the explicit component was either introduced by task, or only tested after motor adaptation had already occurred (i.e. only probing retention). In this study (n=32) we aimed to impair the learning and retention of the fast process by introducing a continuous load on the declarative memory system. The declarative memory task, consisting of word list learning, was indexed by either recognition or recall, and was compared to a vowel counting task using a within-subject design. Adaptation was probed in a spontaneous recovery paradigm and performance within each trial was assessed in terms of the adaptation index, representing the degree of force compensation to the force field. A hierarchical, Bayesian dual-rate model was used to estimate the most likely parameters given experimental data and how they are affected by the different memory tasks. The posterior distributions show that the learning rates of neither the slow nor the fast process are affected by the declarative memory interventions. Also, the retention rate of the slow process was not significantly affected. Only for the retention rate of the fast process the data hints at a small effect of the declarative memory task, consistent with previous studies. Our results suggest that declarative memory processes only minimally affect fast retention but leave the fast learning rate and the slow processes in motor adaptation untouched.

1-A-8 - Dissolving the barrier between mental rehearsal and physical execution: Imagined prior movements enhance adaptation performance

Magdalena Gippert [1], **Pei-Cheng Shih** [2], **Tobias Heed** [3], **Ian Howard** [4], **Mina Jamshidi** [5], **Arno Villringer** [1], **Bernhard Sehm** [1], **Vadim V. Nikulin** [1]

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Details

Motor imagery and overt movement have been hypothesized to be functionally equivalent. At the same time there is evidence that hints at distinct mechanisms of both processes. To resolve this controversy, we investigated whether prior imagined movements had the same effect as prior overt movements on motor adaptation performance during a subsequent reach. Additionally, we aimed to identify neuronal correlates of motor imagery predicting such motor adaptation.

Movement kinematics (exoskeleton robot, Kinarm Lab) and EEG of 60 participants were recorded to investigate direction-specific adaptation during a reach of the right arm in an interference force-field paradigm. We compared performance of three experimental groups: 1) no prior movement (visual static cue) 2) active (overt) prior movement, 3) imagined prior movement.

In line with previous research, we found that active prior movements facilitate adaptation to opposing force-fields, while visual static cues do not. Moreover, we found that motor imagery of prior movements leads to adaptation to some extent. In addition, we revealed that event related synchronization of oscillations in alpha and beta band in a simple motor imagery task is associated with motor adaptation performance.

Taken together, our results indicate that motor imagery and overt movements share similar neural mechanisms, suggesting that motor imagery can be leveraged to improve the performance of linked overt movements.

1-A-9 - How are three tactile acuity tasks modulated by electrical repetitive tactile stimulation: evaluation of the remote effect on the unstimulated hand

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Details

Tactile spatial resolution - or tactile acuity - is a fundamental aspect of human tactile perception as it is involved in fine motor skills and object recognition. Repetitive Somatosensory Stimulation (RSS) is known to improve tactile acuity locally on the stimulated finger by inducing transient plastic changes in the corresponding primary (S1) and secondary (S2) somatosensory representations after passive stimulation, either mechanical (vibrating membrane) or electrical (electrocutaneous). Three main tasks have been proposed in the literature to assess tactile acuity: the Two-Point Discrimination Task (2PDT), the Two-Point Orientation Task (2POT) and the Grating Orientation Task (GOT). So far, the local effect of RSS has been predominantly documented using the 2PDT, while using the GOT brought somewhat controversial findings, and it has never been investigated with the 2POT. In addition, while RSS-induced tactile improvement has long been thought to be local (i.e., specific to the stimulated region), recent work from our group showed remote tactile improvement on the unstimulated hand. Specifically, mechanical RSS on the right index finger (rD2) induced tactile improvement at this finger as well as at the left thumb (lD1) and middle finger (lD3), while tactile acuity of the fingers adjacent to rD2 (right D1 and D3) remained unchanged. While these results show promising potential for applications in rehabilitation, the much shorter (and potentially more efficient) electrical RSS protocol would be more appropriate in this context. But whether this remote effect is also found following electrocutaneous RSS remains unknown.

The aim of the present study is twofold: (i) assessing how performance in the three tactile acuity tasks is modulated by RSS and (ii) assessing the remote effect of electrical RSS.

To these aims, we conducted a study in which 24 right-handed healthy adults performed the three tasks on rD2, lD2 and lD3 before and after 45 minutes of electrical RSS. To maximize tasks comparability, the experimental setup, the design (hand posture, number of trials and sessions) and threshold computations (psychometric curves) in the three tasks were made identical.

Our results show that electrical RSS significantly reduced 2PDT thresholds on rD2 and lD3 and 2POT thresholds on lD3 only, but did not alter GOT thresholds.

These results reveal that the remote effect of mechanical RSS has been successfully replicated with electrical RSS on 2PDT and 2POT thresholds. Moreover, our results suggest that the three tasks are not impacted by RSS in the same way, which indicates that they might not reflect the same aspects of touch perception.

1-A-10 - Visual error-induced motor memory in targeted walking

Kenta Yamamoto [1], **Tsuyoshi Ikegami** [2], **Masaya Hirashima** [2]

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Details

Although it is well established that visual error feedback effectively induces learning during arm-reaching movements, a previous study (Roemmich et al. 2016) has shown that for gait control, visual error feedback does not induce learning (i.e., formation of motor memory), but rather is only used for online movement correction. Here, we show that visual error feedback indeed induces learning during walking if the context of motor control has been matched between learning and retrieval of motor memory.

We developed a virtual-reality system in which participants walked on a treadmill while viewing an avatar as visual feedback of their movements. Two parallel rails were presented as the visual targets to be stepped on with each foot. We examined two contexts of gait control by manipulating the absence and presence of the rails "natural walking" without looking where to step next (i.e., no aiming control) and "targeted walking" to step on the rails (aiming control).

First, the participants performed targeted walking while a discrepancy between the actual movement and the avatar movement was gradually implemented so that the avatar's steps landed increasingly inside the rails (learning phase). Following learning, the participants' actual step width widened. We then examined memory retrieval of the learned gait without visual feedback from the avatar (retrieval phase). We noted that during natural walking (characterized by the absence of the rails), the participants immediately decreased their step width to the original level, but during targeted walking (characterized by the presence of the rails), the participants continued to widen their step.

The results for the natural walking replicate those found by Roemmich et al. (2016), where the context of gait control was not matched between learning and retrieval (i.e., a new gait pattern was learned with a visual target, whereas the retrieval was tested without the target). The results here suggest that visual error feedback induces gait learning, but the context difference in gait control prevents motor memory from being retrieved. The visual error-induced learning and the contextual retrieval of motor memory both mimic the motor learning mechanism established using the arm-reaching movement, suggesting a common error processing mechanism between arm-reaching and walking.

1-A-11 - Autonomic responses to visual and proprioceptive errors during motor learning

Motoko Nogami [1], **Nobuhiro Hagura** [2], **Atsushi Yokoi** [2]

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Details

Recent studies indicate that the autonomic nervous system in not only regulating peripheral organs but can also significantly modulate information processing in the brain. For example, formation of contexts for episodic memory is influenced by individual’s surprise and subjective uncertainty about environmental states, which is reflected in the pupil diameter (Clewett et al., Nat Comm, 2020). One unexplored question is, whether/how autonomic system contributes to the formation of motor memories. To test the potential link between autonomic system and motor learning, we assessed sensitivity to errors in motor learning and autonomic responses to movement errors by simultaneously measuring autonomic signals (pupil, skin conductance, and electro-cardiogram) during a single-trial learning paradigm.

In two experiments, participants made center out reaching movements to a target while they maintained fixation on the target throughout the trial. After every 4~6 trials of normal reach without any perturbation, we introduced a triplet of trials to assess single-trial motor learning. This triplet consists of two probe trials with one perturbation trial in between. Comparisons between the movements for pre- and post-perturbation trials allow us to quantify the single-trial motor learning induced by the perturbation. For the first experiment (Exp 1, n=30), we induced various sizes of proprioceptive error by mechanically constraining the reach trajectory away from the straight line towards the target (±45,

±30, ±10, ±5, and 0 degrees). Similarly, the reach trajectory was constraint in 0 deg for the two probe trials to measure the lateral force during reaches. We also occluded the online visual cursor feedback and gave only terminal feedback of hand position throughout the experiment. For the second experiment (Exp 2, n=30), we induced various sizes of visual error by applying visuomotor rotation of hand position (±45, ±30, ±10, ±5, and 0 degrees). For this purpose, we displayed the online visual feedback of the hand position as a visual cursor with approximately iso-luminant color to the background. In contrast to the Exp 1, the two probe trials were not constrained, but no visual feedback was given on the second probe trial after the perturbation.

In both experiments, all autonomic measures showed phasic response to sudden perturbations. We further found that the size of the phasic pupil dilation and skin conductance response were scaled with the size of errors. Interestingly, the sensitivity to errors decreased as the error size increases. The results, thus, suggest possible influence of phasic autonomic arousal on error sensitivity in motor learning, while the underlying mechanism is still unclear. In summary, our data constructs the first step toward understanding the role of autonomic system in motor learning.

1-A-12 - Revisiting cortical face-to-hand area remapping after cervical spinal cord injury

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Details

Following cervical spinal cord injury (SCI), individuals experience a loss of muscle function and sensation in their limbs and torso. Seminal non-human primate studies have found that this leads to extensive remapping in brain areas containing detailed map-like body representations (e.g., the primary somatosensory cortex; S1). Explicitly, cortical area deprived of sensory inputs, such as the hand, becomes responsive to touch on intact body parts, such as the face. While animal models of SCI have consistently revealed remapping in S1, the degree and pattern of cortical remapping in humans following SCI is less clear. This study aimed to uncover the full architecture of S1 face remapping in human cervical SCI patients non-invasively using fMRI and uni- and multivariate analysis techniques.

We acquired 3 tesla fMRI measurements while suprathreshold vibrotactile stimulation was applied to the forehead, lips, cheek, and thumb of 16 chronic cervical spinal cord injury patients and 21 matched healthy control participants. The patient sample was heterogeneous in terms of their neurological level of injury (C1-C7), the severity of neurological loss (ASIA A-D), and retained hand functioning (GRASSP score 22-188, healthy score = 232). Tactile stimulation was provided in a blocked-design fashion using an in-house build MRI-compatible pneumatic stimulator device. We inspected remapping using several approaches: 1) by extracting the level of forehead, lips, and chin activity in an anatomical S1 hand area; 2) by extracting the activated area in the S1 hand cortex during forehead, lips, and chin stimulation; 3) by assessing potential representational shifts through calculating the geodesic distance of the peak S1 forehead, lips, and chin activity to an anchor in the S1 foot area; and 4) through multivariate representational similarity analysis (RSA) to characterise more subtle representational changes in the relationship between facial activity patterns in the S1 hand area.

Our results did not show any significant changes in face representation in the hand area after cervical SCI compared to control participants. Moreover, we did not find any significant correlations between our indicators of remapping and patients' retained hand functioning, time since injury, or anatomically defined amount of tissue bridges at the level of the spinal injury. In summary, our results did not show evidence for face-to-hand area remapping in S1 of human cervical SCI patients. Given that we aimed to match our approaches to those used in classical non-human primate experiments demonstrating face-to-hand area remapping in S1, we suggest that face remapping is not apparent in humans.

1-A-13 - Repetition- but not learning-related corticospinal plasticity is enhanced during sensorimotor mu rhythm trough phases

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Details

The sensorimotor cortex plays a critical role in motor learning. Recent studies show that transcranial magnetic stimulation (TMS) applied to the primary motor cortex (M1) preferentially induces long-term potentiation-like changes in corticospinal output and boosts motor learning when delivered during mu rhythm trough but not peak phases. These studies suggest that the neurophysiological mechanisms (i.e., corticospinal plasticity) supporting motor learning may be most active during mu trough phases. If so, learning-related corticospinal plasticity should also be mu phase-dependent. To address this possibility, we recruited healthy right-handed adults for a study involving TMS, EEG, EMG, and behavioral assessments. We randomly assigned participants to a sequence or repetition group (N=18 per group). Participants in the sequence group practiced a serial reaction time task (SRTT), which contained an embedded, repeating 12-item sequence. Participants in the repetition group practiced a control version of the SRTT that contained no such sequence. To evaluate learning- and repetition-related changes in corticospinal output, we delivered suprathreshold single-pulse mu phase-dependent TMS to the left M1 before, immediately, and 30 minutes after the SRTT in each group. Participants in each group also performed a shorter version of the SRTT one hour after initial practice to evaluate retention. Statistical analysis revealed that real-time targeting of mu peak and trough phases recorded over the left sensorimotor cortex was accurate in both groups ($p < 0.01$ for all). As expected, the sequence group showed greater sequence-specific learning than the repetition group during SRTT acquisition and retention (BLOCK x GROUP interaction; $p < 0.001$ for both). In both groups, the amplitudes of MEPs elicited during random mu phases increased following SRTT acquisition, indicating that practicing each task induced mu phase-independent corticospinal plasticity. However, mu phase-dependent corticospinal plasticity differed across groups: MEP amplitudes elicited during trough phases were only significantly larger than those elicited during mu peak phases thirty minutes after SRTT acquisition for the repetition group ($p < 0.001$). Our results demonstrate that corticospinal plasticity induced by movement repetition but not implicit sequence learning is enhanced during sensorimotor mu rhythm trough phases. These findings suggest that repetition-related corticospinal plasticity varies across mu rhythm phases, such that use-dependent-like plasticity occurs preferentially during brief windows of increased excitability embedded within ongoing brain rhythms.

1-A-14 - The cerebellum acts as the analog to the medial temporal lobe for sensorimotor memory

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Details

While it is widely established that the cerebellum is critical for sensorimotor learning, its specific role remains unclear. Inspired by the classic finding that, for declarative memories, medial temporal lobe structures provide a gateway to the formation of long-term memory but are not required for short-term memory, we hypothesized that the cerebellum is differentially involved in the formation of long-term vs short-term sensorimotor memories.

A clue may lie in differences between the severity of impairment reported in previous sensorimotor adaptation studies. Three studies using the same upper-limb force-field (FF) paradigm have observed impairment as low as 30% and as high as 75%. Interestingly, the two studies with the lowest impairment (30-40%, Gibo et al,2013; Criscimagna-Hemminger et al,2010) had short inter-trial time intervals (ITIs) of 5-7s on average, allowing short-term sensorimotor memories to add to performance. In contrast, the study with the highest impairment (75%, Smith and Shadmehr,2005) had much longer ITIs of 20-25s on average. These long ITIs would dramatically reduce the contribution of these rapidly-decaying (Ï„<20 sec) short-term sensorimotor memories.

To test our hypothesis, we reanalyzed previous data (Criscimagna-Hemminger et al & Gibo et al) of individuals with severe ataxia from cerebellar degeneration (*n*=20) and age-matched healthy controls (*n*=28). We measured the amount of FF adaptation in relationship to the duration of the memory window since previous exposure to the FF, over the course of hundreds of movements in each individual. This let us dissect the memory formed during sensorimotor learning into a temporally-persistent component that is stable for >60 sec and leads to long-term retention, and a temporally-volatile component that decays rapidly (Ï„<20 sec) and does not. Based on this dissection, we examined whether these two components were differentially impaired in individuals with severe cerebellar ataxia.

Remarkably, we find that individuals with severe cerebellar ataxia display spared and even elevated levels of temporally-volatile sensorimotor memory, despite a dramatically reduced ability to form temporally-persistent sensorimotor memory. In particular, we find both impairment that systematically increases with memory window duration over shorter (<12 sec) memory windows (p=0.0066) and a near-complete impairment of memory maintenance over longer (>25 sec) memory windows (p=0.00016).

This dissociation uncovers a new role for the cerebellum as a gateway for the formation of long-term but not short-term sensorimotor memories, mirroring the role of the medial temporal lobe for declarative memories. It thus reveals distinct neural substrates for short-term and long-term sensorimotor memory, and it explains both newly-identified trial-to-trial differences and long-standing study-to-study differences in the degree to which cerebellar damage affects sensorimotor learning.

1-A-15 - Combining proprioceptive stimulation and action observation to evoke plasticity in primary motor cortex: a TMS-fNIRS pilot study

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Details

Combining action observation (AO) and proprioceptive stimulation (PS) evokes a kinaesthetic illusion (KI of movement and plastically increases the excitability of the primary motor cortex (M1) up to one hour after the end of its administration. Although M1 excitability during the stimulation is an individual marker of plasticity, other cortical areas might determine the consequences of AO-PS. Furthermore, previous AO-PS protocols were based on repeated stimulations aimed at evoking KI. However, KI is very subjective and variable among subjects. Finding a protocol that succeeds in evoking plasticity not constrained to the individual KI would led to more robust results. In the present study we assessed the changes in hemodynamic activity of a fronto-parietal network by means of functional near-infrared spectroscopy during the administration of a new AO-PS protocol and we tested its ability in evoking M1 plasticity in 12 healthy participants.

AO-PS was composed of 50 bursts of combined stimuli. Each burst consisted in 5 couples of AO-PS, each one lasting 1s, interleaved by 1s-pause, for a total duration of 10s. Each burst was separated from the next by a pause of 10-13s. During each couple, participants observed a video showing thumb abduction towards the palm and simultaneously received a mechanical vibration of the extensor pollicis brevis muscle (stim. freq.: 80Hz). Before, immediately, 30min and 60min after AO-PS, recruitment curves (RC) were measured by means of transcranical magnetic stimulation to evaluate changes in M1 excitability. During AO-PS administration, the optodes were arranged resulting in a total of 44 standard channels (3cm) and 8 short-separation channels (8mm), covering a fronto-parietal cortical network. RC were compared at the different evaluation epochs to test the occurrence of M1 plasticity. To assess the cortical activations during AO-PS, the mean oxy-hemoglobin concentrations in the first and in the last 20 AO-PS bursts were measured.

Preliminary results showed a significant increase of M1 excitability 30min after AO-PS, suggesting the possibility for this new AO-PS protocol to evoke plasticity in M1. During AO-PS, a significant increase in oxy-hemoglobin concentration was found in a fronto-parietal network including the following Brodmann's areas (BA): BA4, BA6, BA1,2,3, BA43 and BA40. Significant correlations were found between oxy-hemoglobin concentration changes measured in the first 20 and the last 20 AO-PS bursts in the different areas separately. At last, the amount of plasticity evoked by AO-PS significantly correlated with the activity of pre-frontal brain regions involved in attentional mechanisms.

These preliminary results show that the new AO-PS protocol plastically increased the M1 excitability irrespective of the possibility to evoke an illusory sensation of movements and point to the role of fronto-parietal network including somatosensory, motor and associative areas in evoking this phenomenon.

1-A-16 - Motor learning mechanisms are not modified by feedback manipulations in a real-world task

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Details

Error and reward feedback are the primary drivers of motor learning and are thought to be processed by two distinct mechanisms: error-based learning and reward-based learning. In lab-based tasks, they are often isolated, while in real-world scenarios it is not easy to separate them. We established pool billiards as a motor learning paradigm (Haar, van Assel, & Faisal, 2020) and showed that individuals use different contributions of error and reward during real-world learning (Haar & Faisal, 2020). Then, to allow for perturbations and visual manipulations, we integrated it into an embodied Virtual Reality (EVR) environment (Haar, Sundar, & Faisal, 2021). In the EVR setup, the VR headset provides visual feedback as the participant plays pool with a physical cue stick and table. Here, we introduced visuomotor rotations and delivered exclusively error or reward feedback to explore the impact of forcing the use of a specific learning mechanism.

32 participants completed two sessions, learning one rotation with error feedback and another with reward, which was in the object's behaviour and not the world coordinates. The sample was counterbalanced in terms of rotation direction and feedback order. While the error feedback displayed the cue ball trajectory until the ball collision but no pocketing, the reward feedback consisted of a fixed trajectory with ball pocketing for every successful trial. Following previous works in lab-based tasks (Therrien, Wolpert, & Bastian, 2016), a success zone was defined based on improvement from previous trials.

Our behavioural results showed differences between the learning curves with the two feedback. Participants managed to correct the entire rotation with the error feedback but only part of it with reward (Nardi, Haar, & Faisal, 2023 ICORR). Analysing several measures known to behave differently while learning with different mechanisms, such as lag-1 autocorrelation and inter-trial variability decay, we found no difference between the two sessions, indicating that the visual feedback provided in EVR was not enough to force the participants to learn only from specific mechanisms.

We further quantified the brain activity pattern of the two learning sessions, looking at the trend of post-movement beta rebound (PMBR). Previous studies showed PMBR increase during error-based learning and decrease over reward-based learning, even though not in the same task and with the same participants, as done here. While our data suggest different trends with a clear PMBR decrease with the reward feedback, there was no PMBR trend during the error session, suggesting again that while the reward feedback was eliminated in this condition, participants kept using reward-based learning.

These findings underscore the distinction between lab-based tasks and real-world situations, emphasising that while the former are valuable, they may not fully capture the intricacies of how humans learn movement in complex scenarios.

1-A-17 - Can the somatosensory cortex integrate a tactile representation of an extra robotic body part?

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Details

Motor augmentation technologies, such as the use of an extra robotic finger, present novel sensory and motor challenges that probe the adaptability of our body representation. This study investigates the primary somatosensory cortex's (S1) role in integrating a new robotic limb, the Third Thumb (Dani Clode Design), by examining changes in somatosensory processing and motor skill acquisition over a seven-day period. We assessed changes to the tactile hand representation before and after a week of altered finger-synchronisation motor training: either due to extended Third Thumb training (*n=30*), or training to play the keyboard (*n*=20), with an additional passive control group that receive no training (*n=20*). We used fMRI to study the representational similarity patterns across the biological fingers and Third Thumb (via intrinsic touch) before and after training.

During the training, participants engaged with the Third Thumb in a range of tasks, with most of the training achieved during an unsupervised, at-home, training regimen. Participants achieved significant improvements not only in tasks they directly trained but also in untrained tasks, showcasing a broad learning effect, underscoring the capacity for flexible motor learning to achieve versatile skills. The active control group also demonstrated significant improvement in keyboard playing tasks.

Next, we examined whether the brain is able to use tactile input arising as a natural by-product of wearing the Third Thumb (intrinsic feedback) to support motor learning, and how this information is integrated with that of the biological fingers. At baseline we observed that S1 processes vibrotactile feedback from the Third Thumb in a topographically appropriate alignment to the biological fingers, but distinctly from that of the skin where it is attached. Following training, the representational similarity between the intrinsic feedback of the Third Thumb and the biological fingers and palm has increased, hinting at an integrative adaptation to the augmentation device.

In addition, both the Thumb and the keyboard training groups showed a reduction in the biological inter-finger information content. This suggests that the effect may be at least partially due to the abrupt changes in the finger synchronisation patterns these active training paradigms induces.

Overall, our preliminary findings suggest that successful Third Thumb training triggers adaptive changes to the representation of the Thumb in relation to our body, above and beyond an alternative finger skill learning. While training-induced changes to the biological hand representation may be tied to the alterations in finger synchronisation patterns over the week of training, we also find early evidence of further Third Thumb specific changes. We tentatively conclude that the primary somatosensory cortex is able to change the representation of the biological body to account for the use of an additional limb.

1-A-18 - Human-machine interaction: inferring cognitive state from motor control

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Details

The use of complex human-machine interfaces (HMIs) has grown rapidly over the last few decades, in both industrial and personal contexts. Now more than ever, the study of mental workload (MWL) in HMI operators appears essential: when mental demand exceeds task load, cognitive overload arises, increasing the risk of work-related fatigue or accidents.

In this work, we propose a data-driven approach for the continuous estimation of the MWL of professional helicopter pilots in a realistic simulator. Equipped with an eye-tracker, a head-tracker, and a sensor belt, the ocular activity, vestibular inputs, heart rate, breathing rate and motor commands of eight professional helicopter pilots (age: 38.5 ± 6.3) were recorded during two flight scenarios. Physiological, contextual and operational parameters were used to train a novel machine-learning model of MWL. Our algorithm achieves good performance (Area Under the Curve = 0.805 ± 0.085) and shows that operational information outperforms physiological signals in terms of predictive power for MWL.
Our results pave the way towards intelligent systems able to monitor the MWL of HMI operators in real time and question the relevancy of physiology-derived metrics for this task.

1-A-19 - Real-time personalized brain state-dependent TMS: a novel neurostimulation technique to improve poststroke corticospinal tract activation

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Details

The corticospinal tract (CST) is primarily responsible for voluntary human hand movement. Many stroke survivors have residual CST connections, the presence of which are strong prognostic markers of poststroke motor recovery. Strengthening residual CST transmission could promote poststroke hand motor recovery. In healthy adults, TMS interventions enhance CST transmission and motor learning only when delivered during brain states associated with strong CST activation. These studies require intact sensorimotor rhythm-generating circuits that may be disrupted post-stroke. Further, because individual stroke survivors have unique lesion patterns, stroke-related brain reorganization, and varying motor impairments, poststroke brain state-dependent TMS interventions should instead be delivered during personalized brain states. Here, we developed and tested a novel machine learning-based EEG-TMS approach that delivers TMS during personalized strong and weak CST states in real-time. 16 healthy adults completed a study involving 600 single TMS pulses to the right M1 at 120% of resting motor threshold (RMT) during 64-channel EEG and EMG recordings from the left first dorsal interosseous (FDI) and abductor pollicis brevis (APB). Pre-stimulus EEG data and corresponding FDI motor-evoked potential (MEP) amplitudes were used to train personalized machine learning classifiers to discriminate between strong and weak states. Personalized classifiers were then used to deliver single-pulse TMS during these states in real time at 100, 110, and 120% RMT as well as during random states. Real-time EEG analysis accurately identified and targeted strong and weak states 93.5 ±1 and 93 ±2% of the time, respectively. At 120% RMT, FDI MEPs elicited during strong states were larger than those elicited during weak and random states ($p<0.001$). APB MEPs elicited during strong and weak states were similar in size ($p=0.25$) but were larger than MEPs elicited during random states ($p<0.003$). MEP amplitudes did not differ across states for either muscle ($p=0.39$) at either 100 or 110% RMT. MEP amplitude variability was similar across states for all intensities and muscles ($p=0.30$). Consistent with the personalized nature of our classification approach, the spatiospectral characteristics EEG activity preceding TMS delivered during strong versus weak states varied across participants. Findings demonstrate the feasibility of real-time personalized brain state-dependent TMS in healthy adults, showing that this approach best activates the CST during strong states. However, real-time personalized brain state-dependent TMS only performs well when targeting the same muscle and intensity used to train each individual's classifier. Our results represent the first step towards using personalized brain state-dependent TMS interventions to improve residual CST transmission and promote poststroke hand motor recovery.

1-A-20 - Changes in kinematic variability in the very early stages of motor learning

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Details

Variability in sensorimotor learning has gained recent attention, indicating exploration during early learning stages. Moreover, whether inherently structured or artificially added, neuromotor noise may significantly influence motor learning in a redundant task. While prior research has highlighted the relationship between motor variability and learning within the contexts of reinforcement and error-based learning, the role of variability in acquiring novel multi-joint coordination remains unclear. This study aimed to explore whether early-stage motor variability correlates with performance outcomes after extended practice, utilizing a multi-joint learning paradigm. If the role of initial variability aligns with that in reinforcement or error-based motor learning, we anticipate early-stage variability to predict performance outcomes post-practice.

Thirty-eight healthy young adults (12 males, 26 females, mean age 23.1 years) participated in a 2:1 multi-frequency coordination task, involving bilateral forearm rotation on a horizontal plane. The dominant arm rotated at twice the tempo of the non-dominant arm, with no specific instructions regarding relative phase or movement amplitude. Over five daily sessions involving approximately 4000 attempts per participant, performance feedback was provided every 45 seconds, computed through instantaneous Hilbert phases. Kinematic variability was quantified using discrete Fréchet distances between consecutive orbits in the Lissajous plot, representing angle-angle relations in the bimanual movement.

While overall performance improved across all participants, individual learning patterns and rates varied considerably. Notably, 21 out of 38 participants demonstrated a 'locked-in' 1:1 pattern in the initial 100-200 cycles, indicating low initial variability. Intriguingly, neither frequency ratio nor arm-specific frequency variability at the onset of practice predicted performance post-practice. However, a significant negative correlation emerged between the number of repetitions required to achieve maximum variability and final performance outcome, observed in both frequency ratio and kinematic variables, including FrÉchet distances. In addition, we found that the amount of practice before reaching maximum variability is linked inversely to prior experience, such as playing musical instruments.

These findings underscore that variability at practice onset is not mere noise or exploratory behavior in tasks necessitating long-term practice; rather, the delayed onset of maximum variability may signal the need for extended practice in acquiring novel multi-joint coordination patterns. Additionally, the fine-grained kinematics employed here serve as a behavioral index to better understand the genesis of motor skill acquisition.

1-B-21 - Saccade kinematics and post-saccadic oscillations in retinitis pigmentosa and age-related macular degeneration

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Details

Eye-movement studies in patients with visual field defects have focused on exploration strategies rather than saccade kinematics. However, saccade trajectories might adapt to optimize vision within the constraints of visual field defects. Here, we compared saccade behavior of subjects with age-related macular degeneration (AMD, n=6) or retinitis pigmentosa (RP, n=5) to normal vision (NV, n=7) using a horizontal saccade task and pupil-based eye tracker. Visual deficits were assessed with Goldman perimetry (RP patients) or fundus autofluorescence imaging (AMD patients). Macular integrity assessment (MAIA microperimetry) was used to determine if subjects used eccentric fixation to compensate for foveal vision loss and to locate each eye's preferred retinal locus. Combined with monocular calibration of the eye-tracking signals from each eye, this enabled precise mapping of each patient's binocular blind areas with respect to gaze at any moment.

We first analyzed reaction times and target localization in relation to the subjects' visual field defects. We also quantified the relations between saccade amplitude, duration, and peak-velocity (the main sequence) in view of recent theories proposing that the saccade kinematics reflect a speed-accuracy trade-off to optimize vision. In addition to deficits in reaction times and localization accuracy, we found alterations in saccade kinematics in both patient groups. Notably, saccades were slower and displayed atypical velocity profiles, particularly pronounced in RP patients. The impact on saccade kinematics was most evident when the target was in the subjects' blind field.

We also noticed distinct post-saccadic oscillations (PSOs). PSOs reflect movements of the pupil and lens relative to the eyeball and thus play a critical role in retinal image stability following saccadic eye movements. Using a damped oscillation model, we found that AMD and RP patients exhibited larger PSO amplitudes, longer decay time constants, and lower frequencies compared to NV controls. While PSO amplitude correlated positively with increases in saccade deceleration across all groups, other PSO parameters did not consistently correlate with saccade kinematics.

Our findings indicate that central and peripheral retinal damage distinctly influence the saccade main sequence, highlighting the importance of visual inputs in planning saccade kinematics. Furthermore, post-saccadic fixation stability is compromised in AMD and RP patients due to abnormal PSOs, rather than altered saccade kinematics, suggesting that anatomical and neuronal variations in the patients' eyes affect PSOs. The observed abnormalities in PSOs underscore the challenges faced by individuals with retinal pathology in maintaining retinal image stability and visual acuity. Further research is warranted to elucidate the underlying mechanisms driving these alterations in eye movement behavior and their functional implications for individuals with visual field defects.

1-B-22 - Development of a system to study visuomotor control of bicycling in a complex urban environment

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Details

While cycling in a bustling urban environment, cyclists encounter highly complex visual surroundings. The brain's attentional mechanism consistently seeks visual cues amidst the abundance of inputs, facilitating the identification of feasible paths and potential obstacles, while concurrently anticipating the movements of vehicles and pedestrians. These perceived environmental dynamics undergo visuomotor transformations, leading to appropriate motor decisions such as pedaling, braking, or steering, heavily reliant on the bicycle's stability and the rider's biomechanics.

To understand this visuomotor control of bicycling spatial navigation more broadly laboratory-based studies have been conducted, combining conventional gaze and motion tracking with minimalistic visual stimuli. However, their ecological validity has been seriously questioned. Here, we propose a system capable of capturing cyclists' visuomotor behavior "outside" in real-world environments, leveraging recent advancements in robotics and computer vision technologies. This system allows us to comprehensively study interactions among vision, movement, and contextual environmental factors during cycling in a complex urban environment.

The cyclist wears eye-tracking glasses with a scene camera (Pupil Invisible), and a helmet with a LiDAR-IMU sensor (Livox Mid-360) and an RGBD camera (Intel RealSense D455) rigidly mounted using a 3D-printed bracket. Frame by frame, the gaze coordinates captured by the eye-tracking glasses are transformed into the helmet camera’s coordinates using a deep-learning-based local feature matching algorithm (LightGlue). Additionally, camera images undergo a deep-learning-based object detection and recognition algorithm (YOLOv8) to extract contextual information on objects in the scene. This scene and gaze information in the helmet camera’s view are registered to the 360 ° depth information acquired by the LiDAR-IMU-based Simultaneous Localization And Mapping (SLAM) algorithm. Another RGBD camera is mounted on the bicycle’s handlebar, tracking the motion of the handlebar-front-wheel compartment and that of the frame-rear-wheel compartment using a fiducial tag attached to the bicycle frame.

A case study demonstrates the efficacy and robustness of the proposed system in capturing details of 3D gaze behavior, body, and bicycle movement, coupled with comprehensive information about the geometric and contextual factors of the navigating environment. It also shows that our algorithm exhibits high robustness against IMU saturation, frequent vibrations encountered on roads, and significant light intensity fluctuations. The proposed methodology not only proves effective in urban cycling studies but also paves the way for studying general human visuomotor behavior during spatial navigation in ecologically valid setups, showcasing its potential as an effective tool for advancing our understanding of human spatial cognition and motor control in real-world contexts

C – Disorders of Motor Control

1-C-23 - Testing a novel paradigm to compare Decision-making in cognitive and motor domains

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Details

Introduction. Learned non-use (LNU) is a frequent complication in neurological conditions such as stroke or traumatic brain injury, reflecting the discrepancy between the functional capacity of the affected limb and its daily use. Considering that any action is a choice, we suggest that revealing more details of how this choice is made in patients with motor impairments may be a fruitful direction for motor rehabilitation. We suggest that applying neuroeconomic principles to understand patient decision-making in both cognitive and motor domains could be a new fruitful area of LNU research and in motor neurorehabilitation in general.

Methods. We designed a 'risk-and-reach' touch screen application (https://risk-n-reach.azurewebsites.net/) allowing us to explore how goal parameters affect motor choices. 20 healthy participants (10 females, age: 24 ± 2.57) were enrolled in the study. Tasks involved reaching for iteratively appearing goals, whose position represents different probabilities and rewards. Participants were provided with round styluses, securely attached to their hands using velcro straps, to operate the touch screen (Figure 1). The experiment starts with individualizing each participant's motor abilities, in the second phase, we created personalized hit probability maps, and in the third phase - we continued with the varying risk-reward scenarios in the motor domain - custom motor lotteries that then were compared with participant risk preferences in the cognitive lotteries and questionnaires-based mental traits such as impulsivity and sensation-seeking.

Results. We showed that the presence of choice in the motor domain increased movement time ($t = -2.58$, $p = 0.032$). When comparing choices from motor and cognitive lotteries, participants preferred risky options in motor tasks compared to the cognitive ones ($p = 0.001$). Impulsivity and sensation-seeking traits were predictive for higher risky motor choice, while the Bomb Risk Elicitation Task scores predicted aversion to risk in the motor domain.

Conclusions. We showed that the presence of choice in the motor domain invigorates reaching movements. Furthermore, we observed that the motor choices were riskier compared to the cognitive ones. In conclusion, we recommend integrating neuroeconomic parameters in neurorehabilitation tasks. It could provide valuable insight into motor impairment, e.g., LNU, leading to more engaging and ecological interventions.

1-C-24 - Impaired impulse control and reduced corticomotor excitability in medicated Parkinson's disease

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Details

Parkinson's disease (PD) has been linked to the development of impulse control disorders (ICDs), with a prevalence reaching ‰ˆ46% [1]. Dopamine medications, though effective for motor symptoms, pose a significant risk for ICD development. However, the neural mechanisms underlying impaired impulse control in medicated PD remain unclear. The present study examined how changes in corticomotor excitability (CME) relate to response inhibition performance in PD, an element of impulse control shown to be impaired previously [2].

Thirteen individuals with PD taking the dopamine agonist ropinirole (66.5 ± 6.9 years) and 14 healthy age-matched controls (71.7 ± 4.5 years) performed the Anticipatory Response Inhibition Task. During ‘Go trials’ (67%), participants depressed switches, which they then released to intercept rising indicators with a stationary target. During ‘Stop trials’ (33%) participants inhibited the prepared movement when the indicators stopped prematurely before the target. Stopping behaviour was assessed via stop-signal reaction time (SSRT). Transcranial magnetic stimulation was delivered during movement preparation (350-100 ms prior to the target on Go trials) and 150-230 ms following presentation of the stop-signal (Stop trials). CME was measured as the motor evoked potentials elicited in the first dorsal interosseous of the non-dominant (controls) or affected (PD) hand.

An independent t-test revealed significantly longer SSRTs in individuals with PD (233 ± 19 ms) versus controls (215 ± 10 ms, p < .005), reflecting an impaired ability to inhibit an anticipated response. Following a mixed ANOVA, successful response inhibition was associated with a reduction in CME across both groups ($F_{1,25}$ = 43.7, p < .001, ´„$^{2}_{p}$ = .636). However, an interaction effect revealed that the medicated PD group exhibited significantly lower CME compared to controls at the initial 150 ms timepoint following the stop-signal (p < .05). Interestingly, these group differences were not apparent during movement preparation, where behaviour (p = .91) and excitability (p = .64) were comparable.

Our findings provide further evidence for impaired response inhibition in medicated PD, demonstrated by delayed SSRTs. Further, the observed behavioural differences were accompanied by reduced CME. These results may be suggestive of an impaired ability to modulate CME in medicated PD, wherein higher excitability cannot be adaptively reduced to successfully inhibit a response. Further research should compare anticipatory response inhibition mechanisms 'on' versus 'off' medication to dissociate the effects of PD pathology from those of dopamine medication.

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1-C-25 - Exercise priming modulates intracortical inhibition to improve cognitive-motor interactions in Parkinson’s disease

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Details

Background: People with Parkinson's disease (PwP) have impairments in gait and cognition. These impairments are further pronounced while performing a cognitive-motor task (i.e., dual task). Previous research has shown that the primary motor cortex (M1) is engaged to a greater extent during performance of a dual task compared with a single task. However, PwP demonstrate reduced intracortical inhibition of the M1 that could reduce its recruitment while performing a dual task. Aerobic exercise (AE) has emerged as a primer for facilitating neuroplasticity of the M1 in healthy individuals and those who have had a stroke. The effects of exercise as a primer to modulate motor cortical contributions to dual tasking in PwP are unknown. Here, we evaluated the effects of AE priming with virtual reality-based gaming on intracortical inhibition and dual task performance. We hypothesized that exercise priming would potentially normalize intracortical inhibition and optimally engage the M1 to improve the cognition-movement interplay in PwP.

Methods: Ten individuals with PD [(mean ± SD) age: 62.7 ± 7.4 years; Hoehn and Yahr: 1.9 ± 0.56; UPDRS III: 20.4 ± 8.87] participated in this study. All participants performed 30 minutes of moderate intensity AE (ˆ¼65% HRmax) on a recumbent stepper followed by 30 minutes of virtual reality-based games 3x/week for 3 weeks. Outcomes were obtained at baseline and post-intervention. Transcranial magnetic stimulation measures included recruitment curves, cortical silent period, and short interval intracortical inhibition (SICI) obtained from the tibialis anterior M1. The PD cognitive rating scale was used to assess cognition. Spatiotemporal measures of gait were obtained during single task and dual task (walking with a concurrent cognitive task) conditions. Paired samples t-tests were used to compare the effects of the intervention between pre and post assessments.

Results: Preliminary findings show that exercise priming significantly lengthened the silent period duration (mean difference: 34.8 ms, 95% CI 13.6, 68.8) and improved cognition (mean difference: 6.8 points, 95% CI 3, 10.3). Immediately after priming, significant improvements in dual-task stride velocity (mean difference: 0.156 m/s, 95% CI 0.05, 0.24) and stride length (mean difference: 0.12 m, 95% CI 0.05, 0.27) were observed. There were no changes in corticospinal excitability or SICI measures.

Conclusion: It appears that exercise priming with virtual reality-based games selectively modulated GABA-B (Î³-aminobutyric acid) mediated inhibition in the M1 and improved cognition, which possibly increased neural resources for performing a dual task. This work provides novel evidence that exercise priming could address both cognitive and motor determinants of dual task performance in PwP. Further controlled studies will utilize exercise priming over long periods of time to identify the longevity of these effects.

1-C-26 - Investigating the effects of aging on sensorimotor performance

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Details

Ageing is associated with various changes in sensorimotor control, such as reduced muscle mass and strength, sensory decline (e.g., vision impairment), decreased balance, increased joint stiffness (limiting the range of movement), and a diminished capacity to integrate sensory inputs. These changes contribute to functional decline, mobility issues, and an increased risk of falls. The understanding of age-related sensorimotor decline is particularly important because of the significant increase in the ageing population in many societies.

Currently, clinicians perform crude assessments to evaluate sensorimotor function, identify factors contributing to functional decline, and initiate preventative and rehabilitative measures, highlighting the need for the development of more reliable, objective testing methods. For instance, a recent study employed iPads for drawing tasks to assess sensorimotor function [1].

The aim of this study was to develop the beginning of a framework for objectively assessing the decline in sensorimotor function due to ageing. We employed the vBOT robotic manipulandum [2] to track hand movements and apply highly-controlled forces, in order to quantify task performance. We designed a simple task with the vBOT to compare performance between healthy young adults (around 20) and older adults (over 60). The task involved making 12cm centre-out movements with the right hand from a starting position to one of eight target locations. The task ended when the cursor reached within 0.5cm of the target at a speed of less than 5cm/s. The experiment included two conditions: a null field condition representing free hand movement, and a resistive viscous field (k=30 Ns/m) condition to investigate forceful movements using the same paradigm.

Performance was assessed using a range of simple metrics, including movement reaction time, duration, maximum force, maximum velocity, trajectory straightness and smoothness, and endpoint accuracy. Preliminary results suggest younger adults exhibit faster movements and generate greater peak forces compared to older participants. They also exhibited shorter movement durations, all findings that align with previous research [3].

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1-C-27 - The effects of central sensitization on motor unit properties in the upper limb

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Details

One in five Canadian adults live with chronic pain, 50% of which have lived with the condition for over ten years. The International Association for the Study of Pain defines chronic musculoskeletal (MSK) pain as persistent pain that lasts beyond the normal tissue healing time, typically at least 3 months duration. This implies that chronic MSK pain is mediated through the spinal cord and higher levels. Central sensitization (CS) is the increased responsiveness of nociceptors in the central nervous system (CNS) to normal or subthreshold afferent input. The least invasive method of inducing CS experimentally is through the use of topically administrated capsaicin cream. This method has been utilized to detail the underlying mechanisms in the development of chronic pain and investigate the maladaptive neuronal plasticity occurring within the spinal cord and supraspinal centers. Previous research suggests that CS may directly impact the ventral root of the spinal cord or motor unit (MU) excitability. The goal of the current study was to investigate the impact of CS induced at the neck on forearm muscle MU activity, which has not been investigated.

CS was induced by applying Zostrix 0.075% capsaicin cream, while the control group has a placebo cream of similar consistency applied. Participants (n=13,7F) were divided into CS and control groups and were required to trace a ramp by gripping a force transducer up to 10% MVC. Either capsaicin or control cream was applied over the participant's neck and shoulder during the study. HDsEMG was recorded from the flexor carpi ulnaris muscle (FCU), a wrist flexor, and extensor carpi radialis (ECR), a wrist extensor using a 64-channel HDsEMG electrode over each muscle belly, being careful to avoid the motor point. Muscle activity was recorded prior to, and 10-, 20-, 30- and 40-minutes post cream application. At each time point, the participant performed 4 blocks of 3 grips each. The purpose was to compare changes in HDsEMG properties relative to baseline. All EMG data was band pass filtered between 10 and 500 Hz, with 250 ms window, 0 ms gap.

The Centroid of the root mean square (RMS) of EMG activity and sample entropy for the plateau phase of each grip were calculated and averaged for the pre cream, and 10-, 20-, 30- and 40-minute post-cream application time points and compared between groups. The centroid represents the spatial distribution of the EMG signals across the electrode array. Differences between CS and healthy were found in the forearm extensor muscles at 10- and 20-minutes post cream application for both the RMS centroid and sample entropy, with no difference between groups for the flexor muscles. These results can provide insight into the neural mechanisms which may initiate chronic pain, and their effect on MU recruitment properties. This information could be valuable in both understanding and detailing the subsequent effects of CS, and chronic pain, on neuromuscular control.

1-C-28 - Hemisphere-specific virtual reality training of the ipsilesional arm in chronic, severely impaired stroke survivors with right-hemisphere damage

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Details

Stroke is a major cause of sensorimotor impairment that can result in chronic disability and reduced quality of life. Although motor impairments of the contralesional arm receive the most attention during rehabilitation, growing evidence has demonstrated the presence of motor deficits in the ipsilesional arm. Acknowledging that severely impaired stroke survivors often rely on the ipsilesional arm to serve as the main or sole manipulator for activities of daily living (ADLs), remediating motor deficits of this limb may improve daily performance of functional activities.

Here, we present data from 9 chronic (over 6 months post-stroke), right-hemisphere damaged (RHD) stroke survivors who were recruited as part of a larger clinical intervention study. All participants were right-handed prior to their stroke (Edinburgh Inventory) and severely impaired based on inclusion criteria of an Upper-Extremity Fugl-Meyer score of < 28. These participants performed 5 weeks (3 x 1 hour sessions per week) of ipsilesional (right) arm motor training, which included a virtual reality (VR) task (20 min) and real-world dexterity tasks (35 min). The real-world dexterity training included a large variety of tasks such as opening and closing bottles and rapidly stacking cups, whereas the VR training involved a shape tracing task aimed at addressing deficits in limb impedance control that have previously been demonstrated to result specifically from RHD. Functional motor performance was assessed using the Jebsen-Taylor Hand Function Test (JTHFT) - a clinical assessment intended to imitate ADLs through manipulation of everyday objects (e.g. paperclips, cans). We then assessed the potential association of changes in ipsilesional arm performance on the hemisphere-specific VR training task with the change in time taken to perform the JTHFT.

The RHD stroke survivors demonstrated small, but statistically significant improvements in virtual tracing task performance (e.g. accuracy and speed) of their ipsilesional arm over the 5-week training period. This group also demonstrated substantial improvement in functional motor performance of the ipsilesional arm, as measured by reduced time to complete the JTHFT (mean [std. dev] = -6.83 [5.36] secs). Notably, an effect size of this magnitude (Cohen's d = 1.27) has been suggested as a strong indicator of clinical significance (Page, 2014. *Int. J. Sports Phys. Ther.*, 9(5), 726-36). We also found moderate strength correlations (r = 0.52 - 0.61) between improvement in measures of virtual tracing performance and reduction in overall JTHFT time, indicating that VR training is partially associated with improvements in functional performance of simulated ADL tasks. This suggests a potential benefit from using a targeted, hemisphere specific training paradigm as a therapeutic adjuvant to mitigate functional motor deficits of the ipsilesional arm for chronic, severely impaired stroke survivors with RHD.

1-C-29 - Altered Lateralized Readiness Potentials in hemiplegic patients following stroke reveal interhemispheric dynamics in motor recovery

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Details

Cortical premovement activity, in particular the lateralized readiness potential (LRP), has been extensively studied as a marker of sensorimotor area activation prior to movement execution. Characterized as a rapid negative deflection ~200 ms before the motor response, the LRP is thought to reflect pre-motor activity in the primary motor cortex (M1) during irreversible stages of movement preparation (Deecke et al., 1976; Neafsey, 2021). Its distinct contralateral topography in healthy subjects makes it a marker of interhemispheric balance during motor preparation. As EEG-registered cotical potentials are a powerful tool in motor neuroscience because they reveal stages of motor processing with high temporal resolution, the LRP has been instrumental in understanding the excitatory/inhibitory balance in cortical networks, providing insights into conditions such as schizophrenia (Luck et al., 2009). However, its dynamics in post-stroke patients remain less explored (Roushdy et al., 2022). Our study examines cortical potentials associated with motor trials in 20 post-stroke hemiplegic patients. We observed variations in LRP patterns, highlighting the role of the unaffected hemisphere in functional recovery of the paretic limb. In particular, patients with chronic stroke and complete functional recovery showed an unusual LRP lateralization, suggesting a bilateral M1 involvement in movement control for contralesional movements, but not for movements of the unaffected limb.

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1-C-30 - Electrophysiology confirmation of quantified anatomy connectivity by individual dystonia patient

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Details

The analysis of brain region connectivity through electrophysiological recordings has become increasingly important [1]. Diffusion tensor imaging (DTI) stands out as a key quantitative method for assessing the anatomical features of brain connectomes, playing a pivotal role in clinical and scientific research by evaluating brain white matter [2]. Damage to the brain’s white matter, such as demyelination or axonal degeneration, impacts the transmission of electrophysiological signals, leading to functional impairments. Yet, the precise manner in which these neural disruptions influence signal transmission mechanisms remains a topic of investigation.
Deep brain stimulation (DBS) is an established treatment for movement disorders like dystonia and Parkinson’s disease, leveraging dynamic measurements of brain electrophysiological signals via stereo electroencephalography (sEEG) [3]. In this study, we hypothesize that incomplete neural pathways affect the transmission of electrophysiological signals. To test this hypothesis, we analyze the relationship between electrophysiological signals and brain white matter characteristics in dystonic patients using

generalized linear models (GLMs). Our analysis involves measuring the amplitude and timing of evoked potentials (EPs) in response to stimulation, as well as calculating the transfer function of recorded signals between specific brain regions to identify energy amplification and flow.
Anatomical characteristics of signal transduction pathways are quantitatively assessed through DTI coefficients derived from tractography between the same brain areas, encompassing tract length, tract intensity, fractional anisotropy (FA), and radial diffusivity (RD). DTI coefficients serve as influential factors in GLM variables, with EP and TF measures serving as output results. Our findings indicate a close relationship between electrophysiological signals and DTI coefficients along the signal pathway. This correlation between brain anatomical characteristics and electrophysiological signals across different regions can provide valuable insight into the impact of brain white matter injuries on brain signal transmission. Ultimately, such insights may contribute to a deeper understanding of neurological conditions and inform the development of more effective treatment strategies.

1-C-31 - Cortico-cortical connectivity is modulated during healthy ageing and by levodopa in tremor-dominant Parkinson's disease

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Details

Parkinson's disease (PD) is a heterogeneous neurodegenerative disorder characterised by progressive motor and non-motor symptoms. Tremor is the most common presenting motor symptom, involving involuntary and rhythmic movements of one or more body parts, which often develops early in the disease. Resting tremor is not associated with the severity of dopamine depletion in the basal ganglia, which suggests that other brain regions might underpin tremor production in PD. The supplementary motor area (SMA) is one of the main targets of the basal ganglia-thalamo-cortical circuit: SMA receives input from the globus pallidus indirectly via the motor thalamic nuclei. The main efferent pathway from SMA is to the primary motor cortex (M1). Evidence from functional magnetic resonance imaging (fMRI) in people with PD shows increased blood-oxygen-level dependent (BOLD) activity in SMA and M1 ON compared to OFF levodopa medication during simple motor tasks[13,14], suggesting that dopamine modulates both SMA and M1 activity in PD. Here we examined whether SMA-M1 connectivity ON and OFF levodopa medication is implicated in resting tremor. Dual-site transcranial magnetic stimulation was used to measure SMA-M1 connectivity in participants with PD with upper limb resting tremor. Tremor was recorded from the tremor-dominant hand using electromyography and accelerometry. Stimulating SMA had an inhibitory influence on M1 excitability OFF levodopa medication and a facilitatory effect on M1 excitability ON levodopa. In addition, SMA-M1 connectivity ON medication remained inhibitory rather than facilitatory in patients with the strongest resting tremor. The facilitatory SMA-M1 connectivity ON medication might be mediated by increased dopamine levels in the basal ganglia, which reduces nett inhibition of the motor thalamic nuclei and increases excitation of the cerebral cortex, including SMA. Our findings implicate SMA-M1 connectivity in resting tremor severity and provide a neurophysiological basis for the development of interventions to treat resting tremor.

1-C-32 - Investigating sleep-dependent consolidation of motor learning in the context of sub-acute recovery after stroke

Matthew Weightman [1], **Barbara Robinson** [1], **Morgan Mitchell** [1], **Emma Garratt** [2], **Rachel Teal** [3], **Nele Demeyere** [1], **Melanie Fleming** [1], **Heidi Johansen-Berg** [1]

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Details

Stroke is a leading cause of worldwide disability, with over 50% of stroke survivors experiencing long-term motor impairment. It is widely believed that good recovery of movement after stroke is dependent on motor learning. However, a key element of motor learning which has yet to be fully explored in the context of stroke rehabilitation - is consolidation of memories during sleep. It is well established that sleep is actively engaged in the offline consolidation of motor memories. The reactivation of task-related neural activity during sleep is believed to underpin offline memory processing, by transforming labile memory traces into persistent representations, readily available for retrieval. Notwithstanding, sleep disruption is commonplace after stroke, with evidence suggesting that poor sleep after stroke, is often associated with slower functional recovery and worse motor outcomes. Given that clinical gains during therapy are likely to depend on both improvements during training and sleep, it is reasonable to suggest that poor motor outcomes may be, at least in part, due to disrupted sleep and thereby associated memory processes. Therefore, the aim of the present study is to test whether measures of overnight motor consolidation mediate the relationship between sleep continuity and clinical motor outcomes over the first 6 months of recovery after stroke.

This is a longitudinal observational study of up to 150 participants diagnosed with stroke affecting the upper limb. Participants are recruited within 7-days of stroke onset and followed up at approximately 1- and 6-months post-stroke. We assess predicted recovery potential (PREP2 algorithm), sleep (using actigraphy, electroencephalography, and self-report questionnaires), overnight motor consolidation with the paretic upper limb (Serial Reaction Time Task), and clinical motor outcomes (Action Research Arm Test, Fugl-Meyer Assessment, Rivermead Mobility Index, 9-Hole Peg Test). This is an ongoing study, which opened to recruitment in March 2023. These outcomes will be used to determine whether sleep in the sub-acute phase of recovery after stroke explains the variability seen in upper limb motor outcomes and whether this relationship is dependent on overnight consolidation of motor memories. We will also test if motor consolidation mediates the relationship between sleep and a broader range of clinical outcomes and explore whether specific oscillatory activity during sleep is associated with motor consolidation post-stroke.

Given that poor sleep is highly prevalent after stroke, but the impact of disrupted sleep on recovery is typically overlooked, we hope the results from the present study will help to understand sleep's role in the recovery of motor function after stroke. As part of a larger body of working investigating sleep after stroke, we believe our findings will inform the development of new interventions for improving rehabilitation outcomes.

1-C-33 - Epidural spinal cord stimulation facilitates motor-unit activity and restores arm motor function after post-stroke paralysis

Nikhil Verma [1], **Erick Carranza** [2], **Erynn Sorensen** [2], **Luigi Borda** [1], **Marc Powell** [3], **Roberto M. De Freitas** [2], **Peter Gerszten** [2], **George Wittenberg** [2], **Lee Fisher** [2], **Elvira Pirondini** [2], **Marco Capogrosso** [2], **Douglas Weber** [1]

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Details

Stroke damages the corticospinal tract(CST), interrupting the connections between the brain and the body, inevitably leading to disorders of motor control. However, the spinal circuits below the lesion remain intact and capable of producing movement. Recently, we reported that epidural cervical spinal cord stimulation(eSCS) improved strength and dexterity in the affected arm and hand of people with chronic hemiparesis post-stroke. Mechanistically, it is well known that SCS directly activates sensory afferents, which form excitatory connections to spinal motoneurons. Thus, SCS could provide additional drive to make these motoneurons more responsive to the residual supraspinal inputs. In this study, we aimed to directly measure the facilitatory effects of SCS on motor unit recruitment. We hypothesized that SCS provides excitatory drive to the motoneurons, amplifying its response to supraspinal input and restoring volitional control over these motoneurons after stroke. Secondly, we used tonic and closed-loop methods to tune SCS parameters to improve volitional motor control during reaching movements. We hypothesized that phasic stimulation, which targets specific spinal segments and muscles for each phase of a movement, would lead to greater improvements in arm function than tonic stimulation, where the stimulation parameters were fixed throughout the different phases of movement.
Five participants with chronic post-stroke hemiparesis were implanted with SCS leads in the epidural space of the cervical spinal cord, ipsilateral to the paretic arm. High-density EMG was used to decompose single-motor unit activity while participants performed isometric contractions of arm and hand to follow a target force trace with and without SCS. Participants also performed planar and 3D reaching and grasping movements with their affected limb with and without SCS. Tonic and phasic stimulation was applied during the reaching tasks.
The peri-stimulus time histogram of MU firing corresponding to each SCS pulse, showed an increased spike probability of motor unit firing at approximately 7-15 ms latency following the the SCS pulse, demonstrating that SCS provides transient excitatory drive to the motoneurons which allows the residual cortical inputs to gain volitional motoneuron control. The duration and magnitude of facilitation varied across the recorded motor units, perhaps reflecting differences in the synaptic strength across the pool of motor neurons. During functional movement tasks, we tested different methods of tuning SCS to improve motor control. The participants were able to perform faster movements and with smoother trajectories with tonic SCS than without. Phasic SCS further improved kinematics by increasing maximum hand speed, reducing movement duration, and smoothing hand trajectories. These results show that although tonic SCS was effective in promoting significant gains in voluntary arm motor function, phasic SCS produced even stronger effects.

D – Fundamentals of Motor Control

Poster Cluster (1-A-34 – 1-D-38)

1-A-34 - Towards human motor augmentation by learning to control novel wrist muscle co-contractions

Josh Chartier [1], **Calvin Kao** [1], **Rishi Rajalingham** [1], **Claire Warriner** [1], **Dano Morrison** [1], **Emanuele Formento** [1], **Mario Bräcklein** [1], **Codie Mcconkey** [1], **Deren Y. Barsakcioglu** [2], **Agnese Grison** [2], **Bruno Grandi Sgambato** [2], **Christopher Collins** [1], **Michael Glueck** [1], **David Sussillo** [1]

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Details

When learning new motor skills, humans expand their repertoire of movements by learning to generate new muscle patterns. In this study, we investigated whether humans can learn to generate novel muscle patterns that rarely occur during natural motor control because they are not that useful for making movements. Specifically, participants learned to control a noninvasive surface electromyography (sEMG) interface by co-contracting two antagonistic wrist muscles (Flexor Carpi Ulnaris (FCU) and Extensor Carpi Radialis (ECR)). Learning movement-null muscle patterns may serve as the basis for augmenting human motor control by granting additional degrees of control that do not interfere with natural motor behavior.

Previous studies attempted to teach humans and non-human primates to generate novel muscle patterns that do not produce force along the axes of the wrist, but were unsuccessful. These experiments provided closed-loop feedback related to task objectives, but not specific feedback relating to each muscle. We hypothesize that explicit guidance and rich muscle-based feedback are crucial for learning a new muscle pattern that is otherwise not practical for natural movements.

We designed an experiment where participants received closed-loop visual feedback of wrist muscle sEMG signals to teach them how to perform a novel wrist co-contraction. Each participant spent approximately 70 minutes completing the following protocol. First, we fit a personalized model to decompose sEMG recordings into four components, each indicating the activation strength of a wrist muscle. Next, participants were provided closed-loop feedback of all four muscles and learned to individually contract each muscle while keeping other muscles at rest. In the next phase, participants were instructed to co-contract the FCU and ECR, a muscle co-contraction that is antagonistic and rare for natural movements. We found that many of the participants were able to learn to make the novel wrist co-contraction within 20 minutes of practice. Finally, participants performed a series of natural behaviors so as to assess the frequency of wrist co-contractions.

A separate in-lab experiment validated the approach by collecting intramuscular EMG data directly from the wrist muscles of interest and showed that one participant was able to successfully co-contract FCU and ECR.

These results demonstrate the feasibility of augmenting human motor control by controlling co-contractions that generally do not occur during natural movement. This augmentation strategy provides an avenue for a control scheme that does not interfere with human's natural abilities.

1-D-35 - Motor unit activation states: Extracting a high-dimensional control signal from a single muscle for novel human machine interactions

Mario Bräcklein [1], **Jorge Menendez** [1], **Najja Marshall** [1], **Emanuele Formento** [1], **Vinay Jayaram** [1], **Niru Maheswaranathan** [1], **Diego Adrian Gutnisky** [1]

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Details

Recent advancements in surface electromyography (sEMG) interfaces have facilitated real-time, non-invasive monitoring of motor unit (MU) activity, opening new avenues for innovative human machine interactions and potentially surpassing the control dimensionality of conventional interfaces. However, while tens to thousands of individual MUs innervate a single muscle, a significant challenge lies in the inherent orderly recruitment of MUs within these pools. This rigid biological phenomena often drastically restricts the degrees of freedom extracted from these novel sEMG interfaces, limiting their potential applications. In this study, we propose a novel interaction scheme that capitalizes on the activity of individual MUs to extend the number of control states achievable with a single pool. We illustrate this through a case study involving a target acquisition task, wherein a participant is trained to maintain the activity of three MUs recorded from the tibialis anterior in seven discrete binary activation states. Our findings show that the participant could circumvent the inherent limitations of MU recruitment through a state-dependent control strategy. Specifically, the participant first activated the corresponding MUs with a standard recruitment order and then exploited differences in the de-recruitment order to isolate higher-threshold MUs while lower-threshold MUs were silent. The participant successfully formed and held for 2 seconds six out of the seven states with an average acquisition time of 4.96 ± 1.89 seconds with an average hit rate of 93.33 ± 7.70 % across targets. Remarkably, five of these states were rarely observed during a free-movement period (false-positive rate of 0.02 ± 0.04 per minute), during which the participant was encouraged to execute free-form movements with the corresponding foot and ankle, highlighting the potential for MU activation states as a high-dimensional decoder with a low false positive rate. Interestingly, the participant demonstrated consistent and target-specific dynamic contractions of the innervated muscle during the experiment, suggesting that state-dependent control can be further facilitated by leveraging these inherent behavioral patterns. Via computational modeling, we hypothesize that this novel control scheme is mainly facilitated by a single input signal to the entire pool and intrinsic feedback loops. In conclusion, our study provides evidence that state-dependent MU control enables the extraction of high-dimensional control signals from a single MU pool, highlighting its potential usage for novel human machine interactions.

1-D-36 - Reliable motor unit tracking across sessions for probing the flexibility of motor unit control

Emanuele Formento [1], **Najja Marshall** [1], **Mario Bräcklein** [1], **Peter Lee** [1], **Jun Ye** [1], **Dano Morrison** [1], **Renxiong Wang** [1], **David Sussillo** [1], **Diego Adrian Gutnisky** [1]

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Details

Human machine interfaces can leverage surface electromyography (sEMG) to create an artificial link between individual motor unit activity and external effectors, enabling the development of innovative interaction paradigms and providing a unique tool to explore the flexibility of motor unit control.

However, current techniques for extracting motor unit activity from sEMG signals are highly sensitive to sensor placements and posture. As a result, these interfaces often require users to undergo lengthy daily calibration procedures, with no guarantee of targeting the same motor units across different sessions. This leads to inconsistent control experiences and significantly hinders the potential for assessing the emergence of skilled motor unit control behaviors over extended training periods.

To address this challenge, we developed a human machine interface that enables users to track and consistently practice control of the same motor units across sessions. We first implemented an online template-matching pipeline to detect the action potentials of individual motor units recorded by a wearable sEMG band. Next, we implemented a platform to track units across sessions. This features three main components: a graphical interface enabling users to adjust their band placement and minimize potential discrepancies with previous recordings; an algorithm to update the templates of previously identified motor units once the detected recording discrepancies are sufficiently small; and a database to keep track of unit templates across sessions.

We validated this system performance in a dual-band experiment. Specifically, we identified individual motor units whose activity could be reliably detected by two sEMG bands worn on the same arm. We then asked participants to remove, wear again, and use the distal band to track the activity of one of the identified units with the developed platform. By comparing the results with the ground truth data provided by the proximal band, we show that participants could reliably track the selected motor units, effectively overcoming the disruptions in detection performance caused by band displacements.

Finally, we demonstrated how the developed interface can be leveraged to promote the emergence of skilled motor unit control through a neurofeedback experiment where participants trained with the same motor units across multiple days.

These results demonstrate the feasibility of developing human machine interfaces that establish a stable mapping between individual motor unit activity and external effectors, empowering future research in interactions and motor control.

1-D-37 - Fine firing rate control of isolated motor units with a noninvasive sEMG device

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Details

Humans possess a unique capacity for fine motor control that underlies skilled tool use and the ability to perform delicate tasks. The force exerted by a muscle increases with the number of recruited motor units (MUs) and their firing rate, and variability in MU firing rates contributes to fluctuations in generated force. Changes in force and firing rate variability have been widely studied during steady ramp-like force modulation and precision grasping, typically with a few predefined and uniformly spaced intensity levels. Yet the capacity to volitionally sustain MU firing rates within a narrow range remains unknown.

To investigate, we leveraged a noninvasive surface electromyography (sEMG) interface, methods for spike sorting isolated MUs online, and an adaptive task. Participants donned an sEMG device with 16 uniformly distributed sensing channels around their wrist and underwent a novel protocol for identifying a subtle movement of the wrist or fingers that could be reliably controlled while recruiting a small number of MUs. sEMG signals were decomposed online and the spikes generated by one MU selected for control were detected in real-time using a beamforming algorithm. Subsequently, participants were provided visual feedback about the firing rate of the selected MU during a task in which they were required to alternate between keeping the MU inactive and sustaining its firing rate within roughly 80% of its dynamic range. After achieving a minimum success rate, the initial target zone was bisected and replaced by two new targets, and so on in a recursive manner for 30 minutes.

We found that participants were able to control motor unit firing rates to a high degree of precision, with some participants learning to sustain their MU's firing rate within a range of 0.5 spikes/s for at least 1 second. We also observed heterogeneity in the control precision across the considered dynamic range with greatest precision typically achieved with intermediate targets in the 8-12 spikes/s range. These results reveal the capacity for fine control over MU firing rates of the hand and wrist through neurofeedback training.

1-D-38 - Multisensory feedback training improves the precision control and learning of targeted muscle activation states

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Details

Augmented feedback about a motor skill learning task acts as a source of information to the user that facilitates changes in motor performance. Over a period of time, these improvements in performance can reflect learning when feedback is removed. We explicitly tested the retention of learning following multisensory feedback in a task where people were required to learn to control different levels of forearm muscle activation measured via non-invasive on-wrist sEMG in performing an overt hand pose. Here we sought to address the contribution of visual and on-wrist haptic feedback in learning to perform 3 distinguishable levels of force exertion. Additionally, we also investigated the contribution of error-augmented visual feedback to this learning process. Participants were trained to perform a thumb tap with 3 targeted levels of muscle activation: 25-35%, 40-50% and 55-65% of their maximum voluntary contraction. The study consisted of baseline, training and testing phases. Vibrotactile haptic feedback with a distinguishable effect for each target was provided throughout the experiment. Additionally, two groups of participants also received visual feedback (either visual or error augmented) during the training phase, while a third group received solely haptic feedback. We assessed the improvements in thumb tap performance from baseline to testing within-subject and between-groups. Successful trials were defined as being able to hold muscle activation in the target range continuously for 0.8s. Baseline performance was statistically similar between the three groups (~35% task success). Visual feedback during training significantly improved retention of the consistently learnt target levels during testing (65%), compared to the haptics-only control group (~40%). Moreover, we also observed that the group that received error augmented visual feedback did not have any differences in performance during learning or testing, compared to the group that received veridical visual feedback. Importantly, we did not observe any differences in task performance with visual feedback between early and late stage training with both being near perfect, further suggesting that visual feedback produced an immediate improvement in performance of a proprioceptive task. Finally, we looked at the forces exerted by the participants in the last 1 second of task performance, segregated into the target levels they corresponded to. Although success within the testing phase was only ~65% after visual + haptic training, we observed that the segregation of exerted thumb tap force into 3 distinguishable targets was significantly higher than before training, indicating that participants were more self-consistent in producing discriminable force levels after training. However, these target levels may not be consistent with preset targets across all participants.

1-D-39 - Preliminary kinematic analysis of the use of a Taichi sword: the working point moves along the length of the tool according to the task intention

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Details

Since Bernstein's seminal work on blacksmiths, it has been accepted that what is controlled by the motor system is the tool tip. This implies that the technical object is incorporated into the body's schema. However, relatively little attention has been paid to the way in which the human motor system directs a working point externalized from the body. In that respect, the paradigm of the Taichi sword (Jian) is interesting because, on the one hand, the technique requires explicit control of distinct segments of the weapon (in the proximal third for blocking, or distally for attacking) and, on the other hand, the practice of codified exercises at reduced speed enables the instruction to be made explicit, with an emphasis on mentalization. In this preliminary and exploratory study, we asked a regular Jian practitioner to perform several codified exercises while recording the 3D position and orientation of the Jian with an Optitrak system. Usual 3D kinematic analyses (Euler angles, axis-angle or instantaneous center of rotation) cannot track the instantaneous position of a center of rotation in a reference system centered on the tool. So, the analysis focuses on the velocity profiles of 11 segments along the sword from its base to the tip. The first exercise which required the participant to rotate the jian while keeping a segment in the first third of the sword relatively still. This was verified by the position of the instantaneous velocity minimum. The second exercise combines an horizontal translation and the explicit instruction to rotate the jian around a vertical axis “at its first third”. To achieve this, the base and tip of the jian moved alternately in the same direction and in the opposite direction, anticipating the jian's horizontal rotation (azimuth). The other exercises reproduced codified 3D defense and attacks gestures. In those exercises, the average speed along the epee varied from task to task, in accordance with the exercise instruction. The instantaneous velocity minimum moved along the jian’s length but it was difficult to attribute this shift to attack/defense instantaneous intention. Other calculation methods and kinematic modellig will be explored and discussed. These observations raise the very general question of 3D kinematic redundancy and the combination of translations and rotations required for the final orientation of technical objects (tools or weapons) according to the task.

1-D-40 - Exploring physical resilience during healthy aging: insights from an inter-joint coordination task

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Details

During healthy aging, motor function declines gradually. However, there is a large heterogeneity in motor function across older (and younger) adults. Some older adults are physically more resilient to age-related motor declines than others are, resulting in better motor function. Physical resilience is one's ability to maintain motor function, despite exposure to a stressor such as brain degeneration or any physical stressor. This means the more physically resilient an individual is, the better s/he will cope with stressors, which is supported by a higher level of one's motor reserve. Yet, the mechanisms that make some adults more resilient are still unknown. A leading theory in motor control states that the control of movements is achieved through so-called internal models. These internal models rely on a brain area, the cerebellum, which helps us predict the consequences of our movements. Given that the cerebellum is heavily affected by aging, the current accepted hypothesis is that age-related cerebellar degeneration directly causes motor deficits. In contrast, consistent with the absence of age-related declines in cerebellar motor tasks, we aimed at testing the idea that the cerebellum can act as a motor reserve, which makes older adults resilient to age-related brain degeneration.

We investigated a group of young (20-35 y/o), old (55-70 y/o) and older old (80+ y/o) adults on an inter-joint coordination task. This task was performed on a KINARM exoskeleton and consisted of reaching to 3 targets that only involved displacement of the lower-arm. To coordinate this movement the internal model function of the cerebellum is crucial. The task was performed at a slow and fast speed. Given that interaction torques at the shoulder increase with increasing elbow rotation velocity, the fast condition will challenge one's motor system more (i.e., speed stressor makes the task more difficult). We will quantify resilience of participants' motor function by comparing task performance between the slow and fast condition: the smaller the difference between both conditions, the higher the resilience of one's motor function. We will investigate task performance by analyzing shoulder displacement as well as timing and magnitude of muscle activity onset of both flexor and extensor muscles of the shoulder (i.e., m. pectoralis major, m. posterior deltoideus) and elbow (i.e., m. biceps brachii, m. triceps brachii). We hypothesize that the cerebellar motor reserve will help maintaining motor performance at older age in an easy (slow) condition, but that it would fail to compensate motor performance in a more difficult (fast) condition. Therefore we expect no differences on task performance between young and old adults in the slow condition, but we do expect a decrease in performance in the fast condition for the old adults. Furthermore, we hypothesize an even worse performance for the older old adults, because we expect motor reserve capacity will decrease with aging.

1-D-41 - PCA does not allow an assessment of dimensionality and mixes population dimensions

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Details

A multitude of studies has shown that behavior-related population activity is confined to a low-dimensional space. The dimensions of this space consist of the combined activity of many neurons. Population dimensions can be grouped into meaningful subspaces capturing distinct cognitive and behavioral processes such as the integration of relevant visual features, movement preparation and movement execution. So far, however, cognitive and behavioral subspaces can only be reliably identified using experiments and methods designed for this purpose. It remains unclear to what extent unsupervised dimensionality reduction methods are also applicable for this purpose.

The most commonly used unsupervised dimensionality reduction method is Principal Component Analysis (PCA). While PCA is without question a powerful tool for many applications, its capability to identify cognitive- and behavioral-related subspaces of neural population activity has not been studied, yet. This is in particular the case, because the subspace structure of many recorded datasets cannot be determined with certainty, which hinders a direct assessment of the low-dimensional space identified with PCA.

For this reason, we developed a model for neural population activity that precisely matched recorded population activity from two monkeys performing a delayed grasping task. Modeled population activity occupied three subspaces comprising visual, preparatory, and movement execution related processing. To resemble recoded population activity, we fit measured properties in the model, such as: the average, behavioral state- and condition-dependent distributions of firing rates and neural temporal on- and offset distributions.

Based on the precise simulation of behavior related population activity, we compared the explicit population subspaces structure of the model with the low-dimensional space identified by PCA. We compared both spaces by means of the (1) estimated dimensionality, (2) the amount of variance captured per subspace and (3) the separation of subspaces. Although the simulated behavior-related population responses had a predefined, low number of dimensions, PCA identified dimensions (PCs) that continuously captured a decreasing amount of variance and thus did not allow to estimate dimensionality precisely. For a limited number of dimensions, the amount of variance captured was significantly different between the subspaces and the majority of variance of all subspaces was only captured with a high threshold of 90% explained variance. Furthermore, individual PCs were in general mixtures of different subspace dimensions and therefore did not allow to draw any conclusions about the underlying subspace structure. Together, these results suggest that the low-dimensional space estimated with PCA reflects the underlying population structure only to a limited extent.

1-D-42 - Spatial microstructure of motor cortical neural dynamics

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Details

Recent advances in silicon electrode technology enable dense, simultaneous sampling of many neurons. As significant computational and theoretical work has begun to understand the computations performed via neural population dynamics, these tools open experimental avenues to explore how these dynamics are organized within neural circuits. We recorded in macaque primary motor and dorsal premotor cortices using NeuroPixels and collected a dataset comprising 6,990 neurons (36 sessions, 2 monkeys). We analyzed neural responses during a reaching task to investigate the spatial, laminar, and synaptic organization of neural populations engaged in motor control. We revisited a long-held view that the motor cortex exhibits columnar architecture organized by shared preferred movement directions (PDs). In contrast with this view, we found that spatial proximity was not predictive of similarity in PD. More generally, nearby neuron pairs did not exhibit increased PSTH correlation or a reduced angle between GPFA loading vectors. We further verified this lack of spatial micro-organization using a mutual information metric relating individual neurons with their spatial nearest neighbor, and comparing this statistic against synthetic cortical models with columnar or spatially clustered organization. Similarly, spatially intermingled neural activity was also observed when the arm was mechanically perturbed during reaching, resulting in sensory errors that evoked corrective feedback responses in the motor cortex. We used current source density to coarsely divide neurons into superficial and deep cells and found that responses to visual task cues and proprioceptive errors (when perturbing the arm mid-reach) appeared earlier in superficial cells than deep cells. We then used a representational similarity metric to assess whether superficial neurons contained response features not found in deeper neurons. This analysis identified transient periods after task cues and mechanical perturbations where local response features emerge in superficial cells before becoming distributed throughout the full population.

Collectively, these analyses depict highly heterogeneous, spatially intermingled neuronal responses throughout the motor cortex. Visual and proprioceptive task inputs evoke local response features first in superficial neurons and then may rapidly spread through recurrent connections. These inputs then initiate and mold pattern-generating dynamics which are finely, spatially intermingled in the cortical population.

1-D-43 - Combining MEG with real-time measures of articulation during speech

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Details

MEG recordings of movement-related brain activity provide an ideal method for the study of the cortical control of movement. However, MEG measurements associated with speech is limited due to the challenge of tracking speech movements in the MEG environment, particularly for small movements of the tongue which requires non-line-of-sight methods. We have developed an MEG-compatible motion tracking system to monitor brain activity in parallel with ongoing orofacial and speech movements. This technology, dubbed MASK (Magnetoarticulography for the Assessment of Speech Kinematics), can be integrated into existing MEG recording systems to acquire 3-dimensional kinematic data simultaneously with neuromagnetic brain activity [1]. This system has been shown to measure speech kinematics comparable to conventional articulography measurement systems [2]. We present data from healthy adults performing a speech task (10 second trials x 10 repetitions) involving reiterated disyllabic non-words (/ipa/, /api/), non-speech mouth opening-closing, and a simple manual motor task (left and right button press). Speech gestures and mouth movements were tracked in real time along with brain measures using a 275-channel MEG (CTF Systems, Vancouver, Canada) from the upper and lower lip (bilabial closure) and tongue body (tongue movements associated with vowel formation (/a/ versus /i/) in addition to the acoustic speech signal. Source analysis of MEG data showed suppression of beta band (15-30Hz) oscillations during speech in portions of the precentral gyrus ventral to the hand motor area activated during button press. Beta suppression during reiterative speech was strongly left lateralized in contrast to non-speech movements which were associated with bilateral beta suppression in lateral motor cortex. These preliminary results demonstrate the ability to measure time-locked brain responses and speech kinematics during speech tasks using a novel MEG compatible motion-tracking system. Differences in patterns of brain activation between non-speech movements and speech tasks demonstrate the importance of both task design and the ability to measure complex speech gestures concurrently with functional brain imaging to understand the underlying mechanisms of speech motor control. This technology provides new avenues for both basic research on articulatory control and speech sound disorders.

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[2] Anastasopoulou, I., van Lieshout, P., Cheyne, D. & Johnson, B. W. (2022), Speech kinematics and coordination measured with an MEG-compatible speech tracking system. *Front. Neurology*, 13:

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1-D-44 - Mapping lower-limb muscle synergies encoded in the human brain through transcranial magnetic stimulation of the motor cortex and functional magnetic resonance imaging

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Details

Voluntary movement is governed by motor-control mechanisms within the central nervous system (CNS). Numerous animal studies indicated that motor system control commands might be organized through muscle synergies, which are distinct motor-activation units activating specific muscle groups. Yet, direct neurophysiological proof of muscle synergies in humans remains elusive. Our study investigates whether lower-limb muscle synergies observed in daily activities can be elicited by stimulating the lower-limb region of the human motor cortex. We aim to provide direct evidence of these lower-limb muscle synergies in the human CNS using focal, non-invasive transcranial magnetic stimulation (TMS) on the lower-limb region of the human primary motor cortex (M1).

This study involved 12 healthy participants across three experimental sessions: behavioral, MRI, and TMS. During the behavioral session, participants performed 10 walking and running tasks, with surface electromyography (EMGs) recording from up to 16 lower-limb muscles of the dominant side. Subsequently, all subjects underwent structural and functional MRI for brain reconstruction and to capture blood-oxygen-level-dependent (BOLD) signals from motor-imagery tasks that involved active imagination of the performance of the same locomotor tasks. In the TMS session, neuro-navigated stimulations were applied to the subjects' scalps along with individual predefined M1 grids when participants were at rest, with TMS-induced motor evoked potentials (MEPs) recorded via the same EMG channels. Muscle synergies were later extracted from both locomotor EMGs and TMS-elicited MEPs using non-negative matrix factorization (NMF), followed by statistical analysis and comparison.

Across subjects, topographical representations of TMS-derived muscle synergies were successfully reconstructed, which partially overlapped with BOLD activation maps. TMS-derived muscle synergies were sparser when compared with locomotor synergies. About 38% of locomotor synergies were very similar to TMS-derived synergies, with an additional 22% explainable by merging TMS synergies. Interestingly, the TMS synergies involved in such merging showed greater similarity in their cortical representations than unmerged ones. A negative correlation was found between the sparseness of TMS synergies and the uniformity of their cortical representations, indicating that TMS synergies with fewer muscle components had more uniform cortical representations.

In conclusion, our findings support that human lower-limb muscle synergies from daily locomotion are encoded in the motor system, accessible and mappable in M1 via TMS and fMRI data. The study provides direct neurophysiological evidence of human locomotor muscle synergies. This research was supported by CUHK Group Research Scheme (NL/JW/rc/grs1819/0426/19hc) and HK Research Grants Council grant (CUHKR4022-18, 14119022, 14114721, N_CUHK456/21) to VCKC.

1-D-45 - The role of supplementary motor area in motor imagery: a transcranial direct current stimulation study

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Details

Motor imagery (imagined movement without overt motor execution) and action observation recruit neural networks overlapping with those involved in motor planning and execution. The supplementary motor area (SMA) is thought to suppress motor execution during imagery via inhibitory connections to primary motor cortex (M1), but its role in imagery and observation is not fully understood. Transcranial direct current stimulation (tDCS) can help to elucidate the role of cortical structures in a particular task by enhancing or inhibiting neural activity in the target areas, which may influence the performance of the task. The present study investigated the effects of tDCS over the SMA on the performance of motor execution, imagery, and observation tasks.

In separate blocks of trials, neurologically healthy participants (N = 23) executed, imagined, and observed a manual aiming action. The difficulty of the movements was varied across trials in a manner previously used to demonstrate a speed-accuracy trade-off characteristic of Fitts' law in the three modalities. Performance on each task was assessed before and after 20 minutes of 1mA tDCS over SMA. Participants received different types of stimulation across three sessions, comparing anodal, cathodal, and sham (inactive) protocols.

Movement time and conformity to Fitts' law were not significantly affected by tDCS in execution, imagery, or observation tasks. However, the correspondence between imagined and physical movement time (mental chronometry) was increased following anodal tDCS compared to the sham condition. Motor overflow (incidental movement) during the motor imagery task was also increased by anodal stimulation. No effects of cathodal tDCS were found in any of the tasks.

The present results suggest that suppression of motor output during motor imagery may be disrupted by anodal stimulation of the SMA, while mental chronometry may be enhanced. This pattern of effects could reflect an unintended inhibitory effect of anodal tDCS on the SMA, or incidental activation of other regions such as pre-SMA or M1.

A limitation of this study is that the mechanisms of tDCS when applied to areas outside of M1 are not well understood. Further research should compare the effects of different protocols and parameters of tDCS on motor simulation.

1-D-46 - Hardware powered ultra low latency (HarPULL) brain-state dependent TMS technology

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Details

The intra- and intersubject variability in transcranial magnetic stimulation (TMS) effect on the nervous system, influenced by physical and physiological factors, limits its application, and cannot be efficiently controlled by such advanced techniques as MRI-navigation and robotic coil fixation.

Existing phase-targeted stimulus timing to modulate responses can reduce variability, however, results from existing studies are inconclusive, partly due to hard to control delay between brain events and stimulus application. Our hardware powered ultra-low latency (HarPULL) system opens a broad range of scenarios to address these challenges, explore and ultimately gain control over the factors affecting the observed variability of the TMS induced effects. According to our hypothesis the key factor is associated with the need for precise timing to lock TMS stimulation to the specific sensorimotor rhythm (SMR) phases.

We present a novel hardware-software complex for the low latency real time phase-dependent TMS neurofeedback. The real-time portion of the instantaneous phase tracking software is implemented on-board of the EEG-recording device and allows us to accurately track the phase with minimal time-delay. Once the target phase is tracked, the TTL output connected to the TMS-device is activated. An accurate phase estimation is achieved by proper Kalman filter-based state-space modeling of brain rhythm using the parameters computed based on the pre-recorded segment of data (the phase determination error is 6 °). The delay from the moment of trigger formation to the arrival of the magnetic field pulse at the recording electrode, measured using a watermelon model, was no more than 5 ms.Spearman's correlation for the SMR phase and the motor evoked potentials (MEPs) amplitude revealed a direct, moderate-strength correlation (r=0.48, p<0.05). TMS mapping of the hand muscles (abductor pollicis brevis - APB, abductor digiti minimi - ADM) for a healthy volunteer (male, 26 years old, right-handed) showed a difference in the areas of motor cortical representations for the 0 phase of the SMR (area APB = 3.5 cm^2, area ADM = 3.89 cm^2), for 180 phase of the SMR (area APB = 3.61 cm^2, area ADM = 4.06 cm^2) compared with random phase mapping (area APB = 2.73 cm^2, area ADM = 2.91 cm^2).

The proposed technology opens a wide range of avenues both for scientific purposes and clinical practice. Implementing the proposed algorithm into diagnostic and rehabilitation TMS protocols based on real-time assessment of the subject's functional state, promises to enhance the precision of stimulation as well as develop new methodological approaches in determining the motor threshold, assessment of the mapping parameters and rehabilitation potential in general.

1-D-47 - Thalamic interaction of basal ganglia and cerebellar circuits during motor learning

Jun Ding [1]

[1] Stanford University

Details

Richard H. Roth, Fuu-Jiun Hwang, Michael Muniak, Charles J. Huang, Yue Sun, Tianyi Mao, Jun B. Ding

The ability to control movement and to refine and learn new motor skills is one of the fundamental functions of the brain. The basal ganglia (BG) and the cerebellum (CB) are two key brain regions involved in controlling movement, and neuronal plasticity within these two regions underlies the acquisition of new motor skills. However, how these two critical motor regions interact and orchestrate together to produce a cohesive motor output remains poorly understood. Here, we used an intersectional viral tracing approach to identify neurons in the motor thalamus that receive inputs from BG and CB and found that a subset of neurons in VM and VAL receive converging BG and CB inputs. Using slice electrophysiology in combination with optogenetic activation of BG and CB projections we show that these thalamic neurons receive functional inhibitory inputs from the BG and excitatory inputs from the CB. Moreover, using chemo-and optogenetic silencing, we demonstrate the role of these thalamic neurons and their inputs in motor learning. Lastly, using in vivo two-photon calcium imaging through an implanted GRIN lens in the motor thalamus, we measured neuronal activity in mice over the course of motor learning and found that neurons in VM show distinct movement related activity patterns. These results indicate that neurons in the motor thalamus receive converging input from BG and CB and may play an important role in integrating movement signals during motor learning.

1-D-48 - Effects of 6 months of endurance exercise and chronotropic status on VO2peak, motor signs, and peak heart rate in individuals with drug naïve Parkinson’s disease

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Details

Background: Endurance exercise benefits aerobic capacity (VO_{2peak}) and motor signs in people with recently diagnosed Parkinson's disease (PD). Some people with PD exhibit signs of chronotropic incompetence (CI) which may impact the effect of endurance exercise on signs of the disease. Objectives: To investigate if CI in people with recently diagnosed PD influences change in VO_{2peak}, motor signs, and peak heart rate following 6 months of endurance exercise training. Methods: We performed secondary analyses of VO_{2peak}, MDS-UPDRS Part 3 score, and peak heart rate data from the Study in Parkinson's Disease of Exercise (SPARX). Data were analyzed at baseline and following a 6-month intervention (participants were randomized into a high intensity [80-85% of peak heart rate], moderate intensity [60-65% of peak heart rate], or usual care group). Within each of the three treatment arms, we further sub-divided participants into those who were chronotropically normal, those with CI, and those taking medication with known negative chronotropic effects. Results: Data from 119 individuals (64.0 ±9.0 years, 57.1% male, 0.3 years since diagnosis [median]) were analyzed. There were no differences among the three chronotropic groups for change in VO_{2peak} (0.23 ±3.64 mL/kg/min, p=0.965), change in motor score (0.29 ±7.90, p=0.953), or change in peak heart rate (-2.79 ±9.82 bpm, p=0.388) following completion of the 6-month intervention. People randomized into the high intensity exercise group improved VO_{2peak} compared to usual care group (p<0.001). Conclusions: The presence of CI did not result in differential responses to 6 months of endurance exercise training in people who were recently diagnosed with PD. All people with early PD should participate in endurance exercise training as part of a comprehensive approach to PD management.

1-D-49 - Non-invasively-recorded spinal cord responses to median nerve stimulation demonstrate stronger high-frequency oscillations in anterior versus posterior electrode locations

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Details

Background: The characterization of neurodegenerative conditions such as ALS, benefits from biomarkers that can quantify sensorimotor dysfunction. However, non-invasive biomarker candidates of dysfunction in the spinal cord (as a critical part of the central neural axis) are not adequately developed. Very-high-frequency oscillations could be a potential biomarker, due to their neurophysiological generators which are believed to involve the long sensory tracts[1]. Invasively recorded evoked low-amplitude high-frequency wave responses (LHWs)[1,2] have shown altered characteristics in patients with neuropathic pain at cervical

spinal levels from posterior location. In this study, we test the possibility of using non-invasive recording technique to evaluate spinal-LHWs.

Objective: To non-invasively characterize the evoked LHW components recorded anteriorly and posteriorly at C6 vertebral level (Cv6) in response to median nerve stimulation.

Methodology: Data were collected from 10 young healthy participants. Non-invasive surface electrodes were placed on the neck in accordance with the ring electrode placement system[3] at Cv6 to record neuro-electrophysiological signals (sampling rate: 8kHz). A total of 1400 responses (trials) were recorded in response to the median nerve (MN) stimulation at the wrist (1.5 X Motor Threshold, 2Hz). The recorded signals were pre-processed to remove artifacts, bandpass filtered between 250-2000Hz, and spatially filtered to increase the signal-to-noise ratio. The power spectrum was calculated using fourier transform for each trial. The high-frequency evoked potential (LHW) characteristics were obtained by averaging the resulting signals in time and frequency across all trials.

Results: LHW responses were observed at anterior cervical (AC) and posterior cervical (PC) electrode locations. The peak amplitude recorded at AC (0.26 ± 0.11 µV) was greater than the peak amplitude measured at PC (0.081 ± 0.029 µV) (p=0.0011, paired t-test). The observed latency (mean ± SD) at peak amplitude was Cv6-PC: 11.5 ± 2.4 (ms), Cv6-AC: 10.5 ± 0.97 (ms).

Increased activity was observed in the 300-600Hz frequency range between 5-20ms after stimulation. AC showed higher band-power between 300-600Hz than PC (p = 0.023, one-sided paired t-test).

Discussion: These results in young healthy participants indicate that LHW responses can be recorded with non-invasive techniques at Cv6. Increased activity in 300-600Hz is observed during LHW responses. Furthermore, the response at the anterior location demonstrated higher amplitude and band-power than the response at the posterior location. This could indicate that long-sensory tracts (eg. spinothalamic tract) located anterior-latterly might be responsible for the LHW response, supporting Prestor et. al [1] findings.

References:

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2. Insola et al, 2008, Clin. Neurophysiology 119.1: 237-245
3. Chander et al, 2022, NeuroImage, 253, 119050

1-D-50 - Co-activation and co-variation of muscles jointly evolve during learning a new redundant isometric myocontrol task

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Details

Learning a new motor task implies using a new coordination pattern among muscles. Two control processes might play a role in the emergence of these new coordination patterns; a) co-activation:

muscles are activated in a proportional way to move the end-effector in the required direction, and b) co-variation: muscles co-vary to stabilise the movement of the end-effector. The current study examined how processes of co-activation and co-variation evolved during the learning of new coordination patterns among muscles. We distinguished two possible scenarios; 1) co-activation and co-variation evolved jointly over learning, or 2) co-activation and co-variation evolved subsequently over learning. In the experiment, EMG signals of muscles in the arm are mapped onto movements of a cursor on the screen to play a virtual game in which a virtual ball has to follow a path. Sixteen righthanded adults participated in the experiment, all had no deficits in their neuromotor system. EMG of the Extensor Carpi Ulnaris (ECU), Extensor Carpi Radialis (ECR), Flexor Carpi Radialis (FCR) and Flexor Carpi Ulnaris (FCU) of their non-dominant arm was measured with a Delsys Trigno system at 1925Hz. Participants wore a wrist brace so that they could produce isometric contractions. They performed 20 min practice sessions on four subsequent days. For each EMG signal, the control signal of the game was computed using an RMS filter over the preceding 750ms in steps of 50 data points. The game showed platforms oriented in different directions that became smaller during game progression. Using the control signals, the virtual ball had to be steered over the platforms to collect boxes by hitting those with the ball. The ball was controlled using a direct mapping between the control signal and ball direction/movement where ECR moved the ball UpLeft, ECU moved the ball UpRight, FCU moved the ball DownRight and FCR moved the ball DownLeft. In the different conditions the ball had to be moved using the activation of one muscle or multiple muscles. The results showed that participants learned the task and achieved higher game levels (smaller platforms) in later sessions. The coordination patterns of the muscles showed that from the first to the last sessions all muscles were active in all conditions. This implies that also in conditions in which the task could be achieved by activating just one or just two muscles, substantial activity in all four muscles was observed. These findings demonstrate that co-activation and co-variation evolved concurrently over the learning of new coordination patterns. Moreover, we found that the muscle activation patterns were not consistent over repetitions of the same condition. The implications of these findings for machine learning myocontrolled assistive devices, such as hand prosthesis, will be discussed.

1-D-51 - Gaze direction influences the generalization of visuomotor memory

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Details

Motor memory can be represented in coordinate systems that are extrinsic (e.g., hand trajectories) or intrinsic (e.g., joint angles) to our body (Braianov et al., 2012). To understand how both representations shape motor memory, learning generalization from trained to untrained workspaces was exploited in arm-reaching tasks (Shadmehr, 2004). While switching across different workspaces usually requires a gaze/head rotation to look at the targets and their hand, research has assumed that the extrinsic coordinate is allocentric, independent of the gaze/head direction. However, if eye- or head-centered coordinates also participate in representing motor memory, the rotation should affect the learning generalization pattern. In this study, after exposure to a visuomotor rotation in a reaching task, we assessed the generalization pattern (function) in both the training and an untrained workspace while manipulating the gaze/head directions.
We conducted two experiments. In the first one, 28 participants performed a shooting reaching task to a

frontal training target, in which they adapted to a gradual counterclockwise rotation increasing up to 30 °. After adaptation, generalization was tested in 13 targets in a workspace rotated of -45 ° around the shoulder axis (right workspace). Participants were divided into two groups, differing in the visualization of the targets and the cursor as a proxy of their hand. One observed them in the actual positions, necessitating a shift in the gaze/head direction (shift group), while the other observed them projected directly ahead, avoiding the shift (no-shift group). We found that the generalization pattern (function) shifted towards the corresponding gaze directions. The peak distributions for the generalization functions in the two groups were compared through a generalized linear mixed model, showing a significant effect of group ($p < 0.001$). Next, to dissociate the effects of the gaze and head directions, we performed the second experiment. Eight participants performed the same task with the targets and the cursor visualized in the actual positions during the generalization as in the GS group, but their head direction was differently manipulated in two conditions. One condition allowed the participants to rotate their head while the other asked them to only move their gaze to look at the targets with their head direction fixed forward. Unlike the gaze direction, the head direction did affect the generalization functions with no significant difference between the peak distribution of the two conditions (post-hoc Tukey test after Kruskal-Wallis ANOVA: $p = 0.38$).
Our findings suggest that the gaze-centered coordinate is utilized to represent visuomotor memory and highlights the importance of controlling the gaze to evaluate the generalization of learning.

1-D-52 - Serial dependence reveals an active suppression in the sequential motor planning

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Details

The implementation of a selected action entails the suppression of related movements that may cause interference. For example, pressing a key with the middle finger entails inhibition of muscles associated with the other fingers on the same hand. This inhibition exists during motor preparation and persists after the movement. In the current study, we turn to sequential behavior, asking how the current movement is influenced by the recent history of related movements.

We employed an online center-out movement task where the target appeared at a random position along an invisible circle. Participants moved their fingers across a trackpad to reach the target in the absence of any feedback. We examined how the current movement is influenced by previous movements. We found a repulsive serial dependence effect such that the heading direction on Trial N was biased away from the heading direction on Trial N-1. The size of this bias increased as the angular difference between the current and previous target increased from 0 ° to around 60 °, and then decreased for larger angular differences. A biasing effect was also observed from the Trial N-2 heading direction, but not from Trial N-3.

It is possible that the serial dependency effect observed in Exp 1 is perceptual rather than motoric; the perceived location of the Trial N target might be biased away from the perceived location of the Trial N-1 target. In Exp 2 we evaluated perception-based and motor-based accounts by including trials (25%) in which the participants were instructed to move in the opposite direction of the target. We again observed a repulsive effect for successive movements on the standard (reach direct) trials. Importantly, the heading angle for the movement following the "opposite" trials also exhibited a repulsive effect relative to the previous movement rather than the previous target location, providing strong evidence that the serial dependence effect in reaching is motoric in nature.

In Exp 3, we asked if the reaching bias required movement execution. We employed a Go/No-Go task. In 25% of the trials, the target turned red 100 ms after its onset, signaling the response should be withheld. The overall pattern of a repulsive serial dependency effect was observed on both Go and No-Go trials although the latter effect was weaker. The presence of a repulsive bias following No-Go trials indicates that at least some of the effect comes from motor planning.

In summary, the current set of experiments demonstrates a robust serial dependency effect in reaching, whereby the current movement is biased in the opposite direction of a recently performed/prepared movement. We speculate that this effect arises from the suppression of recently activated motor plans. This suppression might be invoked to avoid repeating actions in a system evolved to efficiently explore the environment, similar to what has been described in the attention literature as inhibition of return.

1-D-53 - Stochastic Dynamic Operator (SDO) descriptions of neurons can flexibly scale from single-unit to population-level analysis

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Details

In the spinalized bullfrog, the hindlimb wiping reflex is a model spinal motor behavior. During wipe, we record populations of spinal interneurons, single motor units from muscles, and intramuscular EMG activity across the major muscles of the hindlimb. The spike-triggered average (STA) is –ubiquitous to identify the connectivity and effects of spinal interneuron spikes on motor behavior. However, STA does not include spinal state (e.g., locomotor or wiping phase). We find both interneurons and single motor units show strong state-dependent effects. To unify our observations, we use the *Stochastic Dynamic Operator* (SDO) framework to test state-dependent and probabilistic relationships in the data. SDOs describe the predicted *change* in probability distribution of state given an initial state distribution, connected to spiking events. Spike-triggered SDOs from individual interneurons and motor units show significant, state-dependent, relationships across subsets of EMG channels, consistent with synergy. The SDO matches or improves performance over the STA for predicting signal behavior near spiking events during reflexive wipe. SDOs can also be generated from applied stimuli, such as intraspinal microstimulation (ISMS). Using SDOs, the response of a population to stimulus or perturbation is modeled as the superposition of the stimulus-triggered SDOs of component neurons. SDOs may be used as a basis for stochastic controllers recruited by gain schedules. If gain schedules are regulated by cyclical processes, SDO controllers capture rhythmic or oscillatory phenomena (e.g. locomotion). SDOs bridge the state-dependent modulation by individual neurons with the evolution of the spiking population, and the associated motor output. The SDO may thus be a useful tool spanning characterization of neurons as both single units and network components, and their neuromodulation.

1-D-54 - Switching motor cortex dynamical rules influenced by distinct cortical and subcortical regions during skilled movements

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Details

Complex behaviors result from interactions of multiple brain regions. Reach-and-grasp movements are an example of such complex and skilled behaviors. However, the role of these interactions during reach-and-grasp behavior is not understood well. To elucidate the roles of regional interactions in the execution of this behavior, we recorded single-unit activity from thousands of neurons in 10 cortical (motor and sensory) and subcortical (multiple regions in basal ganglia, thalamus and cerebellum) brain regions simultaneously using multiple Neuropixels probes while the mice performed reach-and-grasp task for a food pellet. We first performed a detailed 3D kinematic analysis to understand this task at the behavioral level. By combining the analyses of 3D kinematics of the paw position and paw shape changes, we identified two phases of the movement from start of the reach until the grasp. We demonstrated the kinematic differences between these phases and their associations with the reach outcome. Given the substantial kinematic differences, we hypothesized that the neural underpinnings of these phases are different. We found examples of task-responsive neurons in all 10 brain regions. We first showed that optogenetic M1 inhibition results in the freezing of the paw, indicating that M1 plays a critical role in the execution of this behavior. To better understand the motor cortical dynamical rules, we used recurrent switching linear dynamical systems (rSLDS) model. We found that behavior phase switch times and neural state switch times showed alignments with >70% of variance explained for all time points at the single-trial resolution. Each behavior phase was governed by a single discrete neural state and these discrete neural states were different, but stayed mostly within the same neural subspace. To model the statistical relationship between regional activity, we used data-driven recurrent neural network (RNN) modeling where the number of nodes in the RNN is the same as the number of recorded neurons. After training of the RNN to generate the same activity patterns of the recorded neurons, we performed in silico inhibition experiments and analyzed their effects on M1 neural trajectories. We showed that inhibition of different regions influences the M1 dynamics to varying degrees in each behavioral phase. We confirmed some of these results by in vivo optogenetic inhibition. Overall, our results demonstrate how the reach-and-grasp task is executed at behavioral, neural and computational levels. Specifically, we show that the M1 dynamical rules change during different phases of the reach-and-grasp behavior. We show that interactions between different cortical and subcortical regions influence the M1 dynamics, and the behavior, differently during each behavior phase. These results demonstrate the intricacy and complexity of the motor control of this task, and the importance of regional interactions during complex behaviors.

1-D-55 - Shared neural states, but dissimilar information encoded for motor control in medial parietal areas

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Details

Growing evidence suggests a lack of hierarchical organization in the cortical network involved in motor control. The prevailing view favours the idea that goal selection, movement planning and execution, and error correction occur in parallel within parietal and frontal areas. Indeed, strong reciprocal connections between these two cortical regions give rise to a network with highly integrated functions. Furthermore, parallel computations have the potential to facilitate adaptable flexible behavioural control, such as the execution or withholding of predefined potential actions guided by bottom-up sensory information, as well as the integration of top-down target information according to task rules. Modern approaches reveal that the population dynamics in motor/premotor cortices show patterns of neural states that persist across different motor behaviours. However, it remains unclear *if* and *how* these dynamics are reflected in the parietal cortex. Moreover, since parallel coding assumes that each area processes a part of the final motor plan, the question of how the heterogeneity of information encoded in the different parietal areas is dynamically integrated is still open. To address this issue, we analysed the spiking activity of three parietal areas (V6A, PEc, and PE) in macaques by applying a Hidden Markov model (HMM). During a delayed reaching task, we found motor-like neural states that were temporally linked with the planning, execution, and target hold phases. Furthermore, population activity during the execution phase could be more finely segmented into states associated with arm acceleration and deceleration, like in the motor cortex. Using a decoding-oriented approach, we then investigated whether the main neural states in these medial parietal areas convey information related to target and movement phase. To assess the robustness of our conclusions, we compared the HMM with other algorithms, namely SVM and a LSTM neural network. Our results confirm the strong link between neural states and behaviour, but also highlight the differences between parietal areas, with area PE showing the worst decoding accuracy. Finally, we performed a series of stress tests simulating real BMI applications. Indeed, we tested the decoding performance with subsets of neurons retraining the models, but also without retraining (neuron loss), and introducing noise in the neural data (without retraining). The various algorithms performed differently in the multiple scenarios we explored. For example, SVM was very efficient at decoding from a few units and HMM was more robust to neuron loss. In summary, while the parietal and motor cortices show consistent neural dynamics, for brain-machine interface applications a careful selection of the most suitable source of neural signals is required, considering the rich heterogeneity within the parietal cortex.

1-D-56 - The secret of tiny hand movements to feel and manipulate objects

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Details

This presentation will give insight into sophisticated strategies on how motor control and sensory systems reciprocally cooperate achieving fine control of hand movements. Frictional information is crucial in achieving fine grip force adjustments during manipulation tasks avoiding objects to slip out of hands. Our research has discovered a surprising significant physiological mechanism that small submillimeter range hand movements, which we are not ourselves aware of, significantly enhance human ability to perceive friction differences when object is gripped. The evidence will be presented comprising psychophysics experiments, biomechanical analyses, and object manipulation tasks. By observing hand movement strategies during object manipulation, we notice that, yet another mechanism must be used, especially when an object is just being lifted. Rotational forces (torque) are unavoidably arising when the mass of the object is not perfectly distributed relative to the grip axis and when vertical movement is achieved by rotation in the wrist or elbow joints. We suggest that the advantage of torque-induced object rotation is that it may induce localized slips depending on distance from the rotational canter helping to measure friction without vertical translation with gravity which would endanger grip safety and the object might fall out from the hands.

This knowledge not only contributes to fundamental understanding of motor control mechanisms but might also advance technology. We suggest that implementation of such relatively simple movement strategies enabling acquisition of sensory information may substantially enhance capabilities of the robotic and prosthetic devices.

1-D-57 - Space across the motor cortical sheet as a coding dimension

Nicholas Hatsopoulos [1], **Milan Rybar** [1], **Wei Liang** [1], **Karthikeyan Balasubramanian** [1]

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Details

The functional organization of M1 across the cortical sheet remains obscure. Aside from the crude and static somatotopic organization of M1, there is little evidence of spatially organized dynamic patterning across the motor cortical sheet. We have previously demonstrated that spatially organized propagating patterns of excitability along a rostro-caudal axis signal the initiation of movement but do not specify the details of the movement (Balasubramanian, Arce-McShane, Dekleva, Collinger, & Hatsopoulos, 2023). These propagating patterns of excitability were observed in the attenuation of low frequency beta oscillation (15-35 Hz) amplitude of the local field potential (LFP). We recently discovered that modulation onset times of high frequency components of the LFP (200-400 Hz referred to as high gamma) propagate sequentially across M1 during a simple point-to-point reaching task, and the propagation direction carries kinematic information (Liang, Balasubramanian, Papadourakis, & Hatsopoulos, 2023). Given that the high gamma signal serves as an accurate proxy for multi-unit activity (Ray & Maunsell, 2011), these initial results suggest that a spatially organized recruitment order of multi-unit activity provides behaviorally relevant information.

We have now extended our analysis by dissociating space from time so that we can compute dynamic spatial patterning at every moment in time and not just at movement onset. We do this by computing the spatial gradient of normalized high gamma amplitudes across the array in time using a plane from which we can estimate the gradient direction and its magnitude. The gradient direction across the motor cortex dynamically varies over the course of a reaching movement and is discriminable across different reach directions. Using the time-varying gradient direction, we can decode hand velocity continuously over time using a linear decoder to multiple reach targets. The decoder performs particularly well at the beginning of movement but then degrades over time suggesting these dynamic spatial patterns encode movement parameters intermittently. To test this intermittency hypothesis, we have preliminary data from a simple reaching task where the monkey had been overtrained to make movements to one target thereby making movement paths that initially were directed to the overtrained target and then switched direction to reach the neighboring instructed target resulting in bent paths. By decoding the hand velocity during these bent path trials using dynamic spatial patterns, we demonstrate that these patterns carry intermittent information about hand velocity at the beginning of the movement and after the transition point where the hand changes direction. Overall, these results provide a novel perspective as to how information about movement initiation and execution is encoded in M1 in the form of large-scale spatio-temporal patterns across the cortical sheet.

1-D-58 - The contribution of brainstem and intersegmental spinal cord networks to upper limb force control in mice and humans

Shahab Vahdat [1], **Matteo Grudny** [1], **Vishwas Jindal** [1]

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Details

Our classical view of neural control of movement states that the execution of goal-directed upper limb movements mainly relies on the activation of cortical motor areas, such as primary motor and premotor cortices. On the other hand, postural and balance control, involving axial and more proximal limb muscles, heavily relies on the activation of brainstem motor nuclei, such as the reticular formation. Growing evidence from animal work, however, is starting to challenge this view by demonstrating active involvement of multiple brainstem and intersegmental spinal cord circuits in the execution of goal-directed forelimb movements, including the medullary reticular formation (MRF) and the propriospinal neurons at C3-C4 cervical levels. What is the relationship between the activities of brainstem and intersegmental spinal cord centers, and cortical motor areas in upper limb motor control? To examine the function and connectivity of brainstem and spinal cord centers in hand motor control, we conducted fMRI experiments in humans and mice performing a unilateral hand force control task in the scanner. In humans, we employed our recently developed simultaneous spinal cord-brain fMRI protocols and analysis pipeline (FASB toolbox) to assess brain and cervical cord activations and functional connectivity during a unilateral handgrip force control task in a 3T Siemens scanner. In mice, we developed a novel system and paradigm to acquire awake fMRI data, while head-fixed mice performed a forepaw force control task to receive water reward in an 11T Bruker scanner. In humans, we found significant task-related activations in the contralateral sensorimotor cortical, striatal, and thalamic regions, and ipsilateral cerebellum, MRF, and cervical ventral horn centered at C6-C8 and C3 cervical levels. Functional connectivity analysis as evaluated by partial correlation revealed significant connections between the C3-C4 cervical ventral horn and contralateral M1, premotor cortex, MRF, vestibular nucleus, and cerebellum. In mice, we found an extensive network of brain areas are activated during the forepaw force control task, including contralateral sensorimotor cortex, striatum, thalamus, and ipsilateral cerebellum, lateral rostral medulla and caudal medulla. Contralateral M1 and premotor cortex were significantly correlated with the lateral rostral medulla and caudal medulla in an orderly increasing ventro-medio-dorsal fashion, suggesting a ventrodorsal organization of connections between the MRF and contralateral motor cortex. Overall, our findings reveal active involvement of brainstem and intersegmental spinal centers in upper limb motor control in humans and mice and shed light into their functional organization and connectivity in relation to cortical motor areas.

1-D-59 - Mitigating disruption to voluntary movement caused by velocity-dependent stretch reflex via α-MN collateral projection to γ-MN: A simulation study

Grace Niyo [1], **Lama Almofeez** [1], **Andrew Erwin** [2], **Francisco Valero-Cuevas** [1]

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Details

Muscle spindle afferents contribute to the proprioceptive feedback signals that inform the CNS about the position and movement of the body [1-4]. However, their role during voluntary movement is not fully understood [5]. For example, velocity-dependent Ia afferents in lengthening (antagonist) muscles are thought to be inhibited by reciprocal inhibition from the shortening (agonist) muscles [6]. If not regulated, the stretch reflex produces resistance to muscle stretch that can disrupt or stop joint rotations and compromise movement accuracy [7]. It is an open question, however, the extent to which velocity-dependent stretch reflexes disrupt voluntary movement, and whether and how they should be regulated in limbs with numerous mono- and multi-articular muscles where agonist and antagonist roles become unclear and can switch during a movement. We investigated how velocity-dependent stretch reflexes perturb limb movements in the general case of numerous multi-articular muscles, and whether spinal modulation of velocity-dependent stretch reflex gains mitigates these disruptions.

We simulated 3D movements against gravity in a 25-muscle computational model of a Rhesus Macaque arm. After simulating 1,100 distinct movements across the workspace of the arm with feedforward Î±-MN commands, we computed the kinematic disruptions to the arm endpoint trajectories caused by adding positive homologous muscle velocity feedback at different static gains to the feedforward Î±-MN drive (without reciprocal inhibition).

We found that arm endpoint trajectories were disrupted in surprisingly movement-specific, typically large, and variable ways, and could even change movement direction as the reflex gain increased. In contrast, these disruptions became small at all reflex gains when the velocity-dependent stretch reflexes were simply scaled by the Î±-MN drive to each muscle (equivalent to an Î±-MN excitatory collateral [8-10] to its homologous Î³-MNs but distinct from Î± ˆ’Î³ co-activation).

We argue this Î±-MN collateral projection to Î³-MN circuitry is more neuroanatomically tenable, generalizable, and scalable than Î± ˆ’ Î³ co-activation and movement-specific reciprocal inhibition. We propose that this mechanism at the homologous propriospinal level could be a critical low-level enabler of learning via cerebellar and cortical mechanisms by locally and automatically regulating the highly nonlinear neuro-musculoskeletal mechanics of the limb. This propriospinal mechanism also provides a powerful paradigm that may begin to clarify how dysregulation of Î³-MN drive can result in disruptions of voluntary movement in neurological conditions [5].

[1] Santuz & Akay, 2022 [2] Proske & Gandevia, 2011 [3] Proske & Gandevia, 2012 [4] Strzalkowski et al., 2018 [5] Krakauer et al., 2022 [6] Pierrot-Deseilligny & Burke, 2005 [7] Valero-Cuevas, 2016 [8] Wilson & Burgess, 1962 [9] Bhumbra & Beato, 2018 [10] Beato & Bhumbra, 2022

1-E-60 - Evidence for planning ahead in the whole-body kinematics of climbing routes execution

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Details

Naturalistic motor behaviours are strictly interweaved with the cognitive processing underlying decision-making and planning. The interplay between motor control and decision-making has seen an increasing interest in motor control researchers, with a focus on how decisions are influenced by the agent's state during action execution. The link between motor control and planning has been recently considered as a tool for the study of cognitive development and its embodied dimension. In this work we explore the interplay between motor control and planning from a different perspective: by looking at the impact of planning on the execution of a motor task. We took sport climbing as a testbed and designed a climbing task aimed at inspecting how the planning ahead of a route on a climbing wall may affect its execution at the level of whole-body kinematics. We hypothesize that in experts the kinematics of a move is implicitly modulated by the subsequent action(s) in the prepared plan. We further hypothesize that such modulation is limited in nonexpert climbers. We designed a climbing task consisting of pre-defined two initial foot-moves and two subsequent hand-moves. The first part of the route was fixed, while in the second part the specifics of the hand-moves varied in a set of eight conditions defined by the combination of i) which hand had to perform each hand-move and ii) the location of the hold to be reach in the second hand-move. The design aimed at assessing whether the kinematics executed in the initial part of the climbing route, common to all conditions, could tell apart the remaining unfolding of the route. In dealing with whole-body kinematics, we first derived low (20) dimensional representations of the whole-body kinematics throughout the climbing execution, based on a spatiotemporal principal component decomposition. We then used such representations to train a set of linear discriminant classifiers that could estimate the extent and the way in which planning-ahead for future moves affects the whole-body kinematics during the climbing execution. Results showed that most participants perform preparatory adjustments to the next-to-come movements by adapting accordingly their movements, but with temporal and bodily patterns that depends - on average - on their level of expertise. Non climbers tend to prepare for the next-to-come move with limb-specific adjustments, mostly in the interval between its onset and the end of the previous move. Expert and - to a less extent - non expert climbers tend instead to adapt their kinematics throughout the actual execution of the previous move(s), engaging in adjustments that involve the coordination of different body parts and span across the whole-body. Overall, our study provides new evidence of the interplay between planning and motor control, although on a limited number of participants, and it can inspire new protocols for studying the impact of cognition on motor behaviour.

1-E-61 - A preliminary investigation into the efficacy of training soccer heading in immersive virtual reality

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Details

Recent research has suggested a link between repetitive soccer heading and the increased incidence of neurodegenerative disease in retired players. In response, restrictions have been introduced to limit the amount of soccer heading in training and competitive matches. Therefore, while heading remains an integral part of the game, players are restricted in the amount of training that they can gain on this important skill without potentially harming their long-term wellbeing. The aim of this study was to provide a preliminary investigation into the efficacy of training soccer heading in immersive virtual reality (VR) which allows the practise of the skill without the risk of repetitive head impacts. Thirty-six recreational soccer players were divided into a VR group (n=18) who trained soccer heading on three occasions over a 7-10-day period in VR and a control group (n=18) who received no training in soccer heading. Measures of real-world heading performance (i.e., the number of goals scored and shot accuracy), self-reported confidence and self-efficacy were assessed pre and post training. Results showed that the VR group experienced significant improvements in the number of goals scored and increased their perceptions of confidence and self-efficacy. These results show preliminary support for the inclusion of VR-based training in soccer heading where players can hone their heading skills without exposure to repeated head impacts. Implications and practical applications are discussed.

1-E-62 - Vestibulo-spinal pathway contributes to alpha- band Intermuscular Coherence during rest, but not during voluntary reaching movements

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Details

Background: Intermuscular coherence (IMC) quantifies the degree of synchronization between two electromyography (EMG) signals to reveal their shared neural drive (Boonstra, 2013). As such, it is gaining popularity as a means to pinpoint the origin of neural drive causing upper extremity pathological synergies in stroke as multiple pathways could be responsible (Li and Francisco, 2015).

Purpose: While the imbalance of cortico- and reticulo-spinal tracts is thought to contribute to pathological synergies, this study aims to exclude the vestibulo-spinal tract as a potential contributor (or confound) to arm muscle neural drive as measured by IMC.

Methods: We recorded IMC during three conditions: No stimulation, Galvanic Vestibular Stimulation (GVS), and Sham (vibrating motor at the location of the stimulation). We tested the right arm of 16 unimpaired young adults (mean age: 19.2, range: 18-27 years old) under three tasks: rest, isometric contraction of the elbow (holding of a 2.25 kg weight at 90 °), and voluntary reaching movement by turning a crank. sEMG was recorded from: Biceps (Bic) and Triceps Brachii (Tri), Anterior (ADelt), Middle (MDelt) and Posterior (PDelt) Heads of Deltoid, and Upper Trapezius (UTrap); and one neck muscle, Sternocleidomastoid (SCM), as a control for GVS. Pairwise magnitude-squared coherence from EMG was computed in the 8- 50Hz frequency range. Statistical Parametric Mapping (SPM) determined the specific frequencies at which there were significant differences in IMC across Tasks and muscle pairs. Robust Statistical Methods tested for IMC changes with GVS and Sham during each Task for all muscle pairs.

Results and Conclusion: GVS did not induce IMC for any arm muscle pair in any condition or task. It did increase IMC between SCM-UTrap from 11 to 50Hz (alpha-, beta-, and gamma-frequency bands) during the rest condition (as expected) but, surprisingly, not during isometric and movement conditions. These results provide evidence to exclude the vestibulo-spinal tract as a contributor to neural drive to arm muscles during rest or voluntary movement in unimpaired individuals. As importantly, they reveal an unexpected gaiting of vestibulo-spinal signals to neck muscles. Future work will use these results as a baseline against which to interpret task-dependent contribution of the vestibulo-spinal tract to IMC among arm muscles in unimpaired individuals and stroke survivors.

1-E-63 - EEG brain generators during speech production in breathing constraint

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Details

Based on the speech production exercises of Ladefoged (1967), we here introduce a new experimental paradigm consisting of the production of audibly repeated syllables such as '*pa*' without being able to take a breath. This allows us to better understand the complex interactions between, on the one hand, respiratory physiology involving the regulation of pulmonary and glottic pressure, the recruitment of different muscles, and on the other hand, the maintenance of phonatory command (the repetition of '*pa*') despite the imposed restriction on the resumption of inspiration. We recruited 19 French-speaking students (10 men, 9 women) in good health. Each participant completed 20 trials of the ‘pa’ syllable task protocol with their eyes closed. Acoustic and aerodynamic parameters, respiratory muscles, and the electroencephalogram (EEG) activity (64 channels ANT system) were synchronously recorded. All the processing was done using MATLAB and the EEGlab toolbox. Brain generator identification was performed using swLORETA in the ASA software. Four regulation phases of sub-glottal pressure were identified: phase 1 corresponds to the elastic recoil of the external intercostal muscle, phase 2 represents the delay between the end of the elastic recoil and the onset of external oblique activity (which likely corresponds to the internal intercostal activity), phase 3 is characterized by external oblique activity, and finally, phase 4 corresponds to rectus abdominis recruitment. The event-related spectral perturbations and intertrial coherence measurements related to each phase revealed specific power spectrum modulations of alpha and theta oscillations accompanying the 4 expiration phases during the production of the [pa] syllable suite. We found that phase 1 corresponding to the elastic recoil of external intercostal muscle was characterized by the activation of the right primary motor and left primary somatosensory cortex, phase 2 related to the action of the internal intercostal muscle, showed activation in the left premotor cortex, supplementary motor cortex, and the left agranular retro-limbic area, phase 3 linked to the action of the external oblique muscle, exhibited activity in the left and right premotor and supplementary motor cortex and left dorsolateral prefrontal cortex. Phase 4, was characterized by the involvement left opercular Broca's area. These results suggest the existence of a specific cortical control exerted during the 4 different phases of this speech performance exercise highly constrained by the voluntary decision to inhibit the taking of a breath. Interestingly, the contribution of the left dorsolateral prefrontal cortex implicated in cognition such as in decision-making linked to the Broca area involvement (phase 4) for succeeding phonation was present during the last seconds of the muscular effort to produce the last syllable '*pa*'.

1-E-64 - Decoding action and observation of hand gestures in the human brain

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Details

Our hands are the primary means for interacting with our surroundings. As such, they are supported by a plethora of representations in the brain, in particular in sensorimotor and visual systems. For intracortical brain-computer interfaces aiming to restore dexterous hand function, it may be advantageous to target cortical regions with neural signals that capture both visual and motor aspects of hand representation. In the present study, we used simultaneous functional MRI and 8-channel electromyography in human participants (n=60) to compare the neural responses when observing and executing hand gestures. We aimed to identify regions that proficiently capture both the visual and motor aspects of hand representation. Participants performed a visuomotor task that required them to either execute a specific hand gesture with no visual feedback (8 gestures: open, close, pinch, tripod, one finger, two finger, three fingers, four fingers) or to observe a first-person video of a biological perform the same gesture, while keeping their hand still. First, when visualizing the univariate activity for the contrast: actions vs. observations, we found an expected preference for actions over observations in sensorimotor cortex. Within visual cortex (in particular a region known as lateral *occipitotemporal cortex*), we not only found a region showing the expected preference for observation, but an adjacent region that showed a preference for actions. This suggests that lateral occipitotemporal cortex might be a potential candidate region to support visuomotor BCI control, but it is unclear whether the motor information captured in visual cortex corresponds to how it is represented in motor cortex. To test this, we used representational similarity analysis, a multivariate decoding analysis designed to capture the similarities in responses across conditions. Here, the conditions of interest corresponded to the 8 different gestures. We quantified the multivariate representational structure (i.e. all pairwise condition comparisons for representational similarity) of observed, as well as executed hand gestures. Surprisingly, we observed a strong correlation when comparing the representational structure for hand actions between the two regions, suggesting the motor information in this region of visual cortex is highly similar to motor cortex. Further, we observed that the decoding accuracy (quantified as representational dissimilarity, using cross-validated mahalanobis distances) between hand actions during movement execution (with no visual feedback) to be just as high in visual cortex as observed in sensorimotor cortex. Collectively, these results reveal that visual cortex has a fine-grained, systematic visuomotor organization, suggesting it would be a promising candidate cortical region to support visuomotor BCI control.

1-E-65 - tDCS applied to M1 influences temporal and amplitude performance on different time scales across training and retention in a bimanual task

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Details

As we move through the world, the CNS controls the temporal and amplitude features of our limbs by drawing on memories and integrating current control with sensory input. Temporal and amplitude features can be separated to demonstrate independent control of each; yet most of our actions require the integration of timing and amplitude control. This study sought to determine if the use of tDCS over the motor cortex (M1) would influence the control of temporal and amplitude features of a bimanual task during training on a de novo sensorimotor integration task. Studies have demonstrated that tDCS over M1 during training influences performance and retention of serial reaction time tasks and adaptation aiming tasks. However, these studies do not typically separate the temporal and amplitude features of movement control. This study used a rhythmic bimanual task and participants were trained to coordinate their arms (shoulder and elbow) to produce a 90 ° relative phase (RP) pattern, the temporal feature. The 90 ° RP had to be mapped to a circular template with a 12 cm diameter, the amplitude feature. The circular template was shown on a computer monitor at eye-level in front of participants. Amplitude matching was accomplished by mapping arm motion to a cursor, with the right-arm moving the cursor horizontally and left-arm moving the cursor vertically. The participants' arms were blocked from view, with motion constrained to a single axis on the horizontal plane. The cursor and template were visible throughout training and the retention test. Twenty-four training trials were performed over a 20-min interval, with each trial lasting 20 secs. After a 6-hr. interval, participants returned for a four-trial retention test. Three groups were trained with the template and cursor: two stimulation groups, anode over left-M1 and right-M1, and one sham group. The anodal/cathodal electrodes were placed using the 10-20 EEG system: 1) C3 anode/C4 cathode (LARC), or 2) C3 cathode/C4 anode (LCRA). Active stimulation lasted 21 minutes at 2 mA with a 30-sec ramp up/down interval. Sham stimulation ramped the current up/down (60 sec) to 2 mA at the start/end of the 20-min training interval. Temporal variability and error in the 90 ° RP pattern were larger in the LARC group compared to the LCRA and sham groups during training, suggesting tDCS upregulated M1 and influenced temporal stability. At the end of training, the LARC group had significantly smaller amplitude error than the LCRA and sham groups (LARC < RALC < Sham). In the retention test, there were no significant differences in temporal variability/error of the 90 ° RP pattern between the groups, with amplitude error significantly smaller in the LARC and RALC groups compared to the sham group. The results show that tDCS over M1 influenced temporal and amplitude control differently across a training/retention interval, revealing asymmetries in outcome effects associated with left/right M1 stimulation.

1-E-66 - What's touch got to do with musicians' motor performance? The interaction between expertise and tactile perception in a piano key press

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Details

According to the touch paradox, despite the crucial role tactile inputs play in motor performance tasks, tactile perception is suppressed in movement contexts. Central signals block predictable tactile inputs during movement planning. Peripheral and central signals block tactile perception during movement execution.

The aim of our study was to investigate whether the touch paradox is present in expert performance: i.e., does expertise, via more predictive internal models, increase central suppression of tactile inputs crucial to performance? The paradox rests on two hypotheses: 1) expert pianists suppress tactile inputs during planning a piano key press more than untrained participants; 2) increased tactile suppression leads to worse performance.

We separately tested tactile perception during a piano key press, and piano key press performance. Tactile perception was tested in 42 right-handed subjects (18-60 y: *mean 31.0y(SD 10.3)*): 21 expert pianists (Expert: 11 female; *31.6y(10.4))*, 21 musically untrained (Untrained: 12 female; 30.2y*(10.5)*). From this sample, we tested piano key press performance in 12 Expert (6 female; *28.3y(8.7)*) and 12 Untrained (6 female; *33.5y(10.5)*).

We measured tactile perception by presenting weak electrical currents to the skin under 3 piano key press conditions: 1) Baseline (B1: at rest); 2) Planning (P: 300 ms before key press); 3) Execution (E: simultaneous with key press). Baseline was re-tested post-session (B2) to control for time effects. Threshold was defined as the stimulus intensity level at which 50% of stimuli were perceived. Difference in thresholds measured planning (P-B1) and online (E-B1) suppression.

We tested piano key press performance with participants targeting 30% (slow) and 70% (fast) maximum key press velocity (MIDI). Variable error (VE) of peak velocity was used as the measure of performance.

A repeated measures ANOVA of thresholds, 2 group (Expert, Untrained) by 4 condition (B1, P, E, B2), found a main effect of group ($p=.04$), with higher Untrained than Expert thresholds; and main effect of condition ($p<.001$), post-hoc tests showing higher thresholds in P ($p<0.001$) and E ($p<.001$) compared to B1. There was no significant group by condition interaction ($p=0.70$). A further t-test confirmed no group difference in planning suppression ($p=.40$).

Correlations were run between VE and planning suppression, and VE and online suppression. All correlations were non-significant except slow VE to online suppression ($r=.55$, $p=.004$). Further analysis showed this correlation was significant in Untrained ($r=.76$, $p=.004$), but not in Expert ($r=.27$, $p=.40$).

This study produced two novel findings: 1) more online tactile suppression yields worse slow velocity control in untrained performers; 2) greater predictive models from expertise do not produce more central suppression. These findings offer new insight into interactions between tactile suppression, motor performance and expertise.

1-E-67 - Neuronal population coding in the cervical spinal cord for voluntary reaching movements

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Details

Neurons in the spinal cord play a critical role in controlling both voluntary and reflexive movements. Despite extensive research into locomotion circuits in the lumbar region, a significant gap persists in understanding how neurons in the cervical spinal cord are encoded at the population level to control voluntary movements.

Our research utilized advanced linear multi-channel probes, such as Neuropixels, to capture the activity of neurons from the dorsal to ventral regions of the spinal cord during voluntary reaching tasks performed by rats. We investigated whether these voluntary movements induce enhanced functional connectivity among neurons and whether such changes depend on the direction of movement or spinal cord segments. By analyzing functional connectivity through correlations between neuronal pairs, we sought insights into the neural coordination of movement.

In our experiments, we identified neurons 64 in one subject and 100 in another that were selectively isolated during the recording session. Those neurons exhibited distinct firing patterns based on the direction of movement and the phase of the movement, indicating diverse neural processes for controlling voluntary movements. For example, some neurons fired phasically upon a specific movement initiation, but others showed tonic firing throughout the entire movement period. In particular, neurons within the dorsal or ventral regions showed varied neural responses during reaching movements, resulting in a lower correlated firing pattern in those areas. In contrast, neurons in the intermediate region showed similar firing patterns, which correlated highly with one another during reaching movements. This synchrony observed in intermediate areas was relatively irrelevant for the movement directions, suggesting a more organized neural process toward goal achievement as the reaching movement.

The prior understanding of how spinal cord neurons process sensory inputs for motor coordination particularly through population neural activities was limited by technical barriers. By delineating specific neural firing patterns and their coding across different spinal cord regions, our work sheds light on their contributions to voluntary reaching movements. Importantly, we are proposing that the neuronal network within the intermediate layer acts as a dynamic "hub." This hub is potentially pivotal in managing sensorimotor integration during voluntary movements. It can modify its synchronization and coordination to merge descending motor commands with sensory feedback effectively, customizing this integration to meet the demands of the particular motor task.

1-E-68 - Exploring the neural correlates of tactile imagery: significance for non-invasive brain computer interfaces applications

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Details

Mental imagery is a fundamental aspect of human cognition. It involves the ability to mentally represent sensory experiences without external stimuli. While visual and motor imagery have been extensively studied, mental imagery in somatosensory domain remains less explored. Neurovisualization studies indicate that tactile imagery activates the primary sensorimotor cortex and prefrontal areas, enhancing functional connectivity between them. However, research on tactile imagery in human EEG is limited. This study aimed to explore EEG correlates of tactile imagery and compare them with somatosensory perception. 64 healthy volunteers participated in 3 experimental series. After experiencing somatosensory stimulation on the right hand, participants mentally reproduced sensations without actual stimulation. Multichannel EEG recordings were performed to assess mu rhythm event-related desynchronization and somatosensory evoked potentials in response to tactile stimulation and its imagery. Results revealed a stable contralateral activation during tactile stimulation and imagery, localized predominantly in the postcentral gyrus. Application of short vibro-stimuli induced enhanced p200 components in frontal areas and ipsilateral enhancements of p100 and p300 components in sensorimotor areas. Our findings highlight significant correlates of tactile imagery in human EEG, indicating reinforced sensorimotor processing during tactile imagery. This has implications for fundamental research on mental image formation mechanisms and practical applications in neurorehabilitation using brain-computer interfaces.

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1-E-69 - Error monitoring in basketball free-throw shooting – An EEG study

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Details

Theories suggest that the error-related negativity (ERN) in the EEG is driven by processes of an error monitoring system (e.g., Holrod & Coles, 2002). In motor tasks, it is observed prior to upcoming errors, indicating that it represents an outcome evaluation arising from predictions made by internal forward models. As forward models are developed and refined through practice, motor expertise should align with the quality of internal forward models. Experts should be able to effectively monitor and evaluate their own movements and perceive motor errors early or even predictively before they become manifest. This should be reflected by an ERN signal shortly after or even during the expert movement and, importantly, before the final outcome of that movement becomes visible. In the present study, we aimed to verify the occurrence of an ERN signal during free throw shooting in basketball experts. To account for the large movement artifacts due to the throwing motion, we used the dual-layer approach of Nordin et al. (2018), in which a second EEG layer is attached to the scalp EEG that only records artifact signals. These are then used for improved artifact elimination of the scalp EEG data. 30 expert basketball players performed 500 free throws in one session without receiving feedback about the initial ball flight (using liquid crystal glass goggles that occluded vision immediately after release and re-opened 400 ms later, to allow outcome feedback). The ERN and other error related signals (FRN, P300) were determined for the mean difference curves between hits and misses, synchronized to ball release and feedback time, respectively.

Preliminary data of 20 players show on average more negative activation in fronto-central electrodes immediately after release (matching an ERN) and more positive activation in parietal electrodes in a time window about 500ms after re-opening the goggles (matching a P300) in misses compared to hits. No clear negative signal of feedback processing (FRN) was observed after re-opening the shutter goggles. The ERN and P300 signals correlated with free throw performance of the players: The higher the performance, the larger were the ERN and P300 amplitudes, respectively.

These preliminary results suggest that an ERN signal of error monitoring processes can be observed, representing an internal evaluation of outcomes based on forward model predictions. The absence of a FRN signal might be interpreted with a complementarity of the ERN and FRN: If most error valuation is already done predictively, outcome feedback does not provide additional new information for processing. After missed throws, processes of internal model updating are represented by a larger P300 signal. The correlation between performance and EEG signals indicates that higher expertise coheres with higher quality of internal forward models.

1-E-70 - Anterior cingulate cortex is involved with proactive control through modulation of contingent negative variation

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Details

The ability to control movements is critical for physical interactions with the environment. Movements can be controlled in an anticipatory manner (proactive) or as a late-corrective action (reactive). Proactive control uses contextual information to prepare possible action choices based on the predicted nature of the interference event before it occurs. The electroencephalography (EEG) literature has reported the contingent negative variation (CNV) as a neural correlate of proactive control. Based on current neuroimaging correlational evidence, CNV could be associated with the detection of unique stimuli, motor response anticipation, anticipatory response maintenance, and task goal maintenance. Hence, which of these components of proactive control is encoded by the CNV has not been causatively established. There is also speculation about which of the neural sites in the cognitive control network modulate the CNV based on proactive control dynamics. The fMRI literature reports the activation of the anterior cingulate cortex (ACC) in the anticipatory response phase during proactive control simultaneous with the CNV. However, the functional role of ACC in proactive control is still debated. To address these gaps in existing literature, an AX-version of the continuous performance task (AX-CPT) will be used to evaluate the behavioral manifestation and neural correlates of proactive control in the context of motor control. Five participants performed the task in a pilot study. We used low-intensity transcranial-focused ultrasonic neuromodulation (tFUS) to stimulate an area in ACC, i.e., p24pr, to modulate the CNV. A typical AX-CPT trial consists of a contextual cue stimulus, followed by a probe stimulus after a brief interstimulus interval. Custom rules based on the combination of the cue and probe sequence guide the response for the probe. A 500-ms tFUS stimulation was provided on alternate trials 200 ms after the appearance of the cue which is 300 ms before the appearance of the CNV. A sound like the stimulation was presented 200 ms after each stimulus to prevent the participant from knowing when they were getting stimulated (sham trials). Area p24pr-localized CNV measured through 64-channel EEG showed an enhancement in the CNV across the probabilistic and deterministic contexts in AX-CPT. The CNV began earlier and showed a larger amplitude difference between AX-CPT contexts in the stimulated trials compared to sham trials. The effects of tFUS on the context-dependent modulation of ACC suggest that (a) CNV encodes for contextually dependent anticipatory responses, and (b) p24pr area in ACC is associated with proactive control. Ongoing work is addressing the causal relation between ACC, EEG activity, and behavior.

1-E-71 - Somatosensory compensation is faster than auditory compensation in speech motor control

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Details

A sudden force perturbation to the tongue during speech production elicits a quick compensatory response at around 130 ms. EMG signals from the tongue associated with this response supported the hypothesis that it is a reflex. Since masking of auditory feedback did not change the response and the increase of tongue muscle activation was examined at the timing corresponding to this response, this reflex is induced by somatosensory feedback alone. However, speech is auditory in nature. Auditory feedback compensation could still contribute to the response. To assess this, we examined how altered auditory feedback (AAF) perturbation affects the compensatory response due to the tongue stretch perturbation. Twelve native French speakers participated in the experiment. They were asked to sustain the vowel /É›/ for three seconds. The tongue stretch perturbation was applied with a robotic device providing a force of 1 N for 1 second in the forward direction. The AAF was applied to the first formant (F1) by shifting it by 20% relative to the baseline, upward or downward using Audapter (Cai et al, 2011). We tested five perturbed conditions using various combinations of AAF and tongue perturbation: AAF with tongue perturbation (AAFup+PTB and AAFdown+PTB), tongue perturbation alone (PTB) and AAF alone (AAFup and AAFdown). The perturbation was applied in the randomly selected one third of trials. 15 responses were recorded per condition. Trials with wrong estimation (F1<300 Hz or F1>700 Hz) were removed from the analysis. Two participants were also removed from the analysis due to high trial-to-trial variability. The estimated F1 was normalized via its value before the perturbation (baseline). All trials were aligned based on the onset of the tongue perturbation. In the conditions with tongue perturbation (AAFup+PTB, AAFdown+PTB and PTB), the normalized F1 decreased to around 85 % from baseline due to tongue perturbation and returned to around 90 % after the compensatory response. These two phases occurred within a 200 ms interval after the perturbation onset. The peak amplitude of the initial change and the peak amplitude due to the compensation were shown to not be reliably different across the three conditions using a repeated measure ANOVA. In the conditions with AAF alone the normalized F1 trajectory over time due to AAFup diverged from the one due to AAFdown from around 400 ms onwards after the onset of the perturbation. This indicates that both directions of auditory perturbation induced auditory compensation in the opposite direction. The results indicate that auditory feedback also contributed to the speech sound stabilization together with somatosensory compensation, but with a larger latency than the one due to somatosensory feedback. Since we have also recorded articulatory movements data in this experiment, we will further examine how the difference between auditory and somatosensory compensations reflects in articulatory movement.

1-E-72 - The middle ear muscles control eye movement-related eardrum oscillations (EMREOs) and implicate an eye-centered reference frame in the ear for localizing sound

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Details

The visual and auditory systems work together to ensure surrounding stimuli are perceived correctly. Accurate information about eye movements, particularly saccades, is necessary to this process because saccades shift the relative positions of the retina with the head/ears. We have recently reported an eardrum oscillation, time-locked with the onset of a saccade, and occurring in the absence of outside auditory stimuli, that suggests such information about saccades is available as peripherally as the ear (Eye movement-related eardrum oscillations or EMREOs; Gruters et al. PNAS 2018; Lovich et al. PNAS 2023). Additionally, the amplitude of this eardrum oscillation co-varies with the parameters of the synchronous saccade, suggesting this component of the oscillation carries important information about the eye movement. The underlying mechanics of EMREOs in the ear and the saccade-related neural signals that control these mechanics are still unknown. Here, we seek to determine the role of the two middle ear muscles (MEMs), innervated by different cranial nerves, in controlling these oscillations.

We recorded EMREOs in two rhesus monkeys during voluntary saccades before and after unilateral transection of the MEMs and/or their respective neural inputs. The monkeys were head-restrained and saccades were tracked with a video eye tracker while EMREOs were recorded using microphones placed in the ears. We report that surgical transections of the stapedius (St) and tensor tympani (TT) cause changes in the EMREO in opposing ways.

Transection of the St, innervated via the facial nerve, caused the EMREO to be significantly diminished in amplitude (-51%), but not eliminated. This suggests saccade-related neural signals sent through the facial nerve to the St would normally amplify the gain of the EMREO. In contrast, transection of TT, which is innervated via trigeminal nerve, caused the EMREO to be significantly *increased* in amplitude (+48%). This suggests saccade-related neural signals sent through the trigeminal nerve to TT would normally dampen the gain of the EMREO. This data corroborates findings from our lab in humans with St and/or TT dysfunctions and suggests there may be multiple neural and anatomical controllers of this eardrum movement, with the MEMs working as a push-pull mechanism with opposite functions to control the amplitude of EMREOs.

These findings are synergistic with recent work showing that forces applied by the MEMs to the eardrum may be necessary for sound transmission (Cho et al., Hearing Research 2023). That is, during a saccade and resulting EMREO, cranial nerves innervate the MEMs, generating opposing forces across the two MEMs onto the eardrum, which in turn control the amplitude of eardrum movement in a precise way.

This resulting movement may adjust the gain and timing of incoming sound, converting head-centered interaural timing and loudness differences into an eye position-dependent format to aide in auditory localization.

1-E-73 - Sensorimotor prediction facilitates task-relevant visual information uptake in a goal-oriented throwing task

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Details

Introduction: Previous research has shown that action outcomes are internally predicted before outcome feedback becomes available (Wolpert, 1997). To test whether these sensorimotor predictions are used to facilitate visual information uptake for error feedback processing, we measured eye movements during the execution of a goal-oriented throwing task. *Methods:* On each of three days, seventeen healthy, right-handed participants (10 female) executed 500 ball throws using a metal lever while the movement effect was only (virtually) observable on a screen. After receiving continuous visual feedback about ball flight in sessions one and two, ball flight was masked in a subset of trials in session three, with only static outcome feedback being provided for 500 ms at the time of minimum distance between the ball and the target. The latter should ensure that predictions and possible predictive saccades toward future action effects are based on internal movement-related information and not driven by visual information about ball flight. *Results:* In all sessions, we observed a large proportion of predictive saccades that shifted gaze toward the goal region before the ball arrived and outcome feedback became accessible. Gaze positions after predictive saccades covaried systematically with future ball positions in trials with continuous ball flight information, but notably also in trials with masked ball flight when only internal information about the movement and static outcome feedback was available. Fixation durations at the chosen positions after feedback onset were modulated by action outcome (longer durations for misses than for hits) and its uncertainty (longer durations for narrow vs. clear outcomes). Combining both effects, durations were longest for narrow errors and shortest for clear hits (270.88 ms vs. 173.41 ms). Additionally, latencies to induce the predictive gaze shifts were longer in misses than in hits. *Discussion:* Results show that even without external information about action effects, future ball positions could be internally predicted, and gaze could be predictively guided towards these positions. Moreover, fixation durations at these locations differed as a function of task performance, suggesting that chosen locations are of informational value for feedback processing. Thus, humans use sensorimotor prediction to direct their gaze toward task-relevant feedback locations. Outcome-dependent saccade latency differences indicate that also predictive valuation processes are involved in planning predictive saccades.

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1-F-74 - Muscular work feedback during assisted treadmill training to improve engagement and motor learning

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Details

Rehabilitation requires patient effort, yet a persistent problem in assisted gait training is that patients adapt to physical assistance and decrease their effort. Accommodation can be countered with feedback about patient effort, but this feedback requires measurement of assistive forces and patient effort, such as with motorized exoskeletons. Therefore, typical hands-on assisted training with a physical therapist still suffers from patient accommodation. We examined the feasibility of using inverse dynamics to provide step-by-step muscular work feedback during therapist-assisted locomotion. We used this feedback to test the hypothesis that showing participants their muscular work relative to the contributions of the assisting therapist will decrease their reliance on assistance and improve retention. We controlled for variability associated with real disorders by giving healthy individuals a temporary locomotor impairment that combined external resistance with neuromuscular stimulation. During treadmill walking, participants' right leg advancement was opposed with a rearward pull of 3% body weight from an elastic band at the shank while an electrical stimulus triggered involuntary activation of the right hamstrings at every right foot toe-off. While perturbed, participants were asked to walk so they achieve a target muscular work reflecting the force needed to attain their normal unperturbed step length. The same physical therapist assisted each participant's right affected leg as needed during practice; these forces were measured with a load cell. The therapist had feedback of participants' current step length relative to baseline so the therapist could help them achieve their baseline step length. Participants saw a visual display with a bar showing their prior step's work relative to the target work. Based on group assignment, participants either saw the total work (theirs + therapist) or saw their work separated from the therapist. All calculations were performed in MATLAB. Muscular work was determined from inverse dynamics using the OpenSim API, where subject-specific skeletal models were applied to streamed lower-body kinematics from motion capture. The calculations were performed during initial stance of the right leg. Here, we present our pilot results that support the approach's feasibility. We show that inverse dynamics calculations can be performed fast enough for online muscular work feedback - being completed before the next step is taken. Regarding the hypothesis, our pilot data shows mixed responses; some participants appear to rely on physical assistance despite seeing partitioned work contributions, while others maintain their effort with decreased therapist assistance. If showing an individual's muscular work, relative to the work done by the therapist, is effective in preventing accommodation to assistance during locomotor training, it will provide another tool that clinicians can use to improve rehabilitation outcomes.

1-F-75 - Machine learning-based reconstruction of missing kinematic and electromyographic data for electrical stimulation therapy assessment

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Details

In the process of locomotion restoration and rehabilitation employing electrical stimulation (such as epidural electrical stimulation or functional electrical stimulation) on patients, it is crucial to extract kinematic and muscle activation features to quantify the effects of rehabilitation and applied stimulation. Data from inertial measurement units and electromyographic sensors exhibit strong correlation patterns, highlighting the synchronized muscle contractions within the structured support of the skeletal system, essential for ensuring effective walking. Nonetheless, such correlation pattern varies significantly among patients due to their different impairments and in a same patient as rehabilitation progresses.
In this study, we employ machine learning to reconstruct a set of sensor recordings from a complementary set, aiming at two potential future applications: quantifying gait variables in patients during in-hospital rehabilitation and monitoring patients within the hospital outside of rehabilitation sessions, as well as at home. Cheaper cabled models of electromyographic recording sensors present challenges due to cable movements potentially causing unreliable or absent signals at certain points in time. The ability to identify and replace such artifacts with reconstructed electromyographic signals would enable centers with limited resources to conduct such studies. Upon the patient's discharge from the hospital, monitoring becomes crucial. It may involve using a comprehensive sensor set for detailed characterization of joint angles and muscle activities during therapy sessions and transitioning to a minimal sensor setup for monitoring outside of therapy.
In our clinical trial involving patients with incomplete spinal cord injuries, we use data to show how our approach can reconstruct complete datasets from inertial measurement units using a smaller subset of these units. Additionally, we demonstrate how to infer inertial measurement unit data from electromyographic recordings, and the other way around. We perform these reconstruction tasks across different segments of the same recording, on recordings from the same day, recordings from different days (either close together or farther apart in time). Additionally, we introduce a Kalman filter-based algorithm to assess automatically the reliability of intervals in a recording, enabling reconstruction only in unreliable intervals.

1-F-76 - Reinforcement differently changes locomotor learning and retention in older adults

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Details

New locomotor patterns are obtained through trial-and-error practice. Often skill learning is enhanced via providing external reinforcement to enhance correct actions or minimize incorrect movements. Older adults (OAs) have demonstrated mixed effects to reinforcement feedback in the context of skill learning. However, providing different valence of reinforcement has yet to be applied to locomotor adaptation and retention. Thus, there remains a dearth regarding how reinforcement valence, age, and locomotor adaptation interact. 33 young (YAs) and 18 OAs healthy participants (n=51,19-82 years) and were divided into three groups [Reward (YAs=11; OAs=6), Punishment (YAs=11; OAs=6), Sensory (YAs=11; OAs=6)].

During treadmill walking, feedback of the right knee's angular movement during the swing phase was displayed on a screen corresponding to group. Baseline walking was collected for 250 steps. Participants were then visually cued to adapt their walking pattern by matching their knee flexion to a desired angle (+30Ëš baseline) for 500 steps. Reward and Punishment groups were provided a graded number scale corresponding to a monetary gain or loss respectively. The Sensory group was provided a bar graph with the current knee angle and a line representing the desired angle. Following this condition was an errorless retention phase with no feedback to test motor memory for 250 steps. Percent adaptation achieved (PAA) was calculated for each condition and compared using linear mixed models with Age, Feedback, and Condition were held as fixed effects and subjects were held as random factors. PAA was compared during the first 50 steps (Early Adaptation) and the last 100 steps (Adaptation Plateau) of learning and the last 100 steps of Retention. OAs and YAs adapted their knee flexion angle at a similar rate regardless of the feedback condition ($p=0.75$). PAA increased from Early Adaptation to Adaptation Plateau ($p<0.001$), however, there were no differences in group ($p=0.21$). However, OAs who learned with Sensory feedback retained less during Retention compared to Reward ($p=0.002$) and Punishment ($p<0.001$). Moreover, Punishment enhanced motor memory in OAs compared to YAs during Retention ($p<0.001$). Whereas YAs demonstrated greater motor memory with Sensory feedback compared to OAs ($p<0.001$). YAs demonstrated a lower PAA from the Adaptation Plateau to Retention with Punishment ($p<0.001$) and Reward ($p=0.009$). This finding signifies that age does not impair reinforcement processing to learn and retain a new locomotor pattern. OAs developed stronger motor memories of the adaptation tasks with reinforcement, specifically punishment. This reflects changes to cortical processes associated with age, such as decreases in dopamine. Thus, OAs may be using different neural pathways to facilitate locomotor memory, in comparison to YAs.

1-F-77 - The human voice aligns with whole-body kinetics

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Details

Humans use their voice concurrently with upper limb movements, known as hand gestures. Recently it has been shown that fluctuations in intensity and the tone of the human voice synchronizes with upper limb movement (including gesticulation). In this research direct evidence is provided that the voice changes with arm movements because it interacts with whole-body muscle activity (measured through surface EMG and postural measurements). We show that certain muscles (e.g., pectoralis major) that are associated with posture and upper limb movement are especially likely to interact with the voice. Adding wrist weights to increase the mass of the moving upper limb segment led to increased coupling between movement and voice. These results show that the voice co-patterns with whole-body kinetics relating to force, rather than kinematics, invoking several implications how the voice is biomechanically modeled, how it should be simulated, and importantly how the human voice must have evolved in relation to the whole-body motor system. We concluded that the human voice is animated by the kinetics of the whole body.

1-F-78 - Validation of the Equidyn protocol for evaluation of dynamic balance in older adults through a smartphone application

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Details

Different tasks and measurements have been employed to estimate dynamic body balance in older adults. However, due to limitations of these evaluations, results could hardly be taken as valid measures of dynamic balance. Research question: Is the Equidyn smartphone application-based protocol valid and sensitive for the assessment of dynamic balance in older adults? Dynamic balance was evaluated in 52 physically active individuals, age range 60-80 years. The protocol was composed of two unipedal tasks and sit-to-stand with a narrow support base. The unipedal tasks required one leg sway either in the mediolateral (ML) or anteroposterior (AP) direction while supported on the contralateral leg. The three tasks were performed under standardized movement amplitude and rhythm. A smartphone was attached to the trunk, and a custom-made application (Equidyn) was employed to provide guidance throughout evaluation, timed beeps to pace the movements, and to measure three-dimensional trunk acceleration. Results showed (a) that both ML and AP leg sway tasks were sensitive to age and to direction of leg sway movements; (b) referenced to quiet unipedal stance, moderate/strong correlations for the ML/AP leg sway tasks and moderate correlations for the sit-to-stand task; and (c) moderate/strong correlations between the ML and AP leg sway tasks, and moderate correlations between the sit-to-stand and the two unipedal dynamic tasks in the ML acceleration direction. As the main significance, the current results showed that the Equidyn protocol is a sensitive and valid tool to evaluate dynamic balance in healthy older individuals. The protocol tasks standardized in amplitude and rhythm favor their reproducibility and trunk acceleration data interpretation. As the whole assessment is made through a smartphone application, this dynamic balance evaluation could be made either in laboratory or clinical settings.

1-F-80 - Distinct cortical dynamics during stepping responses for recovering balance between people with stroke, healthy older and healthy young individuals

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Details

The risk of falling increases with aging and neurological impairments, such as stroke. EEG studies on recovery from a loss of balance have generally focused on the early cortical response originating from the supplementary motor area (SMA) in healthy subjects, demonstrating relationships with perturbation characteristics and individual balance capacity. It remains elusive whether and how the cortical dynamics of balance recovery are affected in people with chronic stroke (PwS). The current study investigates the SMA response to whole-body balance perturbations in people with chronic stroke (n=26), healthy older (HO, n=14), and healthy young individuals (HY, n=15).

All participants received perturbations in 5 different directions for both legs while 126-channel EEG was recorded. Perturbation intensity was equal for all participants and perturbations directions. Participants received the instruction to recover balance by stepping. Independent component analysis was performed to reconstruct SMA activity. We evaluated the time-frequency decompositions of the SMA activity around four time events of interest: platform movement onset, the N1 latency, onset of the compensatory step and foot landing of the compensatory step. First, we compared the three different groups between each other. In addition, we evaluated the difference in SMA activity between both stepping legs within each group, and within subgroups of PwS with good and those with poorer leg motor recovery (i.e. Fugl-Meyer Lower Extremity (FMA-LE) score above or below 24).

At the time of N1 (~180 ms after platform onset), all participants exhibited an increase in theta (4-8 Hz) power for all perturbation directions, which was higher for HY than for PwS and HO. Simultaneously, HY exhibited a greater increase in alpha (8-12 Hz) and low beta (14-20 Hz) power than PwS and HO. This may reflect more prominent inhibition of the automatic postural response to balance perturbations to enable the transition to compensatory stepping. Upon foot strike of the compensatory step, theta power was higher in both PwS and HO for either stepping leg compared to HY, which may reflect a greater need for reassessment of stability. In HY and HO, cortical dynamics were largely symmetrical between stepping legs, which was also true for PwS with good leg motor recovery. For PwS with poorer leg motor recovery, however, notable asymmetrical cortical dynamics were observed between paretic and non-paretic steps from step onset to foot strike in the theta and alpha rhythms.

In conclusion, our study reveals distinct cortical dynamics during stepping responses for recovering balance following perturbations between HY, HO and PwS. The asymmetric dynamics in the PwS with poorer leg motor recovery may serve as an objective electrophysiological measure related to reduced balance capacity. It remains to be studied whether perturbation-based training may reduce this asymmetry and improve balance performance.

1-F-81 - The cortical dynamics underlying contextual (Dis-)Inhibition of anticipatory postural responses during step initiation

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Details

Interacting effectively within a changing world requires rapid visuomotor transformations. Such transformations can be measured via express visuomotor responses (EVRs), which are target-directed bursts of muscle activity that occur within 100ms of visual stimulus appearance. Recently, we reported an opposing relationship in a rapid stepping task between lower-limb EVRs and anticipatory postural adjustments (APAs) depending on postural instability: EVRs are enhanced but APAs suppressed when postural demands are low, but EVRs are suppressed and APAs enhanced when postural demands are high (Billen et al., 2023). These findings implicate top-down control that contextually up- and/or downregulates both EVRs and APAs.

Here, we investigated the cortical correlates of such modulation in healthy young individuals (N = 21) during the preparation and the initiation of rapid goal-directed stepping to visual targets presented left or right. We recorded high-density EEG (126 electrodes), surface EMG from bilateral Gluteus Medius, and bilateral ground-reaction forces. We manipulated postural demands by varying stance width and target location: postural demands were low with a narrow stance width and forward-lateral targets, but high for wider stance widths and forward-medial targets. Independent component analysis and time-frequency domain statistics were used to investigate the cortical dynamics.

We confirmed strong EVRs and suppressed APAs for steps initiated when postural demands were low. In this condition, we observed a proactive (i.e. before stepping target appearance) alpha (p=.013, t=.29) and beta (p=.010, t=.26) power increase in the left primary motor area. Given that the latency of EVRs preclude extensive cortical processing, we interpret such proactive power increases as suppressing the postural circuits that produce APAs and inhibit EVRs. Such APA suppression permits stronger EVRs that facilitate rapid stepping.

Conversely, when postural demands were high, we confirmed suppressed EVRs and strong APAs. We observed a proactive alpha and beta power decrease in the left primary motor area, as well as a reactive (i.e. during step initiation) increase in theta power (p=.002, t=.11) in the supplementary motor area, along with a broadband power decrease throughout the parietal cortex (mean p<.002, t=.2). APAs are needed in this condition for safe step initiation, and we suggest that the proactive power decrease in the left primary motor area disinhibit the postural circuitries that upregulate APAs and suppress EVRs. Finally, we attribute the reactive broadband power changes in parietal cortex during step initiation and the theta power increase in the SMA as being involved in the elaboration of APAs and monitoring of balance.
Together, these insights into postural demand-dependent modulation of higher-order APA circuitries open up avenues to study neuropathological disorders like Parkinson’s Disease, where those circuitries are likely affected.

1-F-82 - Cortical neuroprosthesis for the recovery of gait control after spinal cord injury

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Details

Most rehabilitation interventions for spinal cord injury (SCI) primarily focus on the sublesional spinal networks and muscles. However, effective locomotion involves more than rhythmic pattern generation; it necessitates the recovery of cortical control for voluntary movement and gait modulation. We have developed an intracortical neuroprosthetic approach aimed at conditioning cortical locomotor control after SCI.

Rats with incomplete thoracic SCI demonstrated immediate improvements in foot-drop and posture when cortical neuromodulation, synchronized with foot lift during gait, was applied. Just one week after hemisection SCI, there was a significant increase in foot lift (+133 ± 39%, n=6) and a reduction in dragging (-50 ± 8%). Moreover, long-term neuroprosthetic training enhanced movement rehabilitation outcomes persisting for a month post-training, as indicated by a +51 ± 10% improvement in ladder crossing scores.

In cats with bilateral contusive thoracic SCI, alternating bi-cortical neuromodulation effectively alleviated bilateral foot-drop deficits (-45 ± 11%, n=3). With intact cats, we discovered a vast array of motor programs that could be instantly activated by microstimulating specific areas within the primary motor cortex during gait. Post-SCI, stimulated hindlimb lift movements were highly stereotyped, yet effective in modulating gait and reducing bilateral foot drag. This suggests that the neural substrate underpinning motor recovery had traded-off selectivity for efficacy.

Both rats and cats underwent longitudinal awake cortical motor mapping, revealing that the resurgence of cortico-spinal transmission was synchronously linked with the spontaneous return of locomotion. The progressive increase in cortico-spinal transmission over time closely mirrored improvements in locomotor function.

Additionally, we employed intracortical microstimulation to investigate the ipsilateral cortical contribution to gait control. A week after hemisection SCI, microstimulation of the ipsilesional motor cortex during gait resulted in a combined contralateral hindlimb flexion and ipsilateral extension. This led to enhanced and prolonged ipsilateral weight-bearing, reversing motor deficits and restoring balanced gait phase distribution between the two hindlimbs. Ankle extensor activity returned to 90 ±18% of its original output, following a loss of over 70%.

In two rats, cortical stimulation in more medial regions of the primary motor cortex induced exclusive ipsilateral flexion movements. During locomotion, stimulating these areas significantly alleviated ipsilateral foot-drop (-46%, -100% respectively in the two subjects).

In summary, the motor improvements achieved through real-time cortical neuromodulation during locomotion underscore a critical role for the motor cortex in the functional restoration of walking post-SCI. This advocates for developing clinical neurorehabilitation interventions that directly target the motor cortex.

G – Theoretical & Computations Motor Control

1-G-83 - Using joint action parameters as biomarkers for theory of mind

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Details

Humans are often involved in interpersonal interaction or joint action in everyday life. The action-perception loop is inherently involved in these scenarios. A key determinant of the emergence of coordination through repetition is the buildup of ‘trust’ between the participants.

Here we used two haptic interfaces interconnected and synchronized, to test dyads of participants in sensorimotor versions of the classic Stag Hunt game. This game simulates a situation where two hunters must independently choose whether to pursue a rabbit (getting a fair payoff, independent of what their partner does) or a stag (getting a better payoff, but only if they both decide so; otherwise, they get zero payoff). The game has two Nash equilibria: the rabbit-rabbit strategy is risk-dominant with a low payoff and can be attained without cooperation; the stag-stag strategy is payoff dominant as both agents get a higher payoff, but only if they cooperate. The Stag Hunt game has been used as a model of the emergence of 'trust' between two individuals.

The experiment involved a total of 32 participants, matched to form 16 dyads. Participants were instructed on the rewards they would receive depending on their actions and their partner's, but during the experiment they were not allowed to speak or look at each other. The experimental protocol consisted of 90 repetitions of the game, organized into 18 blocks of 5 trials each. We tested two conditions. In the first condition, the participants only gather information about their partner at the end of each trial (display of partner position and payoff gained). In a second condition, the participants experienced a haptic force during each motion depending on their own and partner's selected action.

We analyzed the decision time series using a probabilistic model of joint action which includes a model of partner's next action (partner model) which optimally combines prediction and observation, and an action selection module that accounts for multiple strategy choices. For each dyad, we identified the model parameters from the joint decision time series.

Participants selected the stag with a greater probability. Most dyads converged to the stag-stag solution, but most participants kept some degree of exploration. The analysis of the model parameters suggested that the participants who were more prone to pick the stag strategy exhibited lower internal noise and greater retention rate, indicating that they represented their partner as more predictable. Model simulations reproduced the experimental data.

These experiments may contribute to characterizing participants' ability to attribute mental states to others and to predict and describe behavior based on such mental states (theory of mind). Social skills deterioration or theory of mind deficits are a relatively early sign of dementia in otherwise normal functioning subjects, which points to using the proposed experimental paradigm in persons with early cognitive decline.

1-G-84 - Learning coordinated gaits on complex surfaces

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Details

Locomotion involves the precise coordination of different body parts. On structured surfaces, animals additionally have to adapt their gait to properties of the environment. To study the dynamical principles of locomotor learning in novel environments, we trained mice to walk on a motorized treadmill with evenly spaced rungs. We extracted paw trajectories from behavioral videos and analyzed stepping patterns over the course of 10-14 days of learning. In early sessions, mouse gaits were highly irregular, with variable inter-paw coordination. Over sessions, coordination between paws increased, leading to fixed pairwise phase differences in the swing-stance cycle. To understand how stable coordination emerged from highly irregular gaits, we modeled gait dynamics by fitting coupled-oscillator models to the behavioral time series. The introduction of switching dynamical regimes and Gaussian process coupling functions allowed us to extract lawful dynamics in early as well as late sessions, despite frequent adjustments of stepping patterns to the runged surface. With this approach, we find that coordinated locomotion on complex surfaces depends on a dual learning process: On the one hand, mice learned to use advantageous, naturalistic stepping patterns more extensively; on the other hand, dynamic entrainment between paws increased, leading to efficient, fine-grained coordination between paws.

1-G-85 - Reward feedback enhances sustained attention on short timescales

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Details

Attention and learning are intertwined. While previous work has primarily examined how the focus of attention can shape learning, how the dynamics of learning might impact your attentional state on a moment-to-moment basis is an open question. Here we investigated the influence of reward feedback on attentional vigilance during a reinforcement learning (RL) task. Using a task that simultaneously tracked people's attentional vigilance and reinforcement learning performance, we assess the impact of two core components of RL - reward feedback and surprise - on fluctuations in attentional vigilance. In two experiments (N = 161), we demonstrate that intermittent rewards during instrumental RL boost attentional vigilance on a timescale of seconds to minutes. In contrast, we did not find evidence that surprise modulated vigilance. In a third experiment (N = 135), we find evidence that reward feedback during Pavlovian RL also elicits short-timescale boosts in sustained attention, although to a lesser degree. These findings demonstrate that rewards can buffer against lapses and improve attentional vigilance at short timescales. We also show robust correlations between people's overall attentional vigilance and learning rates that were derived from reinforcement learning models. These findings highlight an interaction between core aspects of instrumental learning and attentional dynamics.

1-G-86 - Sensorimotor games to study emergent coordination.

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Details

During life activities, we often interact with other individuals and develop forms of coordinated actions. Game theory is used in the social sciences to study the emergence of cooperative behaviors that involve discrete actions. In a few studies, game theory has been used to interpret forms of sensorimotor interaction. The Prisoner Dilemma (PD) game has been used as a general model of how two agents develop mutual cooperation. Two prisoners, held in separate cells and unable to communicate, must decide whether to accuse the other (defect) or stay silent (cooperate). If both agents cooperate, they serve few years. If they both defect, they get more years. But if only one defects, he goes free and the other gets far more years. When the game is played once, defect-defect is the best strategy (Nash

equilibrium), but several studies suggested that iterated play often leads to the emergence of cooperation. Some studies focused on a sensorimotor version of classical discrete games, like PD, in which two agents interact through haptic interfaces within a continuous action space and the game cost matrix is encoded into the stiffness of a virtual spring whose magnitude depends on the position of both players. In contrast to their discrete counterparts, the haptic version of the PD game showed a gradual convergence to the Nash strategy. To understand this, we studied variants of this haptic PD scenario. As in previous protocols, each player in a dyad was instructed to grasp the handle of a robot and to reach a vertical target (horizontal bar) by moving from a starting region against a virtual spring. The stiffness was defined as a function of the horizontal position of both players and encoded the game's cost structure. However, we used a new interpolation of the discrete cost matrix which preserved both the cost structure of the discrete game and its Nash equilibrium. In addition, we manipulated the overall stiffness magnitude (low, high) and the way information about partner actions was provided (fixed, the stiffness depends on the initial position; or variable, the stiffness varies continuously with the players' positions). The experimental protocol involved a total of 200 trials. We tested five dyads for each of the four conditions. We analyzed the sequence of actions of each dyad by using a computational model, which accounted for both partner representation and action selection. The model extends previous theories of motor control and uses game theoretic concepts to describe the decision-making process in interactive scenarios. We used the model to both simulate the dyad and to estimate the model parameters from the experimental data. Results suggest that the dyads tend to converge to the Nash equilibrium. The effect is more robust with high stiffness and variable information. These results confirm that on each trial each player behaves optimally, by selecting the action that minimizes their own expected cost.

1-G-87 - A modular architecture for trial-by-trial learning of redundant motor commands

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Details

During movement planning and execution, the central nervous system needs to coordinate the activity of a large and redundant set of muscles acting on multiple joints. An ample body of evidence suggests that the central nervous system simplifies the problem of coordinating the multiple degrees-of-freedom of the human body by grouping multiple muscles into a reduced number of motor modules, called muscle synergies, which can be selectively recruited to execute a large repertoire of movements. Studies that investigated adaptation to a novel relationship between motor commands and task outcomes suggested that altering the recruitment coefficients of synergies is faster than learning de novo synergies structures. Although several studies investigated the processes underlying the adaptation of the hand position to perturbed environments in arm-reaching experiments, such as visuomotor rotations and force fields, the adaptation mechanisms governing changes at the muscular level, which likely involve both changes to synergy recruitment and synergy structure, are still unknown. In this study, we present a computational model for the generation of redundant muscle activity patterns during isometric force-reaching tasks where explicitly defined modules, implemented as spatial muscle synergies, can be updated together with their recruitment coefficients, at different learning rates. This update is performed by the backpropagation of the difference between the intended and executed force through a forward model of the isometric task. This model can in turn be updated, reflecting learned changes in the task environment. We show how our model can qualitatively reproduce the results of various adaptation tasks during multidirectional isometric force generation, such as adaptation to the virtual alteration of muscle-pulling directions (virtual surgeries). Our model can predict how muscle synergies structures, their recruitment, and the force error correction change over multiple days of practice with virtual surgeries. Such a computational model may improve the understanding of neural mechanisms through which the different components of a modular architecture are adapted trial-by-trial in the presence of visual errors and may suggest novel experimental protocols and analyses to confirm its predictions about the motor system.

1-G-88 - Bayesian inference in arm posture perception

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Details

To configure our limbs in space the brain must compute their position based on sensory information provided by mechanoreceptors in the skin, muscles, and joints. Because this information is corrupted by noise, the brain is thought to process it probabilistically. According to the Bayesian brain hypothesis, the brain forms a belief here an estimate about the configuration of the arm in space by combining sensory information (likelihood) with prior beliefs (prior) about the default arm posture, following Bayes' rule. Such computations boost precision in the perception of arm posture but go at the expense of a bias. To test this hypothesis, we combined computational modeling with behavioral experimentation on arm posture perception. First, we described the arm as a kinematic serial chain including three angles of flexion and/or extension (shoulder, elbow and wrist) in the horizontal plane. We then made this geometric model probabilistic, by adding Gaussian noise to the joint angles (define the likelihoods) and a Gaussian prior on the probability distributions of joint angles. Best estimates of arm configuration in terms of joint angles follow from the optimal integration of angular likelihoods (i.e., proprioceptive signals) and the postural prior. We set out to test whether this Bayesian model explains biases in posture-matching better than alternative models (e.g., assuming a uniform prior). In the task, implemented in VR, human participants (N = 20) were required to align their unseen right arm to a target posture, presented as a visual configuration of the arm in the horizontal plane. Each visual target posture was presented in the first-person perspective, i.e., three connected visual lines corresponding to upper arm, forearm and hand, matching with the participant's arm length. Results show idiosyncratic biases in how participants matched their unseen arm to the target posture. We used maximum likelihood estimation to fit the Bayesian model to these observations and retrieve key parameters including the prior means and variance-covariance structure. The Bayesian model including a Gaussian prior explained the response biases and variance much better than a model with a uniform prior. The prior varied across participants, consistent with the idiosyncrasies in arm posture perception, and in alignment with previous behavioral research. Our work clarifies the biases in arm posture perception within a new perspective on the nature of proprioceptive computations.

1-G-89 - Dopamine modulator shapes locomotor patterns through ion channel conductance within central pattern generators

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Details

Understanding the intricate link between cellular functions and resulting behavioral outcomes remains a pivotal challenge in neuroscience. Coordinated activation of supraspinal brain regions, spinal neuron assemblies, and muscles, steered by distinct neuromodulators, orchestrates the complexity of locomotor behavior. Key pathways, including the reticulospinal and corticospinal tracts, exhibit differential impacts on force generation, with the former linked to muscle force through dopaminergic signaling from the reticular formation to the spinal cord.
Central Pattern Generators (CPGs), found in the spinal cord's ventromedial region, have emerged as crucial contributors to generating locomotor patterns. Recent investigations underscore the potential of monoamine precursors, such as L-DOPA, in evoking locomotion within CPGs. In this light, a necessity for computational models arises to delve into the nuanced role of neuromodulators within CPGs.
With this aim, we incorporated neuromodulators into a three-layer CPG model comprising rhythm generator neurons reciprocally connected with inhibitory interneuron pools. Subsequent layers consist of a group of inhibitory and excitatory interneurons designed to project to the flexor-extensor motor neuron (MN) pools that innervate skeletal muscles. Leveraging the biological realism of the Hodgkin Huxley neuron model and simulation advances for spiking neural network modeling, we explored how neuromodulators directly alter pre- and post-synaptic neurons by change of Ca influx and indirectly influence the neuron’s firing pattern properties, thus changing the MN output.
Our simulations revealed that manipulating the conductance of different ion channels within the CPG network indirectly elicits changes in MN output and recruitment, underscoring the sensitivity of locomotor patterns to these variations. We found that there is a relationship between persistent sodium channel inactivation and rhythmic activity produced by the model. We also observed that upregulation of persistent sodium, voltage-gated sodium, and L-type Calcium channels can increase force generated by MN in different levels that is coincident with experimental studies. Furthermore, our study reveals how the synaptic weight of dopaminergic spikes directly impacts the MN output. The amount of alteration depends on the weights and neuron populations between which there are dopaminergic synapses. Our results demonstrate that dopaminergic neuromodulation in CPGs during rhythmic movement is as significant as that in the central nervous system.
Such insights hold promise for refining computational models and advancing our understanding of neuronal mechanisms underlying locomotion, with implications for therapeutical strategies targeting motor deficits.

1-G-90 - Motor skills assessment of microsurgical anastomosis

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Details

Microsurgical operations, crucial for anastomosing tiny blood vessels and coapting nerves, primarily deal with vessels smaller than 3 mm. These surgeries require high manual dexterity and visuospatial skills due to minimal tactile sensation and spatial perception. However, the skill assessment in surgical training remains unstandardized and heavily reliant on subjective, qualitative methods. This traditional approach, often biased, demands significant time and resources, involving multiple senior surgeons for evaluations. Hence, developing an objective and automated skill assessment framework that overcomes these limitations may offer a promising solution.

Our study introduces an objective framework for microsurgical skill assessment using quantitative sensory measurements. We adapted metrics from laparoscopic skills and motor control literature, focusing on time, instrument kinematics (via motion capture), and tactile feedback (measured by force sensors on surgeons' fingers). This approach seeks to accurately reflect a surgeon's proficiency, aligned with traditional subjective ALI-Score assessments. We conducted an experiment involving standard microsurgical anastomosis on a chicken model, with twelve participants (age: mean: 35.42, std: 9.78; nine males; varied handedness) from Geneva University Hospitals, categorized into six novices and six intermediates based on their ALI-Scores. The task comprised four key segments: two needle insertions and two knot makings in each stitch.

Our assessment included: (i) temporal metrics for task time and idle time, (ii) kinematic metrics evaluating instruments' motion (path, jerkiness, movement economy, bimanual dexterity), and (iii) tactile metrics measuring tool/finger interaction force. The statistical results confirmed our hypothesis, indicating that the proposed set of objective metrics to assess skill proficiency aligns with subjective evaluations, particularly the ALI-score, and it can effectively differentiate novices from more proficient microsurgeons. Furthermore, we found statistically significant disparities (significance level=0.05), where intermediate-level microsurgeons surpassed novices in achieving higher task speed, less idle time, smoother and briefer hand displacements, and higher bimanual dexterity. This shows that our objective skill assessment system can reveal more differences among subjects of different skill levels, hence providing richer evaluation information than the subjective ALI Score system.

This research marks a significant step in microsurgical training and assessment. Future plans include expanding the participant pool and integrating surface electromyography for in-depth movement analysis. This will enhance our assessment system, aiming for a standardized, comprehensive evaluation in microsurgery training.

1-G-91 - Energy and time minimization predicts real-world reaching movements with objects

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Details

Optimal Reward and Effort trade-offs are a modern approach to understanding human movement (Shadmehr et al. 2016; Berret et al. 2018). Within this framework, energy-plus-time minimization makes explicit the interpretations of each term, where energy expenditure is effort, and time expended is (the inverse of) reward. Energy-plus-time has been a **useful hypothesis** and can even explain the durations and peak speeds of movements as different as walking (Carlisle & Kuo, 2023) and reaching (Wong Cluff & Kuo 2021). While we have tested these reaching predictions using a robotic manipulandum in a laboratory setting, these predictions have yet to be tested within the context of real-world interactions with objects. Here we test the hypothesis that energetic and time minimization govern the selection of natural human preferred movements. Using simulations from our optimal control model we generate predictions of people's movement kinematics as they interact with objects, described below.

Seated subjects (N=6) were asked to pick-and-place objects between different locations on a table. Subjects were required to place objects within 5, 10, 15, 20, and 25 cm targets. Subjects were asked to reach at their preferred speed. The experiment was run under very low time pressure a fixed-duration 10 second audible timer indicated the start of each reach and thereby removed incentives to complete the task rapidly. We used Freemocap (Matthis et al. 2022; freemocap.org) to record limb kinematics, and Inertial measurement units (IMUs) to track the motion of held objects.

A computational model of reaching movements (in Python; available at) was used to minimize the combined cost of energy (Joules) and a linear function of time. To each subject’s set of reaches, a single value indicating a subject’s cost of time coefficient in units of energy-per-time was computed. This value reflects the amount of energy a subject is willing to spend to save a unit of time.

The energy-time model predicts specific, dimensionally-correct scaling laws relating movement distance D, duration T, and peak speed V. Under energy-time minimization, duration scales according to $D^{1/4}$, while peak speed V increases with $D^{3/4}$. Preliminary results show that movement peak speeds and distances were well predicted by energy-time minimization (N = 6; P = 1.3e-20).

While the optimal control framework is untestable any set of data will fit some cost function, with inversely-optimized gains to scale each objective appropriately the Energy and linear Time hypothesis is different. It is

1. independently testable (one can measure energy and time expenditure)

2. mechanistic (follow from physics simulations)

3. physiological (energetic costs from muscle costs)

4. generalizable (applies to all movements)

5. parsimonious (not hyperbolically discounted)

Additionally, modern portable measurement devices and opensource projects such as freemocap make these predictions replicable at a cost below $500.

Poster Session 2

Wednesday, April 17, 2024

A – Adaptation & Plasticity in Motor Control

Poster Cluster (2-A-1 to 2-A-4)

2-A-1 - Similar oscillatory mechanisms map touch on hands and tools

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Details

Numerous studies have found evidence that tools become incorporated into a plastic neural representation of our body, suggesting that our brain re-uses body-based neural processing when we use tools. However, little is known about how this is implemented at the neural level. Here we used the ability to localize touch on both tools and body parts as a case study to fill this gap. Neural oscillations in the alpha (8-13 Hz) and beta (15-25 Hz) frequency bands are involved in mapping touch on the body in distinct reference frames. Alpha activity reflects the mapping of touch in external coordinates, whereas beta activity reflects the mapping of touch in skin-centered coordinates. Here, we aimed at pinpointing the role of these oscillations during tool-extended sensing.

To this aim, we recorded participants' oscillatory activity while tactile stimuli were applied to either hands or the tips of hand-held rods. Posture of the hands/tool-tips was uncrossed or crossed at participants' body midline in order for us to disentangle brain responses related to different coordinate systems. We found that the scalp distributions of alpha and beta modulation were nearly identical when touch was on the body or on a tool. Only alpha oscillations were modulated by posture, suggesting that they are related to tactile processing in external spatial coordinates. Furthermore, source reconstruction of this space-related alpha modulation revealed a similar bilateral network of parieto-occipital regions involved in mapping touch on tools and on hands.

In conclusion, we found that the brain uses similar oscillatory mechanisms for mapping touch on a hand-held tool and on the body. These results support the idea that neural processes devoted to body-related information are being re-used for tool-use. Furthermore, since alpha-band modulation followed the position of touch into external space, this is the first neural evidence that tactile localization on a hand-held tool involves the use of external spatial coordinates.

2-A-2 - Active tool-use training does not change time perception in peripersonal or far space

Jahanian Najafabadi Amir [1], **Christoph Kayser** [1]

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Details

Previous work has suggested that our perception of time is plastic and dependent on the distance of the stimulus to our body. For example, Annelli et al (2015) showed that stimuli presented in peri-personal and far space are judged differently and that this distance-effect on time perception can be shaped by training participants with a tool that effectively extends the reachable space. These studies indicate that the perception of time can be remapped in an action- and effector-dependent manner. We here aimed to replicate and extend these results using a paradigm in which we tested time perception at multiple distances from the body prior to and following active tool-use training.

In our experiment, we probed 36 participants on three temporal tasks (visual bisection, visual categorization and auditory categorization) for stimuli presented at three distances from the body (60 cm, 120 cm and 240 cm). In between testing blocks, participants performed blocks of active tool-use training whereby they used a mechanical grabber to move coins at a distance of 120 cm from the body. For each task we tested for an effect of spatial distance, tool-use training and an interaction. Our data suggest that time perception is not affected by the distance of the stimulus to the body and is not shaped by extension of the action-related body by tool-use training. Hence they call into question to what degree and how robustly time perception is shaped by the distance of the probe to the body and how malleable this is by extension of the peripersonal space by tool-use training.

Keywords: Time perception, Peripersonal Space, Far Space, Space Representation

2-A-3 - Changes of sensorimotor representation of the forearm in peripersonal and far space during active tool-use training through life span

Jahanian Najafabadi Amir [1], **Nakisa Nourzadegan** [2], **Sara Mohammdi** [3], **Alireza Rastegari** [4], **Hadis Imani** [5]

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Details

Prior research has shown that the use of a mechanical grabber induced changes in the sensorimotor representation of the forearm of younger aged participants, but not of older adults. For instance, Martel et al. (2021) highlighted a gradual developmental trajectory in the integration of tools, observing a U-shaped pattern between early and middle puberty, where tool-induced movements suggested a decreased perception of arm length, differing from findings in adults. Furthermore, Jahanian Najafabadi et al. (2023ab) observed a noticeable reduction in perceived distance between two tactile points on the forearm after virtual tool-use training among younger adults, but not in older adults.

In our experiment, we recruited 83 participants across various age groups (12-80 years) who had to use a mechanical grabber in order to grasp coins at different locations in a horizontal plane. The goal was to replicate the well-established tool-use paradigm used in prior research, exploring changes in the hand's body schema plasticity after undergoing active tool-use training across the lifespan. The training involved two blocks using varying tool sizes in a counterbalanced order to grasp objects at different distances in near and far spaces. Before and after each training block, participants performed both tactile distance judgment and reaching distance estimation tasks.

Our results revealed changes in body schema of adolescents and younger adults when using a mechanical grabber to grasp objects in far space compared to close space, supporting previous findings. However, we didn't find plasticity of the body schema in middle-aged and older participants.

Keywords: Sensorimotor representation, active tool-use, forearm, body representation, peripersonal space, far space, life span

2-A-4 - Changes in body ownership and agency associated to body schema modifications across the lifespan in active tool-use training

Jahanian Najafabadi Amir [1], **Sara Mohammdi** [2], **Nakisa Nourzadegan** [3], **Alireza Rastegari** [4], **Hadis Imani** [5]

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Details

Tool-use is a hallmark of humans, enabling us to engage with our surroundings by accessing objects situated at various distances and locations. Recent studies are exploring whether we experience similar sensations of ownership and agency over physical and virtual tools. Prior research conducted by Jahanian Najafabadi et al. (2023ab) have found a link between higher levels of perceived ownership over virtual tools and increased performance in tool-use tasks, as well as greater body schema plasticity in younger adults but not in older ones. Their study also highlighted that, while older adults experienced a similar sense of control over the tool compared to younger individuals, it was not linked to changes in body schema in that group.

In the present study, we aimed to replicate a widely recognized physical tool-use paradigm to explore the emergence of body ownership and sense of agency over the tool. We further aimed at understanding whether changes in ownership and agency are associated with changes in the forearm body schema and if those changes are depending on age. We recruited 83 right-handed participants, aged between 12-80 years, who had to use a mechanical grabber to collect coins localized at various positions in a horizontal plane. The training sessions comprised two blocks, each with a different tool size, and participants had to grasp objects at varying distances in both near and far spaces. Before and after each block, participants performed a tactile distance judgment task. Subjective assessments of ownership and agency over the tool were obtained using questionnaires. Results revealed a stronger emergence of ownership and agency over the tool when reaching objects in far space compared to close space. Furthermore, we found that higher ratings of ownership and agency were associated with changes of body schema in participants aged 12-35 years old but not in older participants.

Keywords: Sensorimotor representation, active tool-use, forearm body schema, body ownership, sense of agency, life span

2-A-5 - Sleep consolidation potentiates skill maintenance

Agustin Solano [1], **Gonzalo Lerner** [1], **Guillermina Griffa** [1], **Alvaro Deleglise** [1], **Pedro Caffaro** [1], **Luis Riquelme** [1], **Daniel Perez-Chada** [2], **Valeria Della-Maggiore** [1]

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Details

The role of sleep in declarative memory consolidation is well established, consistently enhancing memory retention across various paradigms (e.g., face recognition, free recall, paired associates). In contrast, the contribution of sleep to non-declarative motor learning is more equivocal and remains a subject of debate. Motor learning involves skill acquisition and skill maintenance, two critical aspects in achieving movement precision. These aspects of learning are often referred to as motor skill learning (MSL) and sensorimotor adaptation (SMA), respectively. Previous evidence suggests that MSL benefits from sleep, while SMA memory consolidation supposedly depends solely on the passage of time. In this study, we propose that like MSL, SMA memory consolidates both during wakefulness and sleep. To test this hypothesis, we conducted three meticulously designed experiments using the SMA paradigm known as visuomotor adaptation. In Experiment 1 (n=134), we explored the impact of sleep on memory retention when training occurred far from bedtime. In line with previous literature, we found that when training occurs sparsely throughout the daytime, SMA consolidation proceeds independently of sleep. Then, in Experiment 2 (n=92), we sought to establish the time course of memory stabilization during wakefulness using an anterograde interference protocol. This experiment aimed to determine the specific time window during which sleep might be most effective in modulating SMA memory. Our results revealed that SMA memory stabilizes during wake through a ~6 h time window, providing experimental evidence that supports memory consolidation of this type of motor memory. Finally, building upon the insights from Experiment 2, in Experiment 3 (n=44) we examined sleep's impact on long-term memory retention when training occurred immediately before bedtime as opposed to training far from sleep. Here, to ascertain whether sleep operates through an active mechanism, we also quantified the incidence of neural markers of memory consolidation on EEG signals recorded during sleep (i.e., the density of fast sleep spindles and their coupling with slow oscillations). Our findings demonstrate a net 30% memory enhancement when sleep aligns with the memory stabilization window. This marked improvement in long-term memory was accompanied by an increase in spindle density and spindle-SO coupling during NREM, thereby providing support for an active role of sleep behind the behavioral benefit. Altogether, our work advances research at the basic and translational levels. It contributes to resolving a longstanding debate concerning the role of sleep in SMA memory consolidation. It also opens the possibility of common mechanisms supporting consolidation across different memory domains. At the translational level, it may have implications for designing effective training strategies and interventions, with potential applications in sports and rehabilitation settings.

2-A-6 - Reaching and speech adaptation in healthy young, old and older old adults

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Details

In daily life we are often confronted with the fact that the performance of older people decreases, in such way that they can become fully dependent on the help of others. Several studies have shown how age-related deterioration of motor regions in the brain, negatively affects several motor functions like balance, fine motor control and movement speed. However, studies investigating the adaptation of reaching movements found that reaching adaptation was not impaired in most older people between 60-70 years old. We wanted to investigate whether this was also true for even older people, >80 years old, and whether these results could be replicated in a different task paradigm, such as speech adaptation.

To test this, two adaptation tasks were performed by healthy participants from three different age groups: young adults (YA; 20-35 y/o; N = 41), older adults (OA; 55-70 y/o, N = 76), older old adults (OOA; >80 y/o, N = 17). In the visuomotor adaptation task, we measured the implicit adaptation of reaching movement as a reaction to clamped cursor feedback with a 30 ° perturbation (*Morehead et al., 2017*). This task consisted of 30 baseline trials, followed by 230 perturbation trials. In the speech adaptation task we measured speech adaptation induced by a vowel shift of 125Hz in the auditory feedback of the participant's own voice (*Parrell et al., 2017*). This task consisted of 30 baseline trials, followed by 90 perturbation trials and 10 wash-out trials. For both tasks, we compared the responses during the perturbations with the unperturbed baseline responses of each participant, in order to measure the extent of adaptation. We also distinguished between early and late adaptation. For both task this means we took the average adaptation during trial 10-40 after perturbation onset, and late adaptation by taking the average adaptation during the last 30 trials of the perturbation.

We found that participants from each of the three age groups adapted their responses to the perturbation successfully in both tasks, in both the early and late adaptation phase. There was no clear difference in visuomotor adaptation between groups in the early phase (mean adaptation: YA=11.3 (±1.4), OA=11.8 (±1.8), OOA=11.4 (±2.5)), while in the late phase both older groups adapted more than the younger one (YA=18.0 (±1.3), OA=20.3 (±1.3), OOA=20.7 (±2.7)). For the speech task the oldest group adapted at a slower pace compared to the others (early phase medians: YA=23.5 (range=32.4), OA=24.9 (range=20), OOA=15.6 (range=56.8), but ended up with adapting as much as the young adults, but lower than the old adults (late phase medians: YA=17.7 (range=26.6), OA=21.3 (range=184), OOA=17.6 (range=67.8)).

Based on this data we can conclude that adaptation to a perturbation is well retained in the elderly, even above the age of 80 years old. Further, data from both task shows that the adaptation is not task-specific.

2-A-7 - Paired associative stimulation in elbow flexor muscles in humans with spinal cord injury

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Details

Paired associative stimulation (PAS) targeting spinal synapses has been used to enhance voluntary motor output in humans with spinal cord injury (SCI). The goal of our study was to assess the effect of PAS on corticospinal excitability in elbow flexor muscles in humans with and without a chronic cervical SCI. During PAS, corticospinal volleys evoked by transcranial magnetic stimulation (TMS) were timed precisely to arrive at corticospinal-motoneuronal synapses of the biceps brachii muscles 1-2 ms prior to the arrival of antidromic potentials elicited through electrical stimulation of the musculocutaneous nerve at the brachial plexus. The interstimulus interval (ISI) between TMS and peripheral nerve stimulation was calculated individually by using the latency of motor evoked potentials (MEPs), C-roots, and maximal motor responses. PAS was used to target corticospinal-motoneuronal synapses using suprathreshold TMS (100% of Maximum Stimulator Output, MSO) and supramaximal peripheral nerve stimulation (78.6 ±14.0 mA). We tested the effect of PAS on MEPs elicited by TMS over the arm representation of the motor cortex in biceps brachii before and after 180 paired pulses. Central conduction time (CCT) and peripheral conduction time (PCT) were calculated individually in control (CCT= 3.7 ±1.1 ms, PCT= 2.0 ±0.6 ms) and SCI (CCT= 3.4 ±2.2 ms, PCT= 2.5 ±1.4 ms) participants. We found that MEP size in the biceps brachii increased after PAS in control (by 83.3 ±85.0% immediately after and by 38.2 ±54.4% 30 min after PAS) and SCI (by 172.8 ±109.1% immediately after and by 354.2 ±292.8% 30 min after PAS) participants. Our findings suggest that in humans with SCI as in control participants, spike-timing dependent plasticity mechanisms can be engaged in elbow flexor muscles. This knowledge might contribute to the design of targeted therapies aiming to enhance upper limb function after SCI.

2-A-8 - Implicit adaptation is fast and independent from explicit adaptation

Denise Henriques [1], **Bernard 't Hart** [1], **Sebastian D'amario** [2]

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Details

During classical visuomotor adaptation, the implicit process is believed to occur rather slowly; however, recent evidence suggests otherwise. To investigate the time-course of implicit learning, we examined the effects of diverse rotation magnitudes, feedback types, feedback timing delays, and the role of continuous aiming on implicit learning. Contrary to conventional beliefs, we discovered that implicit learning unfolds at a high rate in all feedback conditions. Increasing rotation size not only raises asymptotes as expected but also generally heightens explicit awareness, with no discernible difference in implicit rates. Cursor-jump and terminal feedback, with or without delays, predominantly enhance explicit adaptation while diminishing the extent, but not the speed of implicit adaptation. In a continuous aiming reports condition, there is no discernible impact on implicit adaptation, and both implicit and explicit adaptation progress at indistinguishable speeds. Additionally, investigating the correlation between implicit and explicit processes, we consistently observe a weak or no association across conditions. Our observation of implicit learning early in training in all tested conditions signifies how robust our innate adaptation system is.

2-A-9 - The viscoelastic properties of the legs can enable a wide range of gait initiation dynamics when coupled to a CPG in a simulated quadruped insect

Kaitlyn Kumar [1], **Xiaosi (Horace) Zhang** [1], **Lawrence Bowens** [1], **Francisco Valero-Cuevas** [1]

[1] University of Southern California

Details

Background: Neuroscientists often abstract away the relevance of mechanical system dynamics from discussions of fictive locomotion under central pattern generators (CPG). Coupling a mechanical system model with a CPG can reveal the brain-body co-evolution and co-adaptation for multi-legged locomotion [1-2].

Purpose: We coupled viscoelastic legs to a Matsuoka CPG to explore the specific locomotor patterns and their stability that emerge for multiple viscoelasticity parameters.

Methods: We coupled a 0.1kg ovoid planar body with horizontal translational and rotational degrees of freedom to lateral walls via four second-order viscoelastic legs following the Hill-type muscle model. The resting length of each leg was driven by the out-of-phase output of a feed-forward dual-neuron Matsuoka CPG. We simulated step responses to a CPG frequency of 2 Hz simulating walking starting from rest. The spring constant (k) and damping coefficient (c) were selected at random in the range of 0 ‰¤ k ‰¤ 30 N/m and 0 ‰¤ c ‰¤ 1 Ns/m, with particular interest in the regions of 0.3 ‰¤ c ‰¤ 0.5 Ns/m and 6 ‰¤ k ‰¤ 12 and 17 ‰¤ k ‰¤ 25 N/m from cockroach models [3].

Results: We analyzed our simulations of 10,000 combinations of spring-damping coefficients as having an initial response (i.e., the first ten steps [4]) that can be categorized into eight distinct movement patterns as described by the body's lateral velocity vs. position phase portraits showing versions of single-well, distorted single-well, or two-well attractors. A Phase-Transition diagram of c vs. k. shows these regions of quasi-stability. All simulations converged after 25 s to two movement patterns of single- and two-well oscillations. While some viscoelastic parameters produce straightforward responses, underdamped legs ($c < 0.2$ Ns/m) with large spring constants ($k > 25$ N/m) lead to 2-well attractors (similar to Duffing's) that reveal sophisticated behavior and the potential need for robust controllers that may nevertheless be a built-in enabler of legged agility.

Conclusion: These results indicate that coupled neuro-mechanical systems, tunable via muscle activation and mechanical properties [5], impose limitations and opportunities for the mechanics of legged locomotion [6], at times even being loosely coupled to the Matsuoka CPG's forcing function. This work expands the possibilities for locomotor patterns for the initiation of gait vs. steady state locomotion as well as gait transitions for bio-inspired robots on the basis of the viscoelastic properties of the legs [7].

References:

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<u>2-A-10 - Comparison of pathways for sensory feedback for wearable devices</u>

Lucy Dowdall [1], **Edmund Da Silva** [1], **Matteo Bianchi** [2], **Fumiya Iida** [1], **Dani Clode** [1], **Tamar Makin** [1]

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<u>Details</u>

Our motor system relies on somatosensory feedback to inform about the current state of our limbs and their interactions with the external environment. Accordingly, great resources have been devoted to creating artificial somatosensory feedback for wearable robotics (such as prosthetics and body augmentation technology). However, the natural tactile feedback received from where such devices are worn on and controlled by the body has been crucially overlooked. This 'intrinsic' sensory feedback may be harnessed to inform about device 'somatosensation', and may even be more easily integrated and less cognitively demanding than artificial feedback.

This study aims to consider the utility and limitations of intrinsic feedback compared to its artificial counterparts. We created three sensory feedback systems for use with the 'Third Thumb' (Dani Clode Design), a supernumerary robotic finger worn on the hand. The first had no artificial feedback, and just utilised the intrinsic feedback naturally received on the side of the hand during Thumb usage. We then developed a vibrotactile feedback system where vibration produced by objects engaging with the tip of the Third Thumb elicited an equivalent level of vibration delivered via a ring on the user's ring finger. Lastly, we developed a skin stretch feedback system where deformation received on the tip of the Third Thumb produced a proportional amount of linear skin stretch on the user's inner wrist.

We first considered a series of perceptual tasks, where participants received sensory feedback without actively using the Third Thumb. This informs us about whether participants can extract meaningful information from the feedback. Participants (*N*=20) performed a texture discrimination task and a material density discrimination task with each feedback system. We predicted that the vibrotactile feedback would excel at the texture task whilst the skin stretch feedback would excel at the material task. Our results successfully demonstrate this pattern when the feedback is compared to the respective other artificial feedback system. However, we found that the intrinsic feedback performed comparably to each of the artificial systems on their preferred task. This demonstrates that interpretable sensory information can be extracted from this natural feedback, and artificial sensory feedback may not provide additional value.

We then compared performance differences when these feedback systems are used in an active motor task (*n*=20 per feedback group). In this ongoing study, participants complete a 'fragile egg' task aimed at assessing proportional control abilities before and after training on a series of Third Thumb-biological thumb collaboration tasks. Preliminary findings demonstrate that all participants can perform the task. The outcomes will inform us whether artificial feedback provides helpful information during active object interactions, or conversely - negatively impacts smooth motor control and learning.

2-A-12 - Eye movements may reflect the computed component of strategic re-aiming

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Details

Visuomotor adaptation of reaching movements can be dissociated into two components with differing time constants and differing psychophysics. The slower component operates outside of intentional control and awareness while the fast component is more accessible to conscious control and awareness. Many other differences have been extensively researched in the literature including the responsiveness to different types of error and their generalization properties. There is also evidence that each of these components may itself reflect more than one underlying adaptive process. For instance, the fast component, sometimes called strategic re-aiming, may reflect both a capacity-limited process of retrieval and a time-limited process of mental rotation. One ongoing challenge in the study of the processes underlying adaptation is measuring them. One approach is to fit computational models, such as the two state state space model or the COIN model, to reveal the latent processes. These computational models can be powerful tools, but they are heavily theory dependent. There have also been different methods of separating the consciously accessible processes from other processes through either specific instructions or directed questions. There are a number of disadvantages to these approaches: first, participants can understand instructions or answer questions in idiosyncratic ways; second, the act of querying the subject has known influences on the adaptation itself; third, the results using different methods of question and instruction have been inconsistent. I will discuss these issues and focus on a partial solution: the use of eye movements to reveal specific underlying processes. Our experiments demonstrate that eye movements are associated with strategic re-aiming in some conditions. However, while other conditions for eye movements that is consistent with strategic re-aiming, the amount of eye-movements is not always consistent with the size of the aftereffects. One compelling possibility is that the eye movements reflect only one of the underlying processes in strategic re-aiming, specifically the mental rotation. The poster will show preliminary evidence to support this claim.

2-A-13 - Feedback control mechanism in redundant bimanual stick-manipulating task

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Details

If a movement error occurs while reaching a target, the motor system rapidly corrects the error within a trial. Such a remarkable ability has traditionally been investigated using kinematically non-redundant tasks, such as planar arm reaching movements. Therefore, it remains poorly understood how the motor system alters the movement patterns of our redundant body and corrects the error. To address this issue, we developed a realistic stick manipulation task using a KINARM Endpoint. Participants (N = 21) held a virtual stick with both hands (distance: 15 cm) and moved the right tip of the horizontal stick (length: 40 cm) from a starting point to a target (distance: 15 cm). This task is redundant because the same target can be reached in countless movement patterns. Nevertheless, they showed stereotypical movement patterns during the baseline phase (280 trials; target direction: 0 (horizontal direction), ±30, ±60, ±90 °). When they reached forward or backward targets, they tilted the stick in a counterclockwise (CCW) or clockwise (CW) direction. Each participant's stick tilting angle depended only on the vertical position of the tip, thereby obtaining an inherent relationship between tip position (TP) and stick tilting angle (STA) ("a baseline TP -STA relationship). During the subsequent test phase (160 or 360 trials), the target appeared only in the 0 ° direction, and visual perturbations were introduced. Each participant experienced stick jump or stick rotation perturbations imposed when the tip was 1 cm away from the starting point. In stick jump trials, the entire stick was shifted perpendicularly to the target direction by 3 or -3 cm, whereas the stick angle remained unchanged. The motor system could quickly correct the shifted tip position without or by tilting the stick. Resultantly, all participants (N = 10) corrected the tip errors while tilting the stick (paired t-test, $t(9) = 13.20$, $P < .01$, at 0.3 s after perturbations). Movement patterns of both hands during the correction appeared to be along the baseline TP-STA relationship. Then, does the motor system follow the relationship even when encountering stick angle errors? In stick rotation trials, the stick was abruptly rotated by 6 or -6 ° around the tip. The participants (N = 11) did not have to respond to this rotation because it did not affect the tip position. However, they quickly corrected the stick angle (paired t-test, $t(10) = 3.41$, $P < .01$ at 0.3 s after perturbations). Moreover, the stick tilt correction in the CCW or CW direction was accompanied by a forward or backward tip error (paired t-test, $t(10) = 3.29$, $P < .01$, at 0.3 s after perturbations), as if physical movement patterns were constrained by the baseline TP-STA relationship. In summary, the baseline TP-STA relationship is likely developed to control the redundant motor system and might tell the feedback control mechanism not only how to correct visual errors but also how to alter physical movements.

2-A-14 - The human hippocampus supports implicit motor learning

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Details

Recent evidence suggests that the human hippocampus, traditionally associated with episodic memory, also plays a role in motor skill learning, particularly in learning sequences of finger movements (MSL). These findings have led to the hypothesis that the hippocampus may also be involved in encoding procedural motor memory. However, the initial reliance of MSL on explicit learning raises questions about the hippocampus's involvement in processing the declarative component of the task. Moreover, motor learning not only encompasses motor skill learning but also skill maintenance, often referred to as sensorimotor adaptation (SMA). Using diffusion tensor imaging (DTI), here we examined the broader participation of the hippocampus in procedural motor learning by tracking the temporal dynamics of hippocampal structural plasticity in the classic sensorimotor adaptation (SMA) paradigm, involving both explicit and implicit learning, and in a purely implicit version of this task. We found that, like MSL, training on both SMA tasks consistently engaged the left posterior hippocampus during the early stages of learning, with fast learners exhibiting more pronounced structural changes than their slower counterparts. Remarkably, the classic SMA paradigm induced transient hippocampal microstructural alterations, whereas the implicit version elicited changes that persisted overnight, underscoring the importance of the implicit component for lasting plasticity. Training on both SMA tasks also impacted on motor regions such as the cerebellum and the posterior parietal cortex involved in SMA acquisition. Notably, the temporal dynamics of structural changes in these areas closely paralleled those of the left hippocampus for each task, suggesting that motor and limbic regions operate in a coordinated manner as part of the same network during adaptation. Collectively, our findings provide compelling evidence supporting an active role of the hippocampus in procedural motor memory and argue for a unified function in memory encoding regardless of the explicit or implicit nature of the task.

2-A-15 - Short visual feedback latencies impair implicit sensorimotor learning

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Details

System response latencies are ubiquitous in human-computer interactions, from using a computer keyboard to sophisticated virtual reality systems. Even short (<100ms) latencies have been shown to markedly reduce motor performance in tasks from pointing and steering to operating surgical robotics. Such short latencies are also typical among experiment setups used to study the sensorimotor learning that underlies the acquisition of motor performance in the first place. Reported latencies range from 27 to 80ms, though values >100ms are not uncommon based on personal communications with colleagues. This raises the question of whether latency in these setups affects the very learning processes they try to measure. Previous work showed that latency specifically reduces implicit but not explicit learning. However, as it only examined latencies of ‰¥200ms, the effect of short latencies upon implicit learning remains unknown.

Evidence from neurophysiology suggests that plasticity in cerebellar Purkinje cells, considered to underlie implicit sensorimotor learning, can be disrupted by latencies as small as 20ms as it relies on coincident timing of climbing vs. parallel fiber input. Recent work found that different subpopulations of neurons in the vermis display a wide range of preferred timing latencies (0-150ms), but very tight tuning (<30ms) around each preferred latency (Suvrathan et al., 2016). Thus, if learning relies on neurons tuned to a single preferred latency, it will be impaired by latencies of even 30ms. If it instead can use neurons tuned to multiple latencies, it will be robust against short latencies up to 150ms.

Here we compared the learning of a 30 ° visuomotor rotation under a short 85ms visual feedback latency vs. the optimized latency of our setup (25ms), and a larger latency (300ms) as reference to previous work. Using aim reports, we dissected learning into implicit and explicit components. We observed a dramatic 50% increase in implicit learning when latency was decreased by only 60ms, from 85 to 25ms ($p=0.003$), and a 100% increase when latency was decreased from 300 to 25ms ($p<10^{-4}$). In contrast, explicit learning decreased as latency decreased ($p=0.003$), with changes in implicit vs. explicit learning countering each other so that total adaptation was nearly identical across latencies. We then examined the generalization of learning to different movement directions, observing a sensitivity to latency that mirrored our findings for learning.

The exquisite sensitivity to latencies as short as 85ms suggests that implicit sensorimotor adaptation relies on Purkinje cell populations narrowly tuned to a specific physiologic latency. Also, with similarly short latencies common across experiment setups, our finding may explain large across-study differences in the amount of implicit adaptation attained, highlighting that setup latencies need to be widely measured and reported.

2-A-16 - Assessing the stability of hamstring and quadricep corticomuscular coherence over time: a 3-month test-retest study

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Details

There is a growing interest in understanding the corticomuscular response to anterior cruciate ligament (ACL) injury and ACL reconstruction (ACLr). Recent evidence has indicated that impaired lower limb function following ACLr might be driven by dysfunctions to the functional communication between the sensorimotor cortex and lower limb muscles, as indexed by corticomuscular coherence (CMC). CMC quantifies the frequency-wise synchronisation of neural oscillations at the cortex (as indexed by electroencephalography; EEG) and muscle (as indexed by electromyography; EMG). CMC is observed at several frequencies, including alpha, beta and gamma, and is proposed to support effective neuromuscular control. Impaired quadricep CMC has been observed in athletes with a previous ACLr, which suggests a maladaptive mechanism that could further explain known deficits across a range of functional tasks, such as balance, force control and walking. However, no studies have longitudinally monitored changes in CMC across ACLr rehabilitation. Before this can be addressed, it is first important to establish the stability of CMC over time in healthy adults, and whether CMC is symmetrical across limbs given the potential utility of unaffected limbs as intra-subject controls for ACLr research. Therefore, the aim of this study is to longitudinally assess the lower-limb CMC test-retest reliability and inter-limb symmetry in healthy adults. Twenty-five healthy adults (18-35 years) will attend three identical lab sessions over a period of 3-months. Each session comprises of a treadmill walking task, a static unilateral and reactive bilateral balance task, and a unilateral isometric knee flexion/extension force control task. EEG and EMG of the Vastus Lateralis, Vastus Medialis, and Biceps Femoris short head will be measured for all tasks. Intra-class correlation, standard error of measure, coefficient of variation, limits of agreement, minimum detectible change, standard deviation of the difference and ANOVA will be used to determine reliability. Identifying the reliability, stability, and symmetry of CMC measures over several time points will provide key insights into protocol design, clinical application, data interpretation and more confidence in determining the effectiveness of intervention-variable interactions. This will allow future lower limb literature, including ACLr, to design longitudinal studies to investigate corticomuscular interactions with time and recovery markers.

2-A-17 - Predicting sequences of upcoming sensorimotor events after a brachial plexus injury

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Details

Predicting upcoming sensorimotor (SM) events requires an accurate and constantly updated representation of the body and the environment. We employed an action observation and electroencephalogram (EEG) paradigm searching for EEG signatures in anticipation of SM events in controls (CG) and upper-trunk brachial plexus injury (BPI) patients (Rangel et al., 2021). Participants watched a series of video clips showing an actor's hand and a colored ball in an egocentric perspective. Cluster analysis from EEG signals recorded at electrodes placed bilaterally over the SM cortex in CG revealed distinct neural signatures for predicting an upcoming hand movement vs. the occurrence of a tactile event in the hand. In BPI patients, however, while a specific signature of the upcoming hand movement was detected at the sensorimotor cortex contralateral to the affected hand, the lack of difference between ball movement and no movement conditions suggested that the ability to predict upcoming tactile events was blurred. These results highlighted the role of the SM cortex in creating estimates of upcoming events in the arm/hand and indicated that these signatures were compromised following a BPI. To test whether the effects of these altered BPI-induced prediction signatures manifested at a behavioral level, a videogame called the Goalkeeper Game (https://game.numec.prp.usp.br/) was developed. Playing the role of a goalkeeper, participants were asked to predict, step by step, the successive directions (left, center or right) to where a penalty kicker would send the ball. An animation feedback then showed to which direction the ball was effectively sent. A sequence of a thousand kicks was driven by a stochastic chain with memory of variable length: at each step a new symbol is chosen by a probabilistic function which depends on a suffix of the past, henceforth called context, whose length depends on the past itself (see HernÃ¡ndez et al., 2023). We first investigated in a CG whether reaction times (RTs) varied as a function of the contexts and of their associated transition probabilities. Results showed the distribution of RTs' associated with a stochastic sequence of events depended both on contexts and on the results of previous predictions (Passos et al., 2023). Results in BPI patients indicated that more past elements were needed to estimate an upcoming event after the non-deterministic event occurring to the left direction, corresponding to the BPI's lesioned side. Finally, contrary to the CG, no increase in RTs after the occurrence of prediction errors associated with the stochastic stimuli was identified in BPI, indicating a difficulty in updating response strategies. Taken together, these results suggest that SM prediction draws on distinct brain networks after a BPI. This work is part of the FAPESP NeuroMat activities (grants #2013/07699-0, 2022/00582-9 and 2022/00699-3) and CNPq grant #310397/2021-9.

2-A-18 - Movement smoothness decreases with increasing loads during squats and is higher in the eccentric than concentric phase: a novel framework on inter-joint movement fusion

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Details

Background: Movement fusion (MF) describes the blending of sub-movements into a single observable movement and allows for insights into movement coordination. To date, MF has been measured through velocity profiles of 2D hand trajectories during sequential reaching movements, where sub-movements were identified by velocity bumps (local maxima). As the local minima (via-points) between bumps reduce, sub-movements blend and MF increase, which studies observed after learning (Friedmann et al. 2019) and in rehabilitation processes (Rohrer et al. 2002). However, this approach only quantifies smoothness at the movement endpoint rather than in joint angular motion. Addressing this gap, we present a framework to investigate MF between joints. Exploring coordination's adaptation to increasing loads during squats is uncharted but vital for understanding body's adaptation responses and enhance powerlifting performance.

Methods: 31 elite powerlifters performed squats at 70%, 75%, 80%, 85%, and 90% of their 1-repetition-maximum. 3D-trajectories of 30 lower limb markers were recorded (Vicon Motion System, Oxford, UK) and used to perform musculoskeletal simulations with OpenSim (Delp et al., 2007). The 'Catelli' model (Catelli et al., 2019) was scaled to participants' anthropometry followed by inverse kinematics to calculate joint angles. Sagittal plane hip, knee and ankle joint angles were low-pass filtered, time normalized for eccentric (EC) and concentric (CO) phases separately and amplitude normalized to the participants' maximum angle, to allow comparisons among joints with different range-of-motions. Velocity was determined as the magnitude of the first derivative of the processed angles. After averaging velocity profiles for each pair of angles, the fusion index for two adjacent sub-movements was calculated by subtracting the via-point from the mean peaks, divided by the mean peaks (Sporn et al.

2022). Since more than two sub-movements could occur, MF was quantified as the sum of all fusion indices (lower value = higher fusion). A three-way repeated measures ANOVA assessed the effect of limb sides, phases (EC, CO), and load (70% - 90%) for each joint combination (ANKLE/KNEE, ANKLE/HIP, KNEE/HIP).

Results: Only KNEE/HIP showed a significant difference between limb sides. MF was higher in EC than in CO for all joint combinations and with low loads. Post-hoc analyses revealed that EC MF was only higher at 70% vs. 90%, while CO MF was higher at 70% vs. 80% - 90%, 75% vs. 85% - 90%, and 85% vs. 90%.

Discussion: Results showed a higher smoothness in EC compared to CO conditions. A smaller decrease in smoothness was found with increasing loads in EC compared to CO movements. These suggest a more efficient inter-muscle coordination and a higher ability of the muscles to withstand loads in EC compared to CO movements. Moreover, our proposed framework holds potential for measuring skill and coordination in various movements.

2-A-19 - A gain field adaptation model explains distributive learning across movement and corollary discharge fields

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Details

Existing computational models on motor learning exhibit a zero-dimensional perspective on the spatial map of possible movement goals. In these models, learning alters the movement vector associated with the specific target position for which a previous movement produced an error. Yet, it has been shown that learning does not occur exclusively at the adapted target position but transfers to other positions in the surrounding. For saccadic eye movements, learning follows an adaptation field, i.e. it transfers to saccades as a function of their target distance from the adapted target position. These saccade changes are accompanied by changes in pre- and trans-saccadic visual target localization that show an adaptation field as well. Here we present a gain field adaptation model in which visual and motor representations rely on a population-based response distribution across the two-dimensional visual field. In the model, learning in response to motor errors acts locally on (1) a visual gain field that scales the target on the visual map, (2) a motor gain field, i.e. an inverse model, that maps the visual goal representation onto a motor command, and (3) a CD gain field, i.e. a forward dynamics model, that maps a copy of the motor command (the "corollary discharge" signal) onto an internal representation of saccade size. We fit the model to saccade amplitudes and pre- and trans-saccadic visual localizations for different target positions before, during and after adaptation to a peri-saccadic inward target step. We show that learning and its transfer to other spatial positions can be explained by adaptation of visual, motor and CD gain field maps with a local and distributive pattern around the adapted target position. Hence, also the internal representation of saccade size has a response field that is altered during saccadic motor learning. Moreover, our results reveal that the distribution of learning differs between gains. The motor gain field shows a broad learning distribution while visual and CD learning distributions are more narrow. If the internal saccade representation does not reflect the ongoing motor changes, the CD learning distribution should be the inverse of the motor learning distribution. From the asymmetry between the two learning distributions we conclude that the internal saccade representation monitors part of the actual saccade changes during learning.

2-A-20 - Effects of direct experience with unfamiliar tools on white matter pathways as evidenced by connectometry analysis

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Details

In our previous study, we demonstrated behavioral and brain function changes in 20 right-handed adults learning to use chopsticks over eight sessions. Here, we further explore this by examining associated white-matter changes using diffusion MRI. Initially, participants underwent Diffusion Tensor Imaging (DTI) before commencing a four-week training program (two sessions per week, each comprising ten 60-second trials). The task involved using chopsticks to transfer marbles into a container, aiming for the maximum number of successful marble drops within the time limit. Post-training, a second DTI scan was conducted.

Behavioral improvement was evident, with a significant increase in the number of successful marble drops per minute (MDPM) from the first to the last session (13.99 vs. 18.95, $p < .001$). We used diffusion MRI connectometry to correlate these behavioral enhancements with white-matter changes. Our focus was on the left hemisphere's Areas PF and PFt (subregions of the supramarginal gyrus), identified as functionally significant in prior studies. Utilizing a whole-brain seed region and topology-informed pruning, we observed positive correlations between MDPM increases and changes in the left superior longitudinal fasciculus (SLF-I & SLF-II) and the left parietal aslant tract.

These findings, combined with our earlier reported results, offer deeper insights into the neuroplastic adaptations in the human brain induced by learning new motor skills, specifically through tool use.

2-A-21 - Mechanisms underlying acquisition and durability of newly learned speech-acoustical mapping

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Details

Adaptation to altered auditory feedback is used to characterize speech motor learning. Recent findings uncovered behavioral properties distinguishing adaptation in speech motor learning from that in hand-reaching tasks. Yet, mechanisms underlying acquisition and durability of newly learned speech-acoustical maps remains unclear. We first asked if these maps were durable beyond the learning session using a formant frequency perturbation task as an experimental model. We recruited neurotypical participants (n = 62, 18-40 years of age) to read aloud words (bep, dep, or gep) displayed on a computer monitor, one at a time in a pseudorandomized sequence. During visit-1, participants performed baseline trials with no perturbation, followed by learning trials with first formant frequency (F1) gradually increased to 30% and played back to participants in real-time through headphones. Participants returned either 8 or 24 hours later (visit-2) and completed relearning trials with F1 perturbation. As expected, participants in both conditions showed similar level of F1 adaptation during visit-1. Interestingly, an equivalent F1 retention was observed in 8 and 24-hour conditions, contrary to the expectation of sleep-enhanced consolidation of newly acquired memories. Next, we asked whether durability of the speech-acoustical maps was robust to the introduction of acoustical perturbation in an abrupt versus gradual manner. Additional participants underwent a similar number of trials during visit-1 as described above, but with an abrupt F1 perturbation following baseline trials, followed by relearning session either 8 or 24 hours later. We observed equivalent learning and retention in abrupt and gradual conditions, suggesting insensitivity of speech-acoustical maps to the manner of introduction of perturbation. Moreover, despite no experimental changes to the second formant (F2), participants showed changes in F2 during learning in all conditions above. Consequently, we asked if F2 changes signified functional relevance to F1 retention. Our analysis indicated that only the amount of adaptation to F1, but not F2 changes, accounted for variations in F1 retention, suggesting that F2 changes only co-occurred without any functional relevance for F1 retention. Finally, we asked whether acquisition of speech-acoustical maps via adaptation results into generation of novel versus already learned acoustics in the vowel space. Additional participants underwent their vowel space mapping for /Ã¦/, /Æ/, and /I/, followed by a vowel perturbation identical to previous experiment. Results to date indicate that speech motor adaptation results into generation of new acoustics in an unexplored region in the vowel space in the direction of compensatory speech movements. Taken together, our findings extend critical mechanistic insight into acquisition and durability of newly learned speech-acoustical maps to guide modeling of speech motor learning and consolidation.

B – Control of Eye & Head Movement

2-B-22 - Oculomotor behavior during unimanual vs. bimanual tasks: Comparison between typically-developing children vs. children with cerebral palsy

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Details

Children having cerebral palsy (CP) exhibit motor impairments that can vary according to the task performed (unimanual and bimanual tasks). While typically-developing (TD) children tend to rely more on proprioceptive information when using their non-dominant arm, it has been suggested that children with CP tend to visually monitor their more affected arm. The aim of this study was to compare the oculomotor behavior of TD and CP children during rapid unimanual and bimanual visuomotor tasks, and to assess its relationship with their motor behavior. **Methodology:** Two groups of children (CP [n=12]= 11.4 years old; 58% right-handed; 42% females; TD [n=22]= 10.7 years; 86% right-handed; 36% females) performed an Object Hit task that required them to hit virtual balls moving towards them with virtual paddles attached to each hand in a Kinarm Exoskeleton Lab. The task was performed using both hands (bimanual) or only one hand at a time (unimanual). An integrated Eyelink 1000 system recorded their eye movements. Motor behavior was characterized by the miss bias, i.e., the bias in the number of misses toward one side of the workspace (in X, a positive value representing more missed balls on the dominant / less affected arm side). For the oculomotor behavior, the center-of-mass of gaze position was calculated (i.e., its mean position in X and Y axes; in X, a positive value indicates a bias toward the dominant / less affected arm side; in Y, a larger value indicates a tendency to look further away from the body, something that has been reported to occur during practice-related improvement in performance in a similar task). The variability of gaze position (i.e., range of the 95% confidence interval in X and Y) was also calculated. Mann Whitney comparisons and RankFD Anova Type statistics were performed to compare oculomotor behavior across groups (CP or TD; both tasks) and arms (dominant/less affected arm vs. non dominant /more affected arm; unilateral tasks). Spearman correlation coefficients were computed to assess the relationship between gaze behavior (position of the center-of-mass in X) and motor behavior (miss bias). **Results:** No difference in the center-of-mass was found across groups or limbs in either task. However, the variability of gaze position was larger in the X direction for the CP group (p=0.001), but for the unimanual tasks only. A significant relationship was observed between the miss bias and the center-of-mass in X only for the CP group during the bimanual task (r_s=0.71, p=0.01). **Conclusion:** In contrast with what has been proposed in the literature, our results do not support the view that children with CP visually monitor their affected side more closely on average. Nevertheless, a relationship with motor behavior was observed only in CP children, suggesting that nonoptimal gaze behavior might have more impact on the motor behavior in this group, potentially because of the presence of upper limb proprioception deficits.

2-B-23 - Probing correlates of saccadic suppression in the primate superior colliculus and primary visual cortex

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Details

Saccade generation is often jumpstarted by visual processing. However, every time a saccade is made, there are inevitable sensory consequences, which can have a direct impact on the timing of subsequent motor behaviors (Chen & Hafed, 2017). Here, we focused on one of these sensory consequences: that sensitivity to new incoming visual signals is strongly impaired around the time of saccades. We recently linked the origins of such a phenomenon, called perceptual saccadic suppression, to the rapid visual flow that appears on the retina during saccadic eye movements (Idrees et al. 2020, Idrees et al. 2022). Specifically, we found that the visual appearance of the background (e.g. low or high spatial frequency content) that is translated on the retina by saccades can affect both the strength and duration of saccadic suppression, and that this effect already starts in the retina (suggesting a substantial visual-only contribution to the phenomenon). Moreover, we could additionally show that the presence of motor signals shortens the suppression duration in comparison to the visual flow alone. Here, in order to better understand the link between retinal image processing and the final behavioral perceptual phenomenon, we investigated how visual flows created by rapid image shifts affect the superior colliculus (SC) and primary visual cortex (V1), and how these structures might differentiate between whether the retinal visual flows were exogenous or caused by real saccadic eyeball rotations. We recorded SC and V1 neural activity from two macaque monkeys. The monkeys fixated while we presented a rapid image displacement of different textured backgrounds (similar to Idrees et al., 2020). At different times after texture displacement, we presented a brief probe flash within the visual receptive fields (RF’s) of recorded neurons. The monkeys also performed the same experiment with real horizontal saccades over a static texture (SC RF's were away from the saccade endpoint, allowing us to place probe flashes within these RF's and only assess visual responses, dissociated from saccade motor bursts). Both brain areas responded to retinal texture displacements (whether shifted by saccades or externally) and probe flashes. Moreover, probe flash responses were suppressed in both areas, depending on the presentation time relative to image shifts, consistent with (Idrees et al., 2020). However, the two areas exhibited important differences: V1 probe flash responses were similar whether texture displacements were saccade-induced or external; on the other hand, SC responses were much more suppressed by external texture displacements than by saccade-induced image shifts. These results suggest that SC distinguishes between self-induced and external visual stimulation significantly better than V1, and they highlight the importance of studying the multiple sensory-motor pathways that are typically used to guide, and account for, active motor behaviors.

2-B-24 - Vestibular reflexes drive neck muscles to ensure head stabilizations during locomotion

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Details

Vestibulospinal reflexes play a vital role in locomotion by ensuring the maintenance of balance and head stability. The vestibulo-collic reflex is thought to activate neck muscles to generate compensatory head stabilization during walking. However, to date, the actual extent of the contribution of the vestibulo-collic reflex to head stabilization during locomotion is unknown. This is because prior studies only measured head motion and as a result could not dissociate the contribution of biomechanics from that of vestibular pathways.

Accordingly, here we performed a direct assessment of the contribution of vestibular pathways to head stability during locomotion. We measured motor unit activity in splenius capitis and sternocleidomastoid through intramuscular EMG recordings in normal monkeys and monkeys with complete bilateral vestibular loss. A head-mounted 6D motion sensor and marker-based tracking systems were utilized to simultaneously measure head and trunk position, while high-speed cameras were used to determine limb motion via DeepLabCut. Motor unit activity and head stabilization were measured while monkeys completed overground and treadmill walking at various speeds. In addition, we tested whether vestibular-evoked neck muscle responses were enhanced by increased autonomic arousal, quantified via pupil size.

Normal monkeys demonstrated a unique neck muscle strategy for stabilizing the head during overground walking that differed from that used for treadmill walking at the same speed. Autonomic arousal enhanced this response without changing its structure. Furthermore, despite modest changes in the structure of muscle activation with speed, translation within feature space resulted in minimal tangling, indicating noise robustness. In contrast, after bilateral vestibular loss, monkeys exhibited significant head oscillation compared to normal animals, and head-on-body movement failed to adequately compensate for body movements. Neck muscle activity showed minimal modulation at all speeds, resulting in limited phase-locked activity. In addition, analysis of feature space revealed that bilateral vestibular loss, monkeys failed to maintain a consistent strategy as a function of gait speed, resulting in increased tangling and reduced noise robustness without vestibular input.

Taken together, our findings demonstrate that the vestibular system plays an essential role in organizing neck motor activity to produce compensatory head movement during locomotion to stabilize the head in space. This study underscores a flexible and dynamic strategy of neck muscle activation patterns influenced by various descending and proprioceptive signals, particularly those from the vestibular system.

C – Disorder of Motor Control

2-C-25 - Age-specific distortion of neocortical motor outputs in 5XFAD mice

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Details

Alzheimer's Disease (AD) and related neurodegenerative dementias (AD/NDs) produce frailty of health and create a massive economic burden worldwide. Sensory and motor deficits have been implicated in AD/NDs underscoring a need to understand their mechanisms to support discovery of novel diagnostic and interventional treatments for clinical populations affected by AD/NDs. This study tested neocortical motor outputs in 5XFAD mice, as an experimental model of AD/NDs, in comparison to wild-type controls (WT Controls). Testing was undertaken at 6 and 12 months of age using long-duration intracortical microstimulation (LD-ICMS) using a similar approach to previous studies including from our laboratory. 5XFAD and WT Control mice produce discrete and consistent neocortical motor outputs that present as either SIMPLE (single joint) or COMPLEX (multiple joint) movements. In mice tested here, we observe COMPLEX neocortical motor outputs including: ADVANCE, RETRACT, ELEVATE and DIG and SIMPLE neocortical motor outputs including: DIGIT, WRIST, ELBOW and SHOULDER as previously described. At 6 months of age 5XFAD mice exhibit an increase in overall SIMPLE neocortical motor output relative to WT Controls suggesting a unique change in neocortical motor output that may represent compensation, neural damage or other. At 12 months of age 5XFAD mice exhibit a decrease in SIMPLE and COMPLEX neocortical motor outputs suggesting a deterioration in both forms of neocortical motor output. Further experiments aim to test the cellular, temporal and mechanistic basis for these phenomenon including the potential implementation of this knowledge into clinical practice. The long-term goal of this research is to fully implement somatic motor diagnostic tools as additional identifiers and diagnostic tools of those at risk of developing AD/NDs to enhance the timing and options for long term clinical care.

2-C-26 - Brain-computer interface mediated contingent functional electrical stimulation of stroke impaired upper extremity enhances recovery of motor function in the brain and body

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Details

Noninvasive electroencephalographic based brain-computer interfaces (BCI) can be paired with adjuvant therapeutic techniques such as virtual reality, orthotics, muscle stimulators or robotics to enhance recovery of motor output following stroke. Of the various BCI adjuvant designs BCI-mediated functional electrical stimulation (FES) designs may be clinically viable for delivering meaningful improvement to motor output in stroke survivors with motor impairment. BCI-FES designs cause upper extremity motor task-related brain signal (4-28 Hz) change and functional connectivity change localizing to primary and supplementary motor areas; these changes may be associated with recovery of function, but it is not clear if they are superior to visual feedback BCIs. This sub-analysis of an ongoing clinical trial (NCT02098265) seeks to determine if movement-related brain signals are enhanced when using a BCI-mediated FES unit (FES ON) rather than BCI without FES (FES OFF) and if those changes correlate to enhanced motor recovery in both brain motor areas and motor output. 11 participants with right lesions and resulting left hand motor impairments participated in up to 30 hours of intervention. Time-frequency estimates between -1s to 3s of a cued repeated grasping task were recorded from the scalp over the primary motor cortex (electrode C4) and supplementary motor areas (electrode FC2). Motor function (ARAT) and capacity (Handgrip Strength) were measured at baseline and completion of BCI intervention and compared to measure change over time. Group mean changes were compared and correlation assessed to determine whether these interactions were significant. Significant correlations between change in time-frequency estimates during grasping were recorded at scalp electrodes over motor brain areas and changes in motor function and capacity were found to be stronger and appear earlier during the cued grasping task in the FES ON condition (masked at $p<0.05$, uncorrected for multiple comparisons). The earlier and stronger association of event-related desynchronization in motor areas and increased motor output suggests that FES ON has superior therapeutic effect to FES OFF. This analysis demonstrates that BCI-mediated FES is superior to visual feedback BCI; results in greater task-related brain signal changes over time that also correlate with improvements in motor function and capacity. BCI-mediated motor therapies are enhanced in the brain and the body when they include the facilitating adjuvant FES. The inclusion of afferent signaling from the facilitated muscle activation provides proprioceptive afferents as well as strengthening of distal muscle control. This contingent pairing of user-driven intent-to-move brain signals and FES-enhanced muscle activation leads to greater volitional control of contractile force in the stroke-impaired hand thereby increasing therapeutic outcomes for patients suffering motor impairment as a result of stroke.

2-C-27 - Investigating the propagation of beta bursts across the corticospinal tract in Parkinson's disease

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Details

Increased cortical and subcortical beta band activity (12-30 Hz) and beta bursts are robustly reported neural activity characteristics of Parkinson's disease (PD). Multiple studies suggest their potential as neurophysiological measures for assessing therapeutic efficacy, particularly for closed-loop deep brain stimulation (DBS). While ongoing clinical trials of closed-loop DBS utilise beta power as a physiomarker to adjust stimulation, uncertainties persist regarding how beta power and characteristics of beta bursts respond to stimulation and different symptomatic scenarios. To address these uncertainties, high-density surface electromyography (HDsEMG) emerges as a promising non-invasive neural signal to explore beta activity and bursts' underlying mechanisms along the corticospinal tract.

HDsEMG records muscle activity with high spatial and temporal resolution, enabling a comprehensive electrophysiological assessment. Recent research shows that beta activity occurs in bursting patterns at both cortical and motor unit levels during isometric contractions of the tibialis anterior muscle (Bracklein et al. 2022 JNeurosci). This demonstrates that peripherally measured beta bursts result from cortical projections. Expanding on this, our study replicates these findings using smaller upper limb muscles, and showcases its sensitivity to DBS settings.

We conducted recordings in 15 healthy participants to track beta burst characteristics (e.g. duration, amplitude, rate) at the peripheral and cortical levels. Motor cortex activity was recorded using a 19-electrode electroencephalography (EEG) headset, while forearm muscle activity was monitored using 256-electrode HDsEMG, targeting the extensor carpi radialis (ECR) and ulnaris (ECU). Torque measurements were recorded during a trapezoidal force tracking task during isometric wrist extension, involving various percentages (10%, 20%, and 30%) of maximum voluntary contraction (MVC).

Our analysis involved decomposing a substantial number of motor units for each muscle (up to 21). Exploration into variations in beta burst features showed correlations between HDsEMG and EEG beta bursts, suggesting a degree of coherence between beta bursts occurring within the motor cortex and those in the peripheral regions.

We then ran the paradigm on PD patients who receive DBS therapy, adjusting the amplitude of their DBS during the experiment, to examine HDsEMG signal sensitivity to changes induced by alterations in DBS parameters. Our preliminary results show high sensitivity of the peripheral beta burst features to the changes in the DBS settings.

In summary, we demonstrated the ability to track beta bursts across the corticospinal tract, highlighting its generalisability and sensitivity to DBS settings. This integrated approach holds promise for understanding dynamic changes in the brain during neuromodulation interventions and symptoms fluctuations.

2-C-28 - Deficits in motor cortex function during speech production in childhood apraxia of speech

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Details

Childhood Apraxia of Speech (CAS) is conceived as an impairment within the central motor system's ability to program multiple speech movements, resulting in inaccurate transitions between and relative timing across speech sounds; however, the extant neuroimaging evidence base is contradictory and inconclusive, and the neurophysiological origins of these motor planning problems remain highly underspecified. In this magnetoencephalography study we measured brain activity from typically developing children (N = 20) and children with CAS (N=7) during performance of a reiterated non-word speech task. All children were assessed with a comprehensive clinical test battery for hearing, speech, expressive and receptive language, and oral-motor development. Neuroimaging results for typically developing children showed robust speech-related beta band responses in highly focal and bilateral regions of peri-Rolandic sensorimotor cortex. In contrast, all individuals in the CAS group displayed an absence of the speech-related beta band response and showed significant speech-related responses only in the theta band and only in the right hemisphere. These results provide a novel neurophysiological marker of typical and atypical expressive language development and support an emerging neuroscientific consensus which assigns a central role in motor speech coordination to the motor cortices of the precentral gyrus.

2-C-29 - Characterizing motor unit activity during a standing balance task before and after one week of subacute stroke rehabilitation

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Details

Following stroke, people exhibit impaired motor control. High-density EMG (HD-EMG) and decomposition reveal spinal motor neuron activity, providing insight into motor impairments. Investigations of motor unit (MU) firing in chronic stroke found reduced discharge rates (DRs) in affected compared to unaffected limbs, with varying results on coefficient of variation (CoV) of DRs. However, MU activity during subacute rehabilitation has yet to be investigated. Here we report a case study on 3 patients post-stroke during inpatient therapy. Before and after one week of therapy, subjects performed the Berg Balance Scale (BBS) and 6 minute walk test (6MWT). Then, HD-EMG was recorded on the soleus of both legs while standing feet apart for 30s. Average DR and CoV DR were computed and normalized by dividing affected by unaffected limb to assess asymmetry. All subjects improved greater than minimal clinically important difference (MCID) for BBS, while Sub2 and 3 had increases greater than MCID for 6MWT. Sub1 scored higher than Sub2 and 3 on both assessments. On average, 13.9 ±4.7 MUs were decomposed, yielding at least 7 MUs across visit, subject, and side. As in previous studies, average DR was less on affected than unaffected limbs for all subjects, regardless of visit (Aff=6.2 ±.5pps, Un=7.9 ±1.2pps). Affected DRs did not differ across subjects, but unaffected DRs were greater in Sub2 and 3 (Sub2,3: V1=9.4 ±2.5pps, V2=8.9 ±2.3pps) than Sub1 (V1=6.8 ±1.0pps, V2=6.6 ±1.4pps). Furthermore, normalized DRs demonstrate greater limb symmetry for Sub1 (V1=.94, V2=.91) compared to Sub2 and 3 (Sub2: V1=.73, V2=.71; Sub3: V1=.79, V2=.68) and also reveal a small decrease across visits, increasing asymmetry. Also as in previous results, regardless of visit, CoV DR was less on affected compared to unaffected limbs for Sub2 and 3 (Sub2,3: Aff=.20 ±.05, Un=.28 ±.09) while Sub1 (Aff=.23 ±.06, Un=.17 ±.06) had greater CoV DR on the unaffected limb. Sub1 also had lower CoV DR on the unaffected limb compared to Sub2 and 3. Normalized CoV DRs revealed an increase for Sub1 (V1=1.24, V2=1.50) and decrease for Sub2 and 3 across visits (Sub2: V1=.80, V2=.64; Sub3: V1=.90, V2=.60), all increasing asymmetry but in opposite directions. While previous findings in chronic stroke were replicated in subacute stroke, a trend of increasing asymmetry was found for all subjects, potentially suggesting different compensatory strategies for higher (Sub1) and lower functioning patients (Sub2, 3). Lower functioning patients may rely more heavily on the unaffected limb to account for loss of balance than higher functioning patients, resulting in the increasing/greater DR and CoV DR. These preliminary results suggest MU activity is sensitive to changes in motor control and has potential for clinical use in monitoring and prognosis. Future tracking of MU activity over longer periods of recovery and with a larger, more diverse population may confirm patient clustering and elucidate recovery trajectories.

2-C-30 - Force-dependent dissimilarity of finger patterns in sub-acute stroke as revealed by fPCA

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Details

Humans possess the ability to make selective use of their fingers. This ability is impaired following a stroke. Studies showed that people with hemiparesis due to stroke affecting M1 or the corticospinal tract, exhibit greater difficulty opening their paretic hand than closing it. Observation is attributed to the loss of finger individuation ability, referred to as enslavement, (i.e., the unwanted coactivation of non-intended fingers in individuated finger movements). Previous studies were based on assessments of individuation ability by examining the total sum of enslavements of the non-instructed digits. Although this individuation index is immune to the weakness of the fingers, it lacks the capacity to capture full range of finger control. It overlooks the similarity of force patterns in stroke relative to the healthy population.
We sought to characterize the full capacity of finger control in acute and sub-acute poststroke compared to aged-matched healthy participants. We recruited a cohort of 45 hemiparetic stroke patients with first-event unilateral ischemic (11 females; age 60.9 ±10.1 years; time after onset 41.4 ±16.6 days) and 11 healthy age-matched controls (6 females; age 56.3 ±10.0 years). Participants performed a robotic-based individuation task with their paretic hand. In each trial, participants were instructed to move a single digit in one direction toward a force target. Participants repeated the task separately for each direction (flexion and extension) and in four different force levels (20%, 40%, 60% and 80% of maximal voluntary contraction force). To assess the quality of finger control during flexion and extension finger movements, we used functional principal component analysis (fPCA). This data-driven analysis allows force patterns of each digit to be evaluated without prior assumptions about which pattern features ought to be emphasized. We used fPCA to estimate the Mahalanobis distance (MD) of patients' finger force patterns from the reference healthy population. MD is large for impaired patterns (i.e., it is dissimilar to the healthy controls) and small when the force pattern is similar to healthy controls. Results show that finger force patterns in stroke patients present distinctly different shapes across direction and force levels. Repeated-measure 2-way ANOVA reveals significant direction effect ($F_{1,44}$=4.72, p=0.035), significant force level effect ($F_{3,132}$=3.6, p=0.015) and significant direction X force interaction ($F_{3,132}$ =3.25, p=0.024). Post-hoc analysis revealed that the main differences over force directions in MD measure were driven by differences at low force (t_{45}=3.96, p=0.001) but not at high force (t_{45} =0.27, p=0.78). Data suggests that the quality of finger control in stroke patients distinctly differs from the healthy population only at low forces. Novel interventions for finger control, focused on dexterous movements poststroke, are required to exploit the force level for motor control.

2-C-31 - Ultrasound imaging can track joint kinematics in the presence of functional electrical stimulation

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Details

Functional electrical stimulation (FES) has long been used to restore motor function to individuals with paralysis, however there is increasing focus on the use of FES in individuals with neuromotor disorders such as cerebral palsy both to assist movement and facilitate its rehabilitation. But, achieving accurate and reliable limb movement with open-loop FES is challenging. Closed-loop control that adjusts stimulation parameters in real-time has the potential to improve FES-assisted movement. Noninvasive systems typically utilize surface electromyography and/or limb kinematics measurements for feedback control. However, sEMG systems have limitations such as low signal-to-noise ratio, cross-talk between sensors, random amplitude fluctuations, and interference from the FES, while measured kinematics struggle to differentiate between volitional and spastic movements. Hence, the ability to noninvasively capture more information regarding movement intent to provide effective closed-loop control of stimulation parameters and improve the quality of movement co-driven by surface FES is an unmet need. Recent work has shown the utility of ultrasound imaging of musculature as a human machine interface during movement, a technique termed sonomyography. This method may have an advantage over sEMG because it captures mechanical deformation rather than electrical activation of the muscle, thereby reducing the interference due to FES. In this work, we use a simple image similarity metric to compute the muscle deformation using ultrasound imaging, and investigate if it can be used to track joint kinematics in the presence and absence of FES. We recruited one healthy participant to evaluate our proposed method. The participant performed flexion/extension movements of the wrist, ankle, and knee with and without FES. We recorded kinematics using motion capture, muscle activity using sEMG, and muscle contraction patterns using ultrasound imaging. We time synchronized the ultrasound signals with the motion capture signals by identifying movement onset in each signal. We found that the signal extracted from ultrasound imaging tracked joint kinematics with and without FES in the healthy participant with a mean error of 3.9 ±18.14% for volitional movement and 1.7 ±20.69% during FES, averaged across all the joints investigated. We also found that the peak velocity of movements performed under FES were significantly higher than movements performed volitionally for all joints, resulting in a different characteristic movement trajectory, which resembles the minimum jerk trajectory without FES. These results demonstrate the ability of ultrasound to track limb movement in the presence of FES, and suggest it is a viable modality for closed loop control of stimulation parameters to control FES-assisted movement. This study was meant to describe our methods and approach, which we eventually aim to expand to various clinical populations.

2-C-32 - Neuronal signatures of pallidal activity in Parkinson's disease and dystonia

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Details

The classical basal ganglia model predicts increased or decreased activity of the basal ganglia output structure (GPi) in Parkinson's disease (PD) and dystonia (Dys) respectively. It is known that in both cases, deep brain stimulation (DBS) of this structure has a positive clinical effect. This paradox remains unsolved and initiates a new layer of research of the neuronal processes in the basal ganglia.

We compared the activity of the globus pallidus (GPi and GPe) in a group of patients with PD and dystonia: from single neurons to neuronal populations. Microelectrode recording of single unit activity was performed during 30 neurosurgical DBS procedures. Multichannel recording of local field potentials (LFP) of the globus pallidus was obtained in the postoperative period from temporarily externalized electrodes in 8 patients. We separated neurons into tonic, burst, and pause patterns using hierarchical clusterization and analized the distributions of patterns and their main characteristics: the average firing rate, the coefficient of variation of interspike intervals, the asymmetry index, burst and pause indices, the percentage of bursting discharges, oscillation scores, and other parameters. LFPs were analized by spectral analysis using FOOOF approach.

We found that the firing rate of GPi cells did not differ significantly in the studied groups, while more tonic neuronal activity with reduced theta-alpha oscillations was found in the PD group. We showed a significant increase in the percentage of tonic cells and a decrease in the percentage of pause neurons in PD. This group was also characterized by a significantly higher firing rate of tonic cells and a reduced firing rate of burst cells. Multifactor analysis showed the importance of non-linear characteristics of neuronal activity for classifying patients by type of disease. Neuronal activity of GPe did not significantly differ between studied groups of patients. Spectral analysis of LFP showed a significant increase of theta activity and a decrease of alpha, low- and highbeta activity in both GPi and GPe in the group of patients with dystonia compared to PD. The most important parameters for classifying the studied patients were the highbeta oscillations and the slope of the aperiodic component.

Our results showed heterogeneity of the neuronal organization of the globus pallidus, which is characterized by different patterns. Multidirectional changes in the activity of different types of neurons, differences in the distribution of activity patterns, and the importance of non-linear characteristics are consistent with both the firing rate and pattern basal ganglia models. We suggest that to predict the area of stimulation it is necessary to take into account a combination of linear and non-linear factors of single unit activity, as well as periodic and aperiodic components of LFP.

The study was funded by the Russian Science Foundation (grant 23-15-00487).

2-C-33 - Explainable deep learning for localizing cortical physiomarkers from deep brain stimulation

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Details

Deep Brain Stimulation (DBS) is a common procedure in people with severe movement disorders ““ such as Parkinson’s Disease (PD), Essential Tremor (ET) and Dystonic Tremor (DT) ““ once symptoms are no longer manageable with medications. DBS consists in stimulating specific areas of the patient’s brain through an implanted electrode. However, stimulation approaches are still rudimentary. Reliable physiomarkers for discriminating neural response from the stimulation are needed to enable a closed-loop adaptive DBS system for personalised therapy.

Here, a deep learning model for agnostic physiomarker search in EEG recordings is presented. Our Convolutional Neural Network (CNN) is based on the EEGNet structure, and our proof-of-concept work of classifying EEG activity during DBS. Our Siamese CNN was created for the EEG-based distinction of different DBS settings (same vs different) within a patient. In addition, an explainability method based on ablation studies is proposed for identifying the spectral location of the features utilized by the model, which can be used as physiomarkers. All the work presented here was done on a mixed cohort of DT and PD patients performing their monopolar review. Due to the nature of the dataset, analysis of different DBS settings was only done for the change in amplitude and contact of both electrodes.

We found that our models could learn to discriminate between DBS settings regardless of the patient’s condition. Our models achieved better accuracies when discriminating between contact point rather than stimulation amplitude, suggesting a more pronounced brain response in the former case. Furthermore, we obtained better results when only one hemisphere’s electrode was active at a time. This can be simply justified by the fact that, when stimulating with both electrodes, the combined effect of both leads is perceived and therefore changing parameters in a single lead will have a smaller impact in the EEG response, resulting in a lower classification performance. The theta band extraction was attributed to the patients’ tremor and the NBG extraction was identified as a potential direct physiomarker for DBS response in EEG data The channel-wise ablation studies revealed that, as expected, different channels were used for the classification task for the different DBS leads (left vs right), and overall, it showed that accurate classification of the stimulation can be achieved with a single EEG channel, providing it’s the right one.

Overall, we have here provided a proof-of-concept of EEG-based DBS setting discrimination and have reaffirmed the recent shift in research from beta band (13-30Hz) physiomarkers to physiomarkers in the NBG range. Our future works will focus on further improving the explainability of the model and on expanding these methods for inter-patient classification.

D – Fundamentals of Motor Control

Poster Cluster (2-D-34 and 2-D-35)

2-D-34 - String-pulling behavior in the aging marmoset

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Details

Aims: While physical manifestations of aging are easy to perceive in the ability to walk or run, changes in forelimb functions are more difficult to notice and monitoring their evolution remains challenging. Nevertheless, coordinating movements between the hands are crucial for many activities of daily life, like typing on a keyboard or manipulating objects. Recently, the rewarded string-pulling task, involving cyclically reaching and pulling a string, has been used to study bimanual coordination in rodents. This task has previously been demonstrated to be sensitive to motor pathologies such as Parkinson's disease or shoulder joint injuries but has not yet been investigated in age-related natural decline. Here, using the string-pulling task, we characterized age-related decline in marmoset forelimb coordination.

Methods: Twelve common marmosets were divided into three age groups, each with 2 males and 2 females: young (Y, < 2 years), adult (A, 2-7 years), and old (O, 7-14 years). They were trained to perform a string-pulling task and forelimb kinematics were extracted, based on previous studies: correlation between the vertical position of the left and right hands; movement-scaling calculated as the correlation of peak speed and Euclidean reaching distance; and path-circuitry calculated as the ratio of Euclidean reaching distance to actual movement displacement. These metrics were compared across ages and sexes.

Results: Adult group had a more negative correlation between the vertical position of the hands compared to the young group, both surpassing the old group (A: -0.30 ± 0.02 vs. Y: -0.22 ± 0.03; p=0.03 vs. O: -0.01 ± 0.02; p<0.001; mean ± SEM). Interestingly, we found no reliable differences between sexes, except in the old group (males: -0.07 ± 0.03 vs. females: 0.04 ± 0.03; p=0.04). For movement scaling, no significant differences were found between left and right hands or between sexes within any group. However, the old group showed a significantly higher value than the young and adult groups (Y: 0.55 ± 0.02 and A: 0.48 ± 0.02 vs. O: 0.64 ± 0.01; p<0.001). Similarly, no differences between left and right hands were found for path circuitry, but the old group showed a significantly higher value than young and adult groups (Y: 0.76 ± 0.01 and A: 0.75 ± 0.01 vs. O: 0.79 ± 0.01; p<0.001).

Conclusion: Our results provide evidence of maturation and are-related decline in bimanual coordination using the string-pulling task. We demonstrated consistent kinematics in the young and adult groups, but different from the old group. Indeed, older marmosets showed better scaling and more direct movement, but no correlation between the vertical hands position, indicating a decline in bimanual coordination. Using this paradigm, future studies could investigate the neural substrates associated with this age-related decline.

2-D-35 - Characterizing marmoset forelimb coordination in string-pulling

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Details

Aims: Coordinated forelimb movements used to grasp and manipulate objects are common in daily life, such as driving a car, tying shoe laces, and typing on a keyboard. Motivated by recent work in rodents, we have adapted the rewarded string-pulling task, to study coordinated forelimb movements in the common marmoset. Here we characterize, for the first time, the kinematics and topography of reach-to-grasp movements and bimanual coordination in the marmoset.

Methods: Six adult common marmosets (aged 2-7 years; 3 females, 3 males) were trained to perform a string-pulling task in their home environment. Markerless motion tracking based on DeepLabCut was used to extract forelimb kinematics. We extracted established measures from previous rodent and human studies: correlation between the vertical position of the left and right hands; movement-scaling calculated as the correlation of peak speed and Euclidean reaching distance; and path-circuitry calculated as the ratio of Euclidean reaching distance to actual movement displacement.

Results: All marmosets spontaneously performed coordinated bimanual movements to pull on the string, and thus retrieve a marshmallow attached to the string. For some animals this occurred on the first day and for all animals it occurred within one week of initial exposure. Marmosets were highly motivated by seeing the marshmallow and consistently looked at it while pulling the string to retrieve it. Unlike rodents, marmosets did not appear to use tactile inputs from the face to guide the string-pulling behavior. Marmosets consistently showed a negative correlation between the vertical position of both hands (males: -0.26 ± 0.02; females: 0.27 ± 0.02; mean ± SEM), indicating antiphasic and symmetrical movements typical of string pulling in both rodents and humans. Marmosets scaled the speed of their movements with reach distance (movement scaling: 0.51 ± 0.02) and showed highly directed reaches (path-circuitry: 0.83 ± 0.01). We found no reliable differences in any of these measures between hands or sexes.

Conclusion: Our results show that marmosets perform the string-pulling task in their naturalistic home environment without extensive training. Our baseline characterization serves as the basis for studying bimanual coordination and how it changes over development and aging, as well as in the context of injury and disease.

2-D-36 - Cortical beta oscillations help synchronise muscles during static postural holding in healthy motor control

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Details

How cortical oscillations are involved in the coordination of functionally coupled muscles and how this is modulated by different movement contexts (static vs dynamic) remains unclear. Here, this is investigated by recording high-density electroencephalography (EEG) and electromyography (EMG) from different forearm muscles while healthy participants (n=20) performed movement tasks (static and dynamic postural holding, and reaching) with their dominant hand. In static postural holding without perturbation, beta band (15-35Hz) activities in the motor cortex contralateral to the performing hand were similar to rest, and when dynamic perturbation was applied, beta oscillations reduced to similar level as during reaching movements. During static postural holding, transient periods of increased cortical beta oscillations (beta bursts) were associated with greater corticomuscular coherence and increased phase synchrony between muscles (intermuscular coherence) in the beta frequency band compared to the no-burst period. This effect was not present when resisting dynamic perturbation. The results suggest that cortical beta bursts assist synchronisation of different muscles during static postural holding in healthy motor control, contributing to the maintenance and stabilisation of functional muscle groups. Theoretically, increased cortical beta oscillations could lead to exaggerated synchronisation in different muscles making the initialisation of movements more difficult, as observed in Parkinson's disease.

2-D-37 - Biological stimuli are processed differently from non-biological stimuli and are more influenced by spatial congruence than by perspective

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Details

Introduction:

Previous research has shown that Action Observation can be influenced by perspective (with a preference for first-person perspective over third-person perspective), spatial congruence (the relative position of a stimulus to the required response) and whether the stimulus is biological or not. We conducted two experiments to study how these factors interact to influence action observation.

Experiment 1

Method: Participants completed a reaction time task, responding to biological stimuli (images of hands) or non-biological stimuli (images of letters), presented in the first- or third-person perspective, and which could be spatially congruent, incongruent, or neutral with relation to the position of the required response.

Results: Participants took longer and made more errors when responding to third-person perspective compared with first-person perspective. There was also a greater increase in response times and errors for spatially incongruent stimuli compared with spatially congruent stimuli. Overall, responses to biological stimuli also required longer reaction times and resulted in more errors than the non-biological stimuli.

Experiment 2

Method: Participants responded to the same stimuli from Experiment 1 but in a 'forced response' task in which we effectively controlled the amount of time participants had to prepare their response to each stimulus. This allowed us to assess how response accuracy changed as a function of preparation time.

Results: While perspective had no influence on this experiment, spatial congruence proved essential. Indeed, for spatially congruent biological stimuli, participants initially responded randomly (0 to 200ms) before reaching nearly 100% correct responses with longer preparation times (500ms). By contrast, for spatially incongruent biological stimuli, random responses were followed by a brief period whereby accuracy decreased below chance levels (~300ms) before a subsequent increase. Interestingly, this reduction in accuracy was not present for spatially incongruent non-biological stimuli.

Discussion: As predicted by the literature, the results of Experiment 1 showed a preference for the first-person perspective. However, the influence of spatial congruence was more important with a preference for spatially congruent stimuli. These results suggest that the influence of perspective could be partially driven by changes in spatial congruence. Experiment 2 shows no influence of perspective, whereas spatial congruence seems to play a critical role. Furthermore, the difference between spatially incongruent biological and non-biological stimuli suggests a fundamental difference in the way in which these different types of stimuli are processed.

2-D-38 - Frequency-dependent responses reveal distinct contribution of feedback and feedforward control during longitudinal de novo learning

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Details

Learning a motor skill from scratch, or *de novo* learning, involves creating a new control system. Typically, real-world motor tasks require using a combination of feedback and predictive controls to make ongoing adjustment for smooth and accurate movements. However, since feedback has a time delay and does not reflect the body's current state during movement, a feedforward model is crucial for quick, precise actions. The development of feedback and feedforward controls during the acquisition of new motor skills is not yet fully understood.

In our study, ten right-handed participants (6 females, average age 24.7 ±2.0) underwent a 5-day learning process of a mirror reversal of visual feedback in a continuous tracking task. The task involved tracking a target in a pseudo-random trajectory, shaped by a sum-of-sinusoids, across frequencies from 0.1 to 2.15 Hz. We aimed to discern if participants learned this task through feedforward, feedback, or a combination of both. This was assessed by (1) checking for the presence of after-effects, indicative of feedforward control, and (2) introducing probe trials where the cursor made unpredictable jumps, requiring feedback control for response.

Our findings showed a gradual learning of this new skill, with participants achieving an average learning level of 54.37 ±0.08% by Day 5. Analysis of cursor jump responses suggested that learning achieved mostly through feedback control, evidenced by hand movements aligning closely with ideal feedback responses. Intriguingly, a small yet significant after-effect (15.29 ±0.11%) was observed post-learning ($t(9)=3.47$, $p=0.0032$), indicating a contribution of feedforward control to the overall learning process.

However, it was unclear if learning was solely due to the development of a new feedback controller. Given that target movements at higher frequencies cannot be compensated by feedback control alone due to inherent delays, we speculated feedforward control might play a more significant role than apparent. To verify, we conducted a linear systems analysis, offering a more granular view than trajectory-alignment. We transformed hand movement trajectories into frequency-domain representation using discrete Fourier transform. This analysis revealed two distinct processes: rapid learning at lower frequencies and slower, gradual learning at higher frequencies. Interestingly, higher frequencies showed a greater after-effect, suggesting a more pronounced role of feedforward control ($t(9)=2.55$, $p=0.031$).

These results provide new insight into human acquisition of de novo motor skills. Our findings suggest the existence of two distinct control pathways: corrective feedback responses at low frequencies acting early on learning and improving with practice. At high frequencies, the target's rapid movement limits feedback control, leaving only inappropriate feedforward responses. However, this feedforward controller is flexible and develops slowly with practice.

2-D-39 - Is motor imagery more like movement execution or working memory? A meta-analytic comparison

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Details

Introduction:

Leading models have opposing hypotheses about the basis of Motor Imagery. Motor Simulation Theory suggests Motor Imagery is a ‘covert’ form of Movement Execution, and recruits the same network involved in Executed movements. The Motor Cognitive Model instead suggests that the performance of Motor Imagery is a more cognitive process, sharing similarities with Working Memory. The present study compares recent meta-analyses (Hardwick et al., 2018; RodrÃguez-Nieto et al., 2022) to determine whether the brain network involved in Motor Imagery shares more in common with Movement Execution or Working Memory.

Methods:

Activation Likelihood Estimation (ALE) meta-analyses of Motor Imagery (n=134), Movement Execution (n=71) and Working Memory (n=492) were conducted. Minimum Statistic Conjunction Analyses identified regions consistently recruited across Motor Imagery and Movement Execution, or Motor Imagery and Working Memory. By calculating a series of permutations of each analysis, we compared the volume of each network that is in common with the others, and thus statistically determine whether the brain network for Motor Imagery shares more in common with Movement Execution or Working Memory. Analyses were computed using the revised version of the ALE algorithm, with results calculated using $2mm^3$ voxel resolution.

Results:

Preliminary analyses identified the volumes of voxels recruited by Motor Imagery (16,303), Movement Execution (11,857) and Working Memory (28,143). Initial comparisons show that while 29% of the network for Motor Imagery is also recruited by Movement Execution, there is a much larger overlap with executive function; indeed, 57% of the Motor Imagery network is also recruited by Working Memory tasks. Further analyses will control for factors such as the differing size of the individual networks and examine sub-regions that are recruited by each task.

2-D-40 - Accelerometry as new measurement technique for mapping cortical motor representations – preliminary data

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Details

Introduction: The effects of transcranial magnetic stimulation (TMS) have primarily been studied on the primary motor cortex of the human brain (Hallett, 2000). Stimulating the motor cortical representation of a target muscle induces small movements, with electromyography (EMG) being the gold standard to measure resulting muscle activity. This electrical activity is analyzed to determine the resting motor threshold (RMT), contraction latency, and Motor Evoked Potential (MEP), crucial for mapping the targeted muscle in the primary cortex ((TyÄ� et al., 2005; Wassermann et al., 1992)).

Despite EMG being the current gold standard, it has limitations, such as sensitivity to external noise, and high initial and ongoing costs. Accelerometry emerges as a potential solution to address these limitations. Our recent research (Hamoline et al., under review) demonstrated a strong correlation between recruitment curves assessed with EMG and accelerometry. This study leverages this correlation, employing accelerometry to assess motor cortical brain mapping of the primary cortex.

Methodology: Neuronavigation was used to find the hotspot for the first dorsal interosseus (FDI) and determine the Resting Motor Threshold (RMT;5 out to 10 responses >50 µV) with EMG. A 5x5cm grid was established, centered around the motor hotspot. TMS was delivered over the resulting 25 stimulation points; positions were chosen in a random order and each point was stimulated 10 times at 120% of the RMT. We measured MEP amplitudes (µV) for EMG and the jerk (m/s^3) for accelerometry.

Two types of maps are compared: The 'size-response' heatmap compares the size of the MEP and the size of the jerk along the 10 stimulations per site. The 'binary-response' heatmap is was assessed to determine the presence or absence of 'minimal' responses for EMG (>50 µV) and accelerometry (>95%CI based on the pre-stimulation period) the number of responses induced by the 10 stimulations.

Results: Preliminary findings reveal a significant positive correlation between the 'size-reponse' heatmap generated with EMG and accelerometry. The correlation the 'binary-response' heatmap shows more variability depending on the subject.

Conclusion: The present results showcase accelerometry's potential as a reliable alternative to EMG for cortical brain mapping.

2-D-41 - Yoga as a natural model for motor learning in a null space

Hristo Dimitrov [1], **Alexandra Williams** [1], **Julien Russ** [1], **Tamar Makin** [1]

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Details

Learning how to coordinate muscles across your body to achieve a specific pose often converges around a narrow set of common solutions despite the multitude of possible configurations. This convergence reflects skill learning, which aims to reduce effort and variability. Experts may develop multiple effective solutions within a null space, aligned with their physical capabilities, as long as critical task elements are maintained. This study uses yoga as a rich model for motor control due to its demands for precise muscular engagement, breathing, flexibility and coordination. During practice, natural motor redundancy and practice variations enable multiple executions of a yoga pose, often appearing outwardly correct. However, such variations may conceal risks due to compensatory mechanisms employed to achieve aesthetic alignment. As such, whether experts develop more robust or more versatile pose signatures might offer a unique insight to contrast with lab-based skill learning.

We recorded muscle activations during yoga poses using surface electromyography (EMG) in 10 yoga experts and 10 intermediate practitioners across two sessions in an ecological environment. EMG data from eight muscle groups during 13 yoga poses (eight rounds of repetition) were analysed to extract "pose signatures" and compare them within and between sessions, participants, and expertise levels.

We hypothesized that experts exhibit more consistent muscle activation across sessions than novices due to refined motor skills. Intermediates, in comparison, who are still developing a consistent strategy within the redundant skill space, will show more variability within and across sessions. However, considering the inherent variability in achieving a pose, we anticipate observing more inter-individual variations within the expert group relative to the intermediate group. This is because experts develop unique motor solutions for each pose, while intermediates will demonstrate more versatile strategies with greater overlap across practitioners.

Preliminary findings reveal a high degree of within-session consistency in both groups across repetitions. However, variability across participants remains substantial, indicating multiple viable strategies for pose execution. Further analysis aims to investigate across session results and elucidate temporal dependencies within sessions and assess energy expenditure based on muscle engagement percentages.

This research aims to deepen our understanding of the mechanisms used to reduce the solution space within the complex motor control environment of yoga. By observing the natural variability of practitioners, we seek to explore the complex motor skill learning dynamics between effort and variability minimization outside the imposed constraints of controlled lab environments. Moreover, the techniques developed here for pose signature determination hold promise for enhancing training safety and efficacy across various sports and skill levels.

2-D-42 - Effect of GABA on brain-spine interactions for motor control during cervical spinal cord stimulation in monkeys

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Details

Epidural spinal cord stimulation (SCS) restores voluntary control in participants with paralyzed limbs, yet to date it is not an approved therapy for motor paralysis. Deciphering the underlying mechanisms of SCS can accelerate this transition for widespread clinical use. SCS directly activates primary sensory afferents within the spinal cord, thereby exciting spinal motoneurons. This excitation assists residual supraspinal fibers in conveying voluntary commands to enable movement. Importantly, volitional movement is achieved due to the bidirectional facilitation of excitatory inputs from sensory afferents and supraspinal fibers to motoneurons. However, this facilitation may be contingent upon sensory modulation mechanisms, which can regulate SCS drive. In fact, new studies showed that sensory afferents are strongly regulated by presynaptic mechanisms mediated by GABA interneurons. Without these interneurons, spike transmission fails through sensory afferents to spinal motoneurons. Here we hypothesized that GABA interneurons facilitate excitatory inputs from supraspinal fibers and sensory afferents recruited by SCS to excite motoneurons.

We conducted a terminal experiment in two anesthetized monkeys. We stimulated the cervical spinal cord and conditioned a single pulse of corticospinal stimulation, through deep brain stimulation of the internal capsule, with sub-motorthreshold single pulse of SCS at 5-300 ms delays. Evoked responses were recorded via electromyographic (EMG) intra-muscular needles in the hand muscles. Analogously, we repeated the same experiments but now conditioning SCS with a pulse of internal capsule stimulation. Finally, we performed a causal manipulation by blocking GABAA receptors through the intrathecal administration of the GABAA antagonist drug gabazine and replicated the same stimulation protocols.

We explored the role of GABA during SCS when conditioning a corticospinal pulse at different delays. We measured the peak-to-peak (P2P) amplitudes of the motor-evoked potentials. SCS facilitated the corticospinal input for all delays in both muscles. This modulation was absent after blocking GABA and the P2P amplitudes remained unchanged during SCS conditioning. We then analyzed P2P amplitudes induced by corticospinal conditioning of a SCS pulse at different delays. Corticospinal conditioning facilitated reflex-mediated responses, especially, at short delays. After the delivery of gabazine, P2P amplitudes were suppressed for all delays.

Our results suggest that GABA may be critical to facilitating voluntary input from corticospinal fibers and sensory afferents during SCS for the recovery of motor control. Interestingly, 80% of the innervations from the corticospinal tract in the hand area project directly to spinal motoneurons. The fact that the remaining innervations are influenced by GABA interneurons reinforces the role of these interneurons in motor control after a corticospinal lesion during SCS.

2-D-43 - Reaching movements reflect ongoing deliberation that involves evidence integration and urgency

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Details

We constantly make choices while moving, such as deciding whether to pass to the left or right of someone while walking down a hall. Perceptual decision-making studies have manipulated continuously changing evidence (e.g., individual tokens moving to a left or right target) to manipulate deliberation, before movement and a final decision. Reaching studies have used abrupt changes in evidence (e.g., target colour) during movement to examine motor planning or online decisions. In both paradigms, deliberation remains hidden since continuous changing evidence is not provided during movement. Here we tested the idea that decision circuits continuously interact with motor circuits during deliberation. We predicted online reaching movements will reflect ongoing deliberation, prior to a final decision.

We extended upon the “tokens task” (Cisek, 2009). Participants were required to actively move forward from a start position towards two potential targets, prior to a decision. Once participants left the start position, 15 tokens individually moved in 160 ms increments into one of the two targets. Once they felt confident which target would end up with the most tokens, they were instructed to simultaneously i) press a trigger with their non-dominant hand and ii) move towards and hit the selected target. Interleaved with pseudo-random token patterns were biased token patterns, where the first three tokens moved into the left target (left bias) or right target (right bias). Critically, we measured lateral hand position, prior to the decision, to determine the influence of deliberation on movement. In Experiment 1, the left and right biased token patterns differentially impacted the lateral hand position prior to a decision, supporting the idea that the ongoing deliberation is reflected in movements.

In Experiment 2, we manipulated both the token bias direction and the rate of token movement. For both left and right bias token patterns, we moved the first four tokens either individually in 160 ms increments (slow rate) or all at once (fast rate). Again, we found that the left and right biased token patterns caused differences in lateral hand position prior to a decision. Interestingly, participants made earlier decisions with a slow rate compared to a fast rate token pattern. Decision times were captured with a decision model that considered both evidence accumulation and urgency. We then combined this decision model with an optimal feedback controller that reproduced movement behaviour in our experiments. By considering urgency, we were also able to explain reaching behaviour in past work that was interpreted to reflect a single, flexible movement plan rather than the averaging of parallel plans (Wong and Haith, 2017). Our findings suggest that decisions and movement reflect a deliberation involving evidence integration and urgency, while supporting the idea that decision circuits continually interact with motor circuitry.

2-D-44 - Reward-based motor learning: the direction of exploration deviates from random behavior

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Details

Humans learn various motor tasks based on binary reward feedback. Such 'reward-based motor learning' relies on exploiting rewarded behaviour and exploring following non-rewarded behaviour. Most computational models of reward-based motor learning have formalized exploration as a simple random process, which takes a random draw from a normal distribution centered on zero. While such random exploration suffices when rewarded performance is kept close to the current performance, it would result in unreliable learning when rewarded performance is at a further distance. This study aims to test whether the direction of human exploration deviates from independent random draws. To this end, we compared human behavior and model simulations based on random exploration between groups practicing with either an adaptive reward criterion linked to current performance, or a fixed reward criterion. In contrast to simulations based on random exploration, the behavioural data showed comparable learning in the Adaptive and Fixed groups. Consistent with the direction of exploration being tailored systematically, we found in both groups more same-direction changes than predicted by random exploration. Together, this suggests that the direction of exploration is adapted systematically, which might increase learning when the rewarded performance is far from the present performance.

2-D-45 - The temporal organization of descending activations and their interaction with spinal reflexes in the generation of arm movements

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Details

While many of current neurophysiological studies focus on the brain level control of arm movements, how such descending control interacts with spinal mechanisms and peripheral motor apparatus is not well addressed. Due to the spinal feedback coupling, descending activations from the brain are not the only source in generating muscle activations that ultimately produce the movement. This study aims to decouple descending activations from the measured muscle activation patterns during human arm movements.

To reconstruct descending activations, a mathematical model of descending control considering spinal stretch reflex was first calibrated in passive postural tasks and then fit to the observed joint kinematics and muscle EMG patterns during voluntary arm motion with different speeds.

Key features on the reconstructed descending activations were revealed: (1) they initially dominate muscle activation patterns but after movement onset, their temporal profile differed qualitatively from muscle activation patterns. This could be explained by the involvement of spinal stretch reflex during movement generation. (2) The time course of descending activations was monotonic during slow movements but became non-monotonic during fast movements. This suggests that the descending activations must be adjusted temporally to adapt to different movement dynamics. (3) Changing the spinal feedback gain in the model only effects the temporal patterns of estimated descending activations in the later movement phase.

The approach of reconstructing descending activations can serve as a technical tool to probe the nature of descending control of voluntary movements. The findings in current study highlight the role of spinal feedback in movement generation and emphasize the need for the central nervous system to adjust the temporal structuring of descending activations to accommodate various movement dynamics in motor periphery.

2-D-46 - Somatotopy of the interhemispheric interactions reflected in physiological mirror activity

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Details

Physiological mirror activity (pMA) denotes involuntary contractions in one muscle limb occurring when muscles of the contralateral limb are intensely contracted. This phenomenon reflects interhemispheric balance in the motor system. We hypothesize that pMA is more prominent in homologous compared to non-homologous muscles of the opposite limb, and suggest that pMA may be used as a model to probe the somatotopy of the interhemispheric interactions.

22 healthy right-handed participants (12 females, 22 to 36 years old) without special motor skills were enrolled in the study. Surface EMG was recorded from the abductor pollicis brevis, abductor digiti minimi, and extensor carpi ulnaris from both hands. Subjects were instructed to perform thumb and little finger abduction for 3-4 seconds with 60-80% of the maximal muscle activity with their right upper limb, while pMA was assessed in the left upper limb. The level of the active limb contraction was controlled using EMG-biofeedback. Subjects performed three sessions with 20 movements in each for both motor tasks (thumb and little finger abduction). EMG activity was assessed in all six muscles of both hands, for pMA investigation we assessed its latency, persistence, duration, and area under the curve (AUC).

We observed pMA in all our subjects at least once per session and in 40% of movements on average. All pMA parameters were more prominent in the homologous muscles, pMA AUC was the most sensitive for the somatotopy estimation (3.2 times higher in the homologous muscles compared to non-homologues).

Our results demonstrated the feasibility of pMA to probe the somatotopy of the interhemispheric interactions in the motor system. We suggest that the spatial specificity of pMA may be used in the future to assess the interhemispheric interactions and its somatotopy for neuromodulation planning when it is aimed at changing the interhemispheric balance e.g. in stroke.

2-D-47 - Small scale heterogeneity of high frequency LFP aids movement decoding

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Details

Several types of neural signals have been used to decode movement. Inherent to each type is a set of advantages and drawbacks. Local field potentials (LFP), for example, exhibit high signal stability over time relative to single unit activity (SUA). However, this comes at the expense of high correlation on small spatial scales. In the present work, we show how high frequency LFP (HF-LFP) serves as a good middle-ground between SUA and LFP for movement decoding.

Based on our previous work, we hypothesized that much of the heterogeneity of activity on the level of single units might persist at the level of neural populations. Since HF-LFP has been shown to be correlated with population spiking dynamics, we surmised that it would be an ideal signal to test this hypothesis.

To this end, we analyzed neural recordings from two adult male rhesus macaque monkeys (*Macaca mulatta*) while performing a reach-to-grasp task. Neural data was recorded via four Utah arrays, implanted in the left/right ventral premotor cortices (PMv), the left/right dorsal premotor cortices (PMd), and the left primary motor cortex (M1). Spectral electrode amplitude and pairwise Pearson correlation were calculated from band-passed versions of the signal, effectively defining eight frequency bands, ranging from theta (4-7 Hz) to HF-LFP (200-500 Hz). We then used a machine learning classifier to determine decoding accuracy for various portions of the reach-to-grasp movement. The characterized behavioral states were: Baseline (rest), Pre-reach (motor preparation), Reach, Grasp, and Post-grasp (reward retrieval). Moreover, we defined three metrics of heterogeneity: effect variance (EV), effect coherence (EC) and Δn_PCA. EV is the within-region variance of the Baseline-normalized spectral amplitude. EC describes the proportion of electrodes exhibiting an increase in spectral amplitude relative to Baseline and is standardized such that 0 implies a 50/50 increase/decrease split and 1 indicates either a 100/0 or 0/100 increase/decrease split. Lastly Δn_PCA describes the difference in the number of principal components (relative to Baseline) required to capture 95% variance of the within-region neural activity.

Our results indicate HF-LFP, even from a single electrode, can be leveraged to decode and characterize brain states ranging from motor preparation to execution. Multinomial logistic regression yielded high classification accuracies across several frequency bands with the HF-LFP band boasting near perfect accuracy for the Grasp and Reach states. Furthermore, we show that heterogeneity (EV, EC Δn_PCA) varies as a function of brain area, behavior, and frequency band. Lastly, multiple linear regression revealed that within-region heterogeneity of HF-LFP was associated with increased decoding strength.

2-D-48 - Pre-movement activity in rostral and caudal cervical segment represent a different types of force productions: A simultaneous brain-spinal cord fMRI study

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Details

In non-human primates, the pre-movement activity in the spinal cord occurs in parallel with the motor cortical regions. Yet, the preparatory activity prior to the motor execution in the spinal cord in humans is still unknown. Here, we aimed to illustrate preparatory activity in the human brain-spinal circuit by using simultaneous brain-spinal cord fMRI. Twenty-one healthy participants engaged in the ready-set-go task in a 3T-MRI scanner. In this behavioral task, participants were asked to prepare to respond at the ready cue and to grip the force device as quickly as possible at the go cue. During the ready phase, averaged pre-movement activity was observed in the contralateral primary motor cortex (M1) and bilateral supplementary motor area (SMA), and upper cervical segments at the level of C3-5, containing propriospinal neurons. Notably, the extent of trial-by-trail pre-movement activity in the M1 correlated with subsequent trial-by-trial reaction time. In the spinal cord level, the extent of trial-by-trail pre-movement activity of upper cervical segments at the level of C2-5 and caudal cervical segment at the level of T1 containing spinal motoneurons innervating muscles for hand grip correlated with subsequent trial-by-trial reaction time. Furthermore, the extent of trial-by-trail pre-movement activity of cervical enlargement at the level of C7 correlated with subsequent trial-by-trial peak grip force. Present results suggest that the pre-movement activities of M1 and cervical enlargement represent not only the subsequent initiation of force production but also the strength of force generation, while upper cervical segments represent the subsequent initiation of force production.

2-D-49 - Online navigation in a virtual 3D environment based on primary motor and premotor activity in macaques

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Details

Motor brain-machine interfaces (BMIs) revolutionize human-computer interactions by directly translating neural activity into motor commands that can be executed by an external device. To investigate whether an invasive BMI can be used to navigate in a virtual 3D environment, we implanted three multi-electrode arrays (in primary motor cortex, dorsal premotor area F2 and ventral premotor area F5c) in two macaques and designed two navigation tasks in the game development platform Unity. Liquid crystal shutter glasses and a 3D screen on which pairs of left- and right eye images alternated allowed the simulation of a virtual 3D environment with binocular disparity. In the center-out task, a sphere moved from a predefined starting point to one of five equidistant targets that appeared on a gray plane, which featured a grid to provide additional depth cues in the 3D environment. In the continuous navigation task, the camera view rotated and moved along with the sphere that could move freely in the environment. The experimental design was identical for the two tasks and consisted of three phases. First, the monkey passively observed the task in which the sphere movements were driven by Unity. Second, the obtained neural data combined with the velocities of the sphere during the task were used to train a decoder based on the Preferential Subspace Identification (PSID) model, which aimed to identify behaviorally relevant latent states capturing the underlying dynamics of the neural system. Next, a Nystroem kernel approximation and a regression model were trained to handle the nonlinearities in the data. In the third phase, the model made online predictions of the velocities of the sphere every 50ms based on the neural activity of the monkey controlling the movement of the sphere. A recursive Kalman filter estimated and updated the latent states of the system based on the recorded neural signal. In the third phase of the continuous navigation task, we replaced the sphere by a monkey avatar and the plane by a forest environment to simulate a more realistic environment. In 11 recording sessions in one monkey we achieved high performances in both tasks (i.e. the sphere or avatar reached the target within a predefined time window), with an average success rate of 74% in the center-out task and 69% in the continuous navigation task. The average time to reach the target was 3.7s in the center-out task, and 5.1s in the continuous navigation task (which was only 0.7s or 2.1s longer than the time-to-target in the Unity-driven tasks, respectively). Thus, we achieved robust and fast decoding of neural activity in premotor and motor cortex to navigate in a virtual 3D environment. Furthermore, the decoder was able to generalize to different environments, which has important implications for the clinical development of BMIs that can be used at home, hence drastically improving the quality of life of paralyzed patients.

2-D-50 - Individual differences in motor variability in relation to thalamic and M1 GABA content

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Details

The neural mechanism for decreasing variability during the transformation of actions from controlled to automated is poorly understood. The motor thalamus is a special region of interest. It acts as a circuit bottleneck, receiving GABA-ergic inhibitory input from a variety of regions before relaying motor commands to cortex. This pathway is thought to facilitate action selection by suppressing competing motor representations and neural noise along with selective disinhibition of desired motor plans. However, it is unclear if thalamic inhibition reduces motor variability beyond action selection. Here, we aim to compare individual differences in motor variability during keyboard typing, a highly automated and common skill, with individual differences in thalamic GABA concentrations, measured via single-voxel edited H1 magnetic resonance spectroscopy (MRS), to evaluate relationships between motor variability, skill automation, and thalamic GABA levels. GABA in the primary motor cortex (M1) is also implicated in modulating motor variability and was included as a secondary region of interest.

To assess individual differences in typing variability, healthy participants (n = 24, 22 ±3.3 years old, 9 female) were cued to type five-letter strings selected from an American English lexicon. Bigrams (two letters in a particular order) within strings were grouped into three levels (low, medium, high) based on naturally occurring frequency (SUBTLEX corpus). Interkey Interval (IKI), the time between the start of two consecutive keystrokes, was calculated for all pairs of key presses. Standard deviation (SD) and coefficient of variation (CV) of IKI were calculated for each bigram grouping and participant to assess motor variability. Mean SD and CV of IKI differed significantly across bigram frequencies [($F(38)=13.1$ and ($F(38)=9.4$, p's$<.05$]. Post-hoc t-tests showed low frequency bigram IKI SD was higher than high and medium frequency bigrams [$p<.05$] and medium frequency bigram IKI CV was lower than high and low frequency bigrams [p<.05].

In a subset of participants (n = 5), MRS GABA concentrations were measured using a MEGA-PRESS sequence on a Siemens 3T Prisma MRI scanner. MRS voxels were placed in the left and right thalamus (30x35x20mm) and left and right M1 (25x35x25mm). Average GABA+:Creatine ratios were within the typical range for all voxels [L.thal=0.11 ±0.005, R.thal=0.10 ±0.01, L.M1=0.11 ±0.005, R.M1=0.11 ±0.007]. Data collection is ongoing in a larger sample. Planned comparisons between MRS GABA for all four voxels with IKI CVs and SDs for the three levels of bigram frequencies will be used to assess relationships between the regional capacity for inhibition and metrics of variability. This work shows proof of concept of a novel technique for assessing individual differences in both local GABA content and motor skill variability in humans with high ethological validity.

2-D-51 - Subcortical control of human reaching?

Samuele Contemori [1], **Gerald Loeb** [2], **Timothy Carroll** [1], **Guy Wallis** [3], **Brian D. Corneil** [2]

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Details

The notion that reaching movements in humans are coordinated exclusively via a transcortical pathway neglects the fact that fast and accurate prey-targeting behaviour emerged much earlier in evolution. In lower vertebrates, these actions are initiated subcortically by the optic tectum (~mammalian superior colliculus) and reticular formation, which are phylogenetically conserved in humans and subserve gaze saccades. Crucially, human target-directed reaches often include rapid (~90ms) shoulder-muscle responses that are rigidly locked in time and space to target appearance, suggesting that these “express” responses originate from target-driven collicular inputs to a subcortical reticulo-spinal control module. How would such a subcortical visuomotor network interact with cortical circuits linked to reach preparation and execution? Express visuomotor responses are modulated to reflect prior expectations and task rules, suggesting that their putative subcortical source can be strategically exploited by the cortex. We propose that the cortex plays a supervisory role in reach control by providing contextual state settings and task-dependent movement instructions to a reticulo-spinal subsystem that computes the required reach dynamics. If so, express visuomotor responses should reflect a fully coordinated reach-control signal driving all muscles required to resolve the biomechanics of any reaching action. We tested this idea by recording the activity of eight upper-limb muscles as participants reached to one of eight possible targets from two distinct shoulder postures (i.e. abducted, adducted). For all muscles, the preferred-direction was similar during both express and long-latency epochs, as were the patterns of variation across postures. Further, the agonist/antagonist muscle coordination patterns were similar during the express and long-latency epochs as indicated by a strong positive express*long-latency relationship (linear-mixed-effect-model analysis: R^2=0.76, p<0.001). In a second experiment where participants reached either toward (pro) or away (anti) from the target, the positive express*long-latency association for pro-reaches (R^2=0.77, p<0.001) became negative for anti-reaches (R^2=-0.51, p<0.001). We suggest that a subcortical reticulo-spinal module was always recruited at express latency by the superior colliculus to produce fully coordinated muscle actions directed to the target, and then by the cortex to produce the equivalent (in pro-reaches) or opposite (in anti-reaches) muscle activations during the volitional reaching phase. This would imply an alternative perspective on the division of labour between cortical and subcortical reach control centres in humans. In this view, the cortex provides strategic supervision of a subcortical reticulo-spinal module that transforms sensory (posture, target) and movement-related (reach direction) inputs into the muscle activity required by the task.

2-D-53 - Differences in perception and reproduction of a kinesthetic illusion of movement evoked with different frequencies of vibration: a comparison between healthy young and older adults using motion analysis

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Details

Proprioception is the ability to sense body position and movement. This capacity plays a fundamental role when accomplishing daily activities. Proprioception arises from diverse peripheral and central structures (Proske & Gandevia, 2012). Age-related alteration can affect these structures with negative drawback on proprioception. (Henry & Baudry, 2019). Using a vibro-tactile stimulation, it is possible to selectively activate the muscle spindles and induce a kinaesthetic illusion of movement (KI), by which it is possible to investigate proprioceptive functions. This study aims to investigate the effect of aging on proprioception by comparing the response elicited by a KI on healthy young and older adults.

Participants were seated with both arms placed on a table and secured in a fixed position with a brace. The KI was induced using a mechanical vibrator positioned on the extensor retinaculum of participant's dominant wrist. This position evoked an illusory movement of wrist flexion. Seven distinct frequencies of vibration were employed ranging from 50Hz to 110Hz with steps of 10Hz. While exposed to the stimulation, participants were asked to reproduce the movement felt, using their contralateral wrist. Qualisys motion capture system was utilized to gather the angular displacement and angular velocity of movement reproduction. Lastly, participants had to rate their conscious sensation of the vividness, the quantity, and the fluidity of the illusory movement on three Likert scales.

Fifty participants were categorized by age and divided in two groups, the young group (18 females, 7 males, mean age ±SD=24.84 ± 5.09 years) and the old group (15 females, 10 males, mean age ±SD=68.44 ± 3.02 years). The angular displacement and angular velocity were significantly higher in old than in young subjects in the range of frequencies 50Hz to 80 Hz. Similarly, the scores related to conscious sensation of the vividness, quantity, and fluidity of the movement where higher in the old group compared to the young in the range of 50Hz to 70Hz. Nonetheless, only in the young group there was a modulation of the vibration's frequency on both kinematical and perceptual variables. Indeed, in the young group, the values of both type of measurements increased as the frequency of vibration increased.

Differences between old and young participants were reported in both the kinematic and perceptual parameters. These results might be related to a poorer sensitivity discrimination between the different stimuli in older adults, but also to altered elaboration of the proprioceptive afferences at cortical level.

In fact, young subjects show a more selective response that better represents the results found in literature where the ideal frequency of stimulation to reach KI is about 80-90Hz.

2-D-54 - Grip-to-load force adjustments observed during initial grip might be partially attributed to the passive mechanical behavior of finger pad tissues

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Details

To ensure a stable grasp while handling objects, grip force (GF) and load force (LF) increase in parallel with their ratio scaled by friction until the object lifts off. The GF:LF ratio adjustment has been attributed to the sensorimotor control mechanisms. In this study we demonstrate that mechanical properties of the finger pads determine the friction-dependent time course of load force increase thus to some extent contributing to the GF:LF ratio adjustments. First, we performed object lifting experiments in which we identified representative finger movement kinematics in 12 healthy subjects. The instrumented object with exchangeable different friction grip surfaces was lifted by subjects using their thumb and index finger. Grip force (GF) and load force (LF) were recorded at each finger using 6-DOF force sensors. Finger and object movement kinematics were obtained from video recordings tracking markers placed on the fingernails and the experimental object. Then, we programmed the robot to replicate the range of skin and object interaction patterns. This involved bringing the flat surface of a friction modulation device into contact with the distal segment of a finger fixed in a holder. Kinematic patterns with three friction levels were tested five times each. We recorded normal force (NF) and tangential force (TF); representing GF and LF in lifting experiments, respectively. With all tested kinematic patterns, tangential force with a more slippery surface increased at a slower rate, while normal force increase rate was not affected. TF increased at a maximum rate of 2.71 (2.18-3.34) N/s, 2.14 (1.82-2.94) N/s and 1.69 (1.44-2.50) N/s (median and quartiles) with high, moderate, and low friction, respectively. In comparison, during the lifting task, the LF peak rate showed similar trend and was 6.45 (5.83-8.17) N/s and 5.32 (4.40-6.50) N/s with high and low friction, respectively. The NF:TF ratio adjustments to friction indicate that the analogous GF:LF ratio adjustments in active lifting may arise due to friction-dependent biomechanical interactions at the skin-object interface.

2-D-56 - Characterizing somatotopy and stability of human motor cortical activity recorded with a Stentrode

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Details

The Stentrode is a novel endovascular brain-computer interface (BCI) that is implanted within the superior sagittal sinus to record bilaterally from the primary motor cortices. The first-in-human trial in Australia demonstrated computer control and digital communication in four people with severe paralysis due to amyotrophic lateral sclerosis (ALS). An Early Feasibility clinical trial began in the United States (US) in July 2022 at three sites and a total of six participants have been implanted to date.

To develop effective decoding algorithms, we need to understand the somatotopic representations of these vascular electrocorticography (vECoG) signals. The offline (non-feedback) training tasks consisted of 5-s (± 1 s) rest periods followed by a 5-s period of movement attempt, in which 5 repetitions of attempted movement occurred. The movements attempted included: both ankles, right ankle, left ankle, right hand, left hand, and both hands. Activity across electrodes for a variety of gestures (hands vs feet, single-sided vs bilateral) will be compared. Based on classical understanding of the motor homunculus and combined with the implantation of the Stentrode along the midline, we would expect the strongest representation of the lower extremities. However, we have found a comparably strong representation of the hands, especially the dominant hand, in many participants.

In addition, in order for the Stentrode to be viable long-term, these vECoG signals need to remain stable over time to enable reliable decoding of motor intent. Multiple factors could contribute to signal instability and/or loss of BCI functionality in people with ALS, including neuronal degeneration and cortical atrophy, cognitive decline, inflammatory reactions, and device-related failures. Signal stability was assessed when participants were resting or attempting movement. Each testing session begins with recording two-minutes of resting state activity, followed by training or utilization tasks. The resting state signals were assessed through the root mean square (RMS) of the signal amplitude in the rest period, band power, and bandwidth. The attempted movements were evaluated using the movement (signal) and rest (noise) intervals for band power, percent change in RMS, and signal to noise ratio over the post-implant follow-up period to date. Signals were assessed in the standard frequency bands: alpha (8 to 13 Hz), beta (13 to 30 Hz), low gamma (30 - 60 Hz), and high gamma (60 - 200 Hz). Linear regression was utilized to estimate the rate of change over time.

Results obtained thus far demonstrate that the vECoG signals recorded with the Stentrode are stable across several months (max 12 months to-date). Somatotopic representation of vECoG signals recorded over 4 - 12 months in six participants will be presented. The ongoing early feasibility study will continue to evaluate the somatotopic representation and signal stability beyond one year.

2-D-57 - Error prediction determines the coordinate system used for novel dynamics representation

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Details

Skillful object manipulation requires the object's dynamics to be represented within a motor memory. Despite extensive research, how the motor system represents these novel dynamics is still an open question. Previous studies explored this question by testing the spatial generalization of the learned forces, but did not provide a consistent view of this representation. Instead, each study provided evidence favoring an extrinsic coordinate system, an intrinsic coordinate system, an object-based representation, or mixtures of these coordinate systems. To reconcile these disparate findings, we propose that the motor system combines different representations based on their reliability. Specifically, since noise distorts our movement plan and related estimations, for example, the estimated target location or the estimation of the arm state, it creates an error between the ideal force pattern and the executed force pattern, with different effect sizes for each dynamical representation. According to our model, the motor system represents dynamics by weighing the different representations based on these effect sizes, giving higher weight to the less affected representation. To test this hypothesis, we conducted a series of experiments using a novel force field design and showed that participants represent the same dynamics differently depending on the spatial location in which they are learned and generalized. However, we can predict the experimental results almost perfectly by combining simulated motor memory representations according to the noise-effect criterion. Moreover, by simulating experimental designs of previous studies, we show that our noise-based model predicts the different past conclusions, solving the inconsistency between them. Overall, we are able to reconcile all of the apparently disparate findings under a single cohesive model of dynamics representation.

However, if our model of motor memory representation is correct, then we should be able to shift the stored representation by providing additional information. We tested our model by changing the reliability of the different representations in a series of experiments. Specifically, we tested the force generalization patterns after participants adapted to two force fields differing in spatial location but matching in terms of a coordinate system. In this case, matching forces across different arm postures change the uncertainty about each coordinate system globally; it reduces the uncertainty about one coordinate system while elevating it for other coordinate systems. Participants changed their representation according to the experimental coordinate system used, exactly as predicted by the model. Not only does our model reconcile previous disparate studies, but it also explains how motor memory representation can be tuned according to additional information, allowing the sensorimotor system to adjust representation to a variety of possible environmental dynamics and body states.

2-D-58 - Can I catch this ball and do I know if I can? — Examining the interceptability of a ball for oneself

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Details

Prior research has evidenced the use of prospective control strategies in lateral interception. However existing studies mainly focus on attainable interceptive actions without differentiating interceptable from uninterceptable cases. This distinction is pivotal for athletes to make prompt action decisions on whether to pursue or relinquish a ball. Our two experiments used a lateral interception paradigm to assess the interceptability of balls ranging from interceptable to uninterceptable ones. We hypothesized that the action boundary depended on distance to be covered in a given time. Beyond a defined spatiotemporal threshold a ball was hypothesized to be uninterceptable. Participants were tasked with intercepting virtual balls using a paddle controlled by a handheld slider. We varied three ball speeds with five ball departure and arrival positions each. Participants' sensitivity to the action boundary was examined in a judging task wherein participants were instructed to call "No" when they perceived a ball to be beyond their reach. They were allowed to move their paddle while making these action judgments. Generalized linear mixed effects regression (GLMER) analyses revealed that both distance to be covered and the available time co-determined interceptability as hypothesized. Surprisingly, time (based on the ball speed) played a dual role: 1) performance was worse for larger distances and faster ball speeds and 2) performance diminished even for shorter distances as a function of ball speed, indicating a speed-accuracy trade-off. We also observed a significant angle-of-approach (AoA) effect on interceptability, implying that the ball's approach angle co-determined the action boundary alongside the spatiotemporal factors. This AoA effect was previously identified in control of action through kinematic variables despite a shared interception location and time. Identifying the same AoA variable enabled linking interceptability to prospective control of action in a novel finding. Participants' verbal judgments of their action capabilities showed over 80% accuracy. Model comparisons of actions and action judgments revealed similar trends for actual and perceived interceptability respectively. However, participants' judgments reflected sensitivity to the action boundary but not to the speed-accuracy effect. In a follow-up study we demonstrated that increasing paddle size eliminated the speed-accuracy effect in actual interceptability. In conclusion, our studies demonstrate that alongside the hypothesized effect of distance and time, the AoA also influences interceptability of a ball, consequently linking action and perception systems. Additionally, while individuals may not be sensitive to the speed-accuracy effect in their judgments, it still impacts their action capabilities.

E – Integrative Control of Movement

2-E-59 - Role of variability in exploration for new coordination patterns during de novo learning

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Details

De novo learning involves developing specific coordination patterns of joint angles to achieve task goals. The acquisition of these coordination patterns relies on exploration during the learning process, characterized by systematic changes in individual joint angles over time and influenced by variability. The role of exploration in forming these coordination patterns has not been systematically studied, prompting our investigation into the impact of variability on exploration during de novo learning. In our initial study, we manipulated extrinsic variability and hypothesized that participants engaging in random practice would exhibit higher exploration than those in constant practice. The expectation was that the random practice group's heightened exploratory behaviour would result in greater variability of joint configurations within the solution space compared to the constant practice group. To assess this, a learning task was conducted with constant and random practice groups, followed by a transfer task. Twenty-two participants (Age: 23.8 ±3.2 yrs, 7M & 15F) learned a virtual lateral interception task where wrist, elbow, and shoulder movements controlled a paddle intercepting a downward-moving ball. A novel redundant mapping was introduced between the joint angles measured by the inertial measurement unit (IMU) sensors and the paddle position in VR. Learning the mapping to accurately move the paddle required the formation of new coordination patterns. Results showed successful learning of the mapping and required movement coordination in both practice conditions. Exploration, operationalized as the difference in path length within the joint space between successive trials, was higher in random practice than constant practice during each learning phase, supporting our hypothesis.

The uncontrolled manifold (UCM) analysis indicated that in the last phase of learning, VUCM (task irrelevant variability) was higher than VORT (task relevant variability) for both practice conditions, suggesting the formation of coordination patterns. Furthermore, random practice resulted in higher VUCM, signifying the use of more diverse joint configurations for the task. These preliminary findings suggest that increased variability during practice enhances exploration, leading to the formation of more diverse coordination patterns. A follow-up study will explore how intrinsic variability, combined with extrinsic variability, influences exploration.

2-E-60 - Feeding mental imagery with our own self-generated touch feedback alleviates sensory gating

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Details

To interact with the world around us, internal model theory argues that the central nervous system holds representations of the state of the sensorimotor system that are essential for predicting and controlling our future actions. To prevent from fading, these motor representations require updating through sensorimotor activity. Mental imagery is considered as an effective method for investigating processes related to motor representations (Jeannerod 1994). However, the absence of sensorimotor feedback during mental imagery may result in a fading of the motor representations. Our hypothesis is that integrating sensory signal during motor imagery should improve and update such representations.

To test this hypothesis, we used a novel vibrotactile feedback system, the Piezotact device, during a mental imagery task and a control task with no cognitive or motor task to perform. During these two tasks, and for each participant (N=10), the Piezotact device reproduced the vibrations recorded when the participant actively explored one of 3 textured surfaces. The surface recognition was used as an index of the accuracy of the motor-based tactile representations during the imagery and control tasks. The cortical processing of tactile information was assessed using time-frequency analyses of the electroencephalography (EEG) signals. These analyses showed smaller alpha (8-12 Hz) desynchronization (ERD) within the somatosensory area during natural rubbing movement as compared to the control task indicating a movement-related sensory attenuation. Importantly during motor imagery the results showed greater alpha ERD compared to the natural rubbing movement. This suggests that the sensory gating that is normally observed during overt and imagined movements (Kilteni et al. 2018) was partly alleviated during mental imagery when the participants received tactile feedback normally associated with their natural movement. In addition, the accuracy in recognizing the different surfaces increased during mental imagery as compared to the control condition where similar tactile feedback was given. Reducing the gating of self-generated tactile feedback might be a mean to improve internal motor representations. This offers potential applications for the use of mental imagery associated with reproduced sensory feedback in neurorehabilitation.

2-E-61 - Local muscle pressure stimulates the principal receptors for proprioception

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Details

Muscle spindles are considered the principal receptors for proprioception, sensing muscle stretch and signaling limb position and velocity. We used microneurography to record from muscle spindle afferents (n=14) in the right radial nerve of eight awake individuals, while a probe (5 mm tip diameter) applied percutaneous pressure periodically on a small part of the spindle-bearing forearm muscles (wrist extensors and common digit extensor muscles). A kinematic sensor tracked movement about the wrist in the flexion-extension dimension. Surface EMG electrodes recorded muscle activity of wrist and finger extensor muscles from which the recorded spindle afferents originated. A monitor displayed two visual targets and a cursor representing hand movement. The experimental task involved two conditions. In the 'isometric' condition, the semi-pronated hand was immobile whereas in the 'sinusoidal' condition the experimenter moved the participant's hand continuously in the flexion-extension dimension so that the cursor reached the visual targets at a 0.5 Hz pace. Some participants also performed the sinusoidal movements actively, for comparison of spindle behavior. We show that local muscle pressure is an adequate stimulus for human spindles in isometric conditions, and that pressure enhances spindle responses during stretch, as hypothesized to occur due to compression of the spindle capsule. Our findings redefine basic muscle feedback and urge a reconsideration of proprioception's role in sensorimotor control and various neuromuscular pathologies.

2-E-62 - Cross-area sensorimotor subspace contains distinct prehension features

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Details

How motor and sensory areas communicate during complicated prehension behavior is not fully understood. We approach this problem from a neural manifold perspective. Using dual chronic 64-channel microwire electrode arrays (Tucker-Davis Technologies), we recorded extracellular spiking data simultaneously from dorsal premotor cortex (PMd) and area 2 of somatosensory cortex of non-human primates (rhesus macaques) performing reach-to-grasp tasks that are likely dependent on touch and proprioception of the hand and arm.

By monitoring of kinematic features of the arm and fingers (DeepLabCut) during task performance, we are able to show evidence of a multidimensional cross-area neural subspace between premotor and somatosensory cortices whose cross-area factors correspond to different features of prehension behavior in reach-to-grasp tasks. We hypothesize that the time-varying activation of these cross-area neural modes may facilitate the time-sensitive coordination of regions that must cooperate to complete sensorimotor tasks.

We also present the analysis of these simultaneous PMd-Area 2 recordings over the course of recovery from sensorimotor stroke lesions. By binning sessions by subject performance relative to pre-stroke metrics, we can compare aspects of the cross-area subspace for days when the subject was still in the early phase of behavioral recovery to days when the animal had behaviorally recovered from stroke. These aspects include trial-to-trial variability of latent activity, dimensionality, and the kinematic features present within the cross-area subspace dimensions.

2-E-63 - Generating realistic arm movements in reinforcement learning: a quantitative comparison of reward terms and task requirements

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Details

The mimicking of human-like arm movement characteristics involves the consideration of three factors during control policy synthesis: (a)~chosen task requirements, (b)~inclusion of noise during movement execution and (c)~chosen optimality principles. Previous studies showed that when considering these factors (a-c) individually, it is possible to synthesize arm movements that either kinematically match the experimental data or reproduce the stereotypical triphasic muscle activation pattern. However, to date no quantitative comparison has been made on how realistic the arm movement generated by each factor is; as well as whether a partial or total combination of all factors results in arm movements with human-like kinematic characteristics and a triphasic muscle pattern. To investigate this, we used reinforcement learning to learn a control policy for a musculoskeletal arm model, aiming to discern which combination of factors (a-c) results in realistic arm movements according to four frequently reported stereotypical characteristics. Our findings indicate that incorporating velocity and acceleration requirements into the reaching task, employing reward terms that encourage minimization of mechanical work, hand jerk, and control effort, along with the inclusion of noise during movement, leads to the emergence of realistic human arm movements in reinforcement learning. We expect that the gained insights will help in the future to better predict desired arm movements and corrective forces in wearable assistive devices.

2-E-64 - Neural representation of mechanical reasoning while using novel tools

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Details

Research on apraxia has established deficits in using tools as an independent symptom following brain damage, independent from primary motor deficits or failures in task understanding. Neuroimaging in healthy individuals has likewise revealed distinct brain networks associated with imagining or actually using familiar tools. In our work, we have interpreted observed brain activations along the theory of ventral, dorsal and ventro-dorsal streams from vision to action. It needs to be determined how much an understanding of the mechanics of tool use contributes to successful tool use and consequently forms part of the streams.

We therefore investigated functional magnetic resonance imaging (fMRI) using novel tools whose mechanics could be inferred from observation but were never manipulated before. To this aim, we used an established test (Novel Tool Use Test by Goldenberg et al. 1998), which is highly sensitive to apraxia. A particular go/no-go design enabled fMRI investigation of the planning of real tool interactions without movement artefacts.

In agreement with our previous study on familiar tools and previous lesion studies in stroke patients with apraxia, we found predominantly left-lateralized brain activations with the inferior parietal cortex as a central hub for praxis processing. In addition, areas in the prefrontal and premotor cortices contributed to planning the manipulation of novel tools. Unlike previous studies, we found no larger contributions from the ventral temporal lobe and the superior parietal lobe, which were previously attributed to tool/object identification and interaction, respectively.

The specific involvement of the frontal areas and lack of ventro-temporal contributions argues against theories of an essential role of mechanical reasoning in everyday familiar tool use. However, the overlap suggests a flexible contribution that can be integrated when we learn to use a novel tool or when we use a known tool for an unfamiliar purpose, such as when using tongs for hammering. It remains to be resolved how modern digital tools like automatic door openers, which do not involve mechanics' experiences, are processed in the tool networks of the brain and how their spread affects our tool use skills.

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2-E-65 - Anisotropy of temporal resolution on the hand dorsum

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Details

Spatial perception of touch on the dorsum side of the hand has been shown to be distorted. Specifically, the tactile stimulus is perceived relatively longer on the mediolateral axis (across the hand) and shorter on the proximodistal axis (along the hand). The reason for this distortion is assumed to arise from the anisotropic nature of the receptive fields (RFs), which are generally oval-shaped with the long-axis aligning proximo-distally. Stimulus covering more receptive fields may have resulted in longer perceived distance on the skin. If this receptive field shape governs the tactile processing in general, its signature should be also detected in the domain of temporal processing. Here, we show that temporal perception of touch on the hand dorsum follows a pattern similar to that of spatial perception, where the mediolateral and proximodistal axes have different temporal resolutions of touch.

Twenty participants underwent a temporal order judgment task (TOJ), where they judged the temporal order of two stimuli successively delivered on the hand dorsum with various SOAs (stimulus-onset-asynchrony). The temporal resolution of touch between the two axes was compared by calculating the slope of the logistic function calculated from the participants' responses. The experiment was designed in a 2 by 2 factorial design. One factor was the axis on the skin; whether the two stimuli were aligned with the mediolateral axis of the hand or aligned with the proximodistal axis of the hand. Another factor was the posture, where the participant's hand orientation was either extended (fingers pointing ahead) or flexed (90 °rotated relative to the body). The latter factor was included to examine the skin-space dependency, thus the tactile RF dependency, of the effect.

We found that the temporal resolution, measured as just noticeable difference (JND) of the TOJ, was higher (smaller JND) for the stimuli delivered on the mediolateral axis compared to that delivered on the proximodistal axis, irrespective of the hand posture (main effect of skin axis; $p<0.05$). This indicates that this axis-dependent difference in the temporal resolution originates from the processing in the skin-centered space, not in the torso- or eye-centered space.

Regarding the anisotropy of the receptive field shape on the hand dorsum, stimuli on the mediolateral axis have a higher probability of crossing more receptive fields than the proximodistal axis, which can enhance the temporal segregation of the tactile inputs. Therefore, our result suggests that the anisotropy of the tactile receptive field may not merely affect the spatial processing of the input, but also shapes the temporal processing of touch.

2-E-66 - Involvement of aIPS and PMv in online adjustments to object size and distance perturbations during reach-to-grasp movements in virtual reality

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Details

Coordination of the reach-to-grasp movement in the face of perturbations is a hallmark of adaptive control. Parietal areas like the anterior intraparietal sulcus (aIPS) and the superior parieto-occipital (SPOC) regions have been shown to play a role in the sensorimotor integration of the reach-to-grasp movement in humans. Moreover, dorsal (PMd) and ventral (PMv) premotor regions are thought to be involved in the selection and control of the reach and the grasp, respectively. We set out to test the hypothesis that dorsomedial nodes (SPOC-PMd) may be preferably involved in the control of reach parameters while dorsolateral nodes (aIPS-PMv) may be more strongly involved in the control of grasp parameters.Nine healthy right-handed participants (24 ±7.3 years old), after providing informed consent, performed reach-to-grasp movements in a virtual environment towards a rectangular virtual object (3.6 X 2.5 X 8.0cm), located 24cm from the starting position. On a minority of the trials (25%), the SIZE or the location (DISTANCE) of the object were perturbed. For size, the virtual object's width expanded from 3.6 to 7.2cm. For distance, the object moved from 24 to 36cm away from the participant.Perturbations were applied either at 100 (EARLY) or 300ms (LATE) after movement onset, requiring participants to make online compensatory responses of the transport and/or grasp. Transcranial magnetic stimulation (TMS) was used to perturb processing, in each of the parietal and premotor nodes (50% of trials) time-locked with the perturbation. Grip Aperture (GA) and Grip Aperture velocity (GAV), Transport velocity of the reach (TV) and Transport acceleration (TA) were selected as outcome measures. Our results showed significant differences only during the LATE perturbations. We observed a disruption in GA for SIZE following TMS to aIPS ($p < 0.001$) as well as a disruption of TV in DISTANCE following TMS to PMv ($p<0.001$). Our data suggest that the dorsolateral grasping network may process both reach and grasp parameters.

2-E-67 - Differential sensitivity of manipulation and grasp forces to task requirements

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Details

The human hand's impressive dexterity allows for interaction with the environment through complex sensorimotor interactions, such as the manipulation of objects through sensory feedback and elaborate coordination of finger forces. However, the coordination of digit forces to effectively prevent object slip and control object position and orientation (pose) in modern daily life remains unknown.

We have previously used manipulation and grasp force decomposition (MGFD), a force analysis tool derived from robotic applications, to identify sensorimotor mechanisms underlying the control of dexterous manipulation (Wu and Santello, 2023). MGFD decomposes digit forces into Grasp Force (F_G), the force required to prevent object slip, and Manipulation Force (F_M), the force required to control object pose. We found that F_G was controlled in an anticipatory fashion at object lift onset, whereas F_M was modulated following acquisition of somatosensory and visual feedback of object's dynamics throughout object lift. However, the extent to which object properties influence the modulation of F_G, F_M, and their coordination has yet to be investigated.

We recruited 20 participants (10 females) to perform a dexterous task that requires simultaneous object slip prevention and pose control with two-digit precision grasping. We instructed participants to reach and grasp an inverted-T shape object using the thumb and index fingertip, lift the object vertically while preventing tilt of the object in any direction, hold the object, and set the object back down. We systematically changed the object's mass or distribution to vary the requirements for object slip prevention and pose control, respectively. The object's mass or moment of inertia were adjusted by inserting two different weights at the same location or moving the same weight to a different moment arm, respectively. We also addressed the effect of predictability of object property by presenting object properties using either blocked experimental conditions, consisting of consecutive trials with the same object property, or employing a pseudo-randomized design across trials.

We found that F_G increased in the heavier mass and decreased for higher moment of inertia conditions. However, F_M was modulated selectively to object pose control requirements. Specifically, the tangential component of F_M (responsible for changing the vertical object position) only increased when changing mass, whereas the normal component of F_M (responsible for controlling object orientation) only increased when changing moment of inertia. These findings were found regardless of object property predictability. Together, the present results point to differential sensitivity of F_G and F_M to task requirements while providing novel insights into how the central nervous system controls digit forces to attain two functionally distinct goals of dexterous object manipulation.

2-E-68 - Information processing during the hand laterality judgement task is primarily driven by rotational angle: insights from a 'forced response' paradigm

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Details

Introduction: Motor Imagery (MI) is the mental rehearsal of a movement without actual physical execution. The neural substrates of MI largely overlap with movement execution, and ample evidence supports the idea that MI can enhance motor skills both in healthy and clinical populations by producing motor learning and use-dependent plasticity. However, the quality of MI substantially varies across individuals, which has led to the development of measures of 'imagery ability'. The Hand Laterality Judgement Task (HLJT) has been extensively used as a measure of *implicit* MI ability. In the task, the individual determines whether a hand image rotated to different angles shows a left or right hand. Prior work has generally demonstrated that MI is used inadvertently to solve the task (i.e., individuals rotate the images by 'simulating' the movement with their *own* hands). Nonetheless, no research has studied how information processing behaves during the task, which is critical to better understand physiological processes underlying MI and movement control.

Methods: Thirteen healthy, right-handed individuals (5 females and 6 males; age = 26.62 ± 4.50 years) participated. The task followed a 'Forced response' paradigm, whereby the time participants had to respond to the stimulus was systematically manipulated, effectively allowing us to study information processing depending on the 'preparation time' available. Stimuli were 16 unique images presenting dorsal views of the hand (8 rotational angles [0 °/45 °/90 °/135 °/180 °/225 °/270 °/315 °] in the clockwise direction x 2 sides [right/left]) and were randomly presented at 75 different preparation times (16-1,200ms) each (N=1200 trials). Accuracy and response times were collected. Speed-accuracy trade-offs were analysed with mixed-effects models.

Results: Overall, participants responded randomly (at chance level) at short preparation times (0-300ms) and the proportion of correct responses increased with preparation time. A main effect of Angle was found, whereby the non-rotated or less rotated stimuli (0 °/45 °/315 °) required the least preparation time to reach plateau (~800ms), as compared to the most rotated stimulus (180 °), which did not reach plateau, even at the longest preparation time available (~1200ms). For the intermediate rotation angles (90 °/135 °/225 °/270 °), the trend was towards plateauing at 1000ms. Accuracy increased above chance level (50%) at approximately 300-400ms for all angles, except for the most rotated stimulus, which needed substantially more time (~800ms).

Conclusion: Information processing during the HLJT is primarily driven by the rotational angle. This provides insights into the use of MI to solve the task and its underlying neural processes.

2-E-69 - Career development support from NIH

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Details

The National Institutes of Health (NIH), as the largest funder of biomedical research in the world, directly supports a large proportion of the rehabilitation science research including studies in the field of motor control and the neural mechanisms that allow the meaningful activities of daily life. Understanding which NIH Institutes might connect to NCM researchers and the NIH peer review process can improve one's chance of getting funded. Outreach efforts by the Program Officers help investigators understand important aspects of the grant submission and review process. With the goal to educate potential NIH grant applicants', key areas for discussion cover: who at NIH to talk to about your application, the basics of peer review and review criteria, what reviewers look for, the review timeline, how to find the right study section, and recent policy initiatives such as those pertaining to rigor and reproducibility, clinical trials and peer review integrity. An overview of the Early Career Reviewer (ECR) program will be presented to encourage potential reviewers to serve. In addition, recent funding opportunities related to NCM at the National institute of Child health and Human Development will be discussed. Outreach efforts help to minimize the influence of grantsmanship and differential knowledge of NIH priorities, policies, and practices, to ensure that review outcomes reflect the strength of applicants' ideas and capabilities as scientists.

2-E-70 - Non-invasive OPM evidence for rhythmic interactions between the human brain, spinal cord, and muscle

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Details

Voluntary human movement relies on interactions between the spinal cord, brain, and sensory afferents. The integrative function of the spinal cord has proven particularly difficult to study directly and non-invasively in humans due to challenges in measuring spinal cord activity. Investigations of sensorimotor integration often rely on cortico-muscular coupling, which can capture interactions between the brain and muscle, but cannot reveal how the spinal cord mediates this communication. Here, we introduce a system for direct, non-invasive imaging of concurrent brain and cervical spinal cord activity in humans using optically-pumped magnetometers (OPMs).
We used this system to study endogenous interactions between the brain, spinal cord, and muscle involved in sensorimotor control during simple maintained contraction. Participants (n=3) performed a hand contraction with real-time visual feedback while we recorded brain and spinal cord activity using OPMs and muscle activity using EMG.
We first identify the part of the spinal cord exhibiting a peak in estimated current flow in the cervical region during contraction using a source reconstruction framework. We then demonstrate that rhythmic activity in the spinal cord exhibits significant coupling with both brain and muscle activity using phase- and amplitude- based functional connectivity metrics. These findings evidence the possibility of concurrent spatio-temporal imaging along the entire neuro-axis, which opens new possibilities for advancing our understanding of how communication is coordinated in the central nervous system, both in health and disease.

2-E-71 - Bilateral tDCS protocols improved ankle-dorsiflexion force control capabilities between feet

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Details

Transcranial direct current stimulation (tDCS) is one of non-invasive brain stimulation techniques that may modulate cortical activation patterns contributing to motor control improvements. For bilateral lower limb functions such as postural control, walking, and running, previous studies have used unilateral anodal tDCS protocols on leg of the M1 (i.e., the vertex; Cz in the 10-20 system for EEG) with cathodal stimulation on the suborbital region as a reference. Considering the distance between anodal and cathodal electrodes presumably influencing the current flow and after effects of stimulation, these traditional stimulation protocols for lower limb function may be adapted for optimizing tDCS effects. A recent simulation study suggested that anodal stimulation on the C1 and cathodal stimulation on the C2 revealed higher electrical field intensities reaching deeper leg regions of the M1. Thus, this study aimed to investigate the effect of bilateral tDCS protocol (anodal on C1 and cathodal on C2) on isometric force control capabilities of lower extremities. Fourteen healthy young adults performed bilateral ankle-dorsiflexion force control at 10% of maximum voluntary contraction while receiving simultaneous visual feedback on the targeted force level and bilateral force outputs. For each participant, we randomly provided active and sham tDCS protocols during force control tasks: (a) current intensity = 2 mA, (b) electrode size = 25 cm^2, and (c) duration of stimulation = 20 min. To estimate force control capabilities, we calculated (a) mean force, (b) force accuracy (RMSE), (c) force variability (SD), and (d) force regularity (sample entropy). The paired *t*-test was used for analyzing differences in force control capabilities between active- and sham-tDCS conditions. The findings revealed that applying active bilateral tDCS protocols failed to alter mean force (t_{13} = -0.170 and P = 0.867) and sample entropy (t_{13} = -0.275 and P = 0.788). However, the analysis found significant reduction of RMSE (t_{13} = -2.692 and P = 0.018) and SD (t_{13} = -2.692 and P = 0.018) in active-tDCS condition as compared with those for sham-tDCS condition. These findings indicate that active bilateral tDCS protocols improved force accuracy and variability of forces produced by both feet. Potentially, modulating motor areas related lower limb function using tDCS protocols may lead to fine motor control improvements in lower limbs.

2-E-72 - Smooth pursuit eye movements contribute to anticipatory limb force stabilization during contact with moving objects

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Details

Mechanical interactions with moving objects require posture stabilization and precise force application. To that end, it is crucial to accurately estimate the relative motion between the object and the body. The visual system employs various mechanisms to estimate object motion, which includes retinal cues derived from the movement of an object's image on the retina, as well as extraretinal signals associated with smooth pursuit eye movements (SPEMs) used for tracking moving objects. It has been previously proposed that the extraretinal signals generated by the ocular motor system for SPEMs might serve as a predictive signal for the limb motor system to control movement. During activities such as catching objects, the motor system adjusts anticipatory muscle activity in antagonist upper limb muscles based on the velocity of approaching objects. Similarly, prehension studies have shown that participants scale grip forces prior to contact when they catch objects dropped into grasped containers. These findings suggest that the visuomotor system can accurately discern between objects with different movement profiles. This leads to the question of whether the extraretinal signals associated with SPEMs play a role in accurately estimating object velocity and subsequently ensuring posture stability and motor planning. To address this question, we predicted that when participants track moving objects with SPEMs, as compared to when their gaze is fixed, they would initiate motor responses closer to the moment of contact and reduce the level of anticipatory limb forces before contact. These predictions were based on studies that have shown that observers overestimate the speed of objects when their gaze is constrained. Participants stopped a virtual moving object by applying a force impulse that matched its momentum. To test our predictions, we proposed a Force Control Model in which we analyzed correlations between SPEM gain (ratio of gaze and object velocity), the timing of motor responses, and anticipatory limb forces before contact. Our data indicated that constraining SPEMs did not affect the timing of motor responses but did lead to a reduction in the magnitude of anticipatory limb forces before contact. Building on these results, we adapted the model and conducted a follow-up experiment in which we manipulated the contact dynamics (soft versus hard contacts) while keeping the object's motion constant. This experiment revealed that, despite the similarity in SPEM signals for hard and soft contacts, the timing of motor responses and anticipatory forces changed. These findings suggest that SPEMs contribute to the adjustment of anticipatory responses, but the timing of these responses and the magnitude of anticipatory limb forces are also influenced by the dynamics of object contact. These results provide insights into the processes underlying visuomotor transformations associated with SPEMs and their role in shaping anticipatory postural responses.

2-E-73 - Robust neuroprosthetic control using cerebellar activity in the stroke brain

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Details

Over the years, impressive studies in rodent, non-human primates and clinical applications in humans have demonstrated that the activity of sensorimotor neocortical areas can be decoded as a control signal to replace lost motor function using brain-machine interfaces (BMI). Surprisingly, subcortical regions such as the cerebellum (Cb) have not received much attention for implementing direct neural control, despite studies revealing that neurons in the cerebellar cortex exhibit tuning to limb position, velocity, duration, and muscle activity during voluntary arm movements. It is important to study if Cb direct neural control is feasible, as cortical areas such as the primary motor cortex (M1) may not be viable for direct neural control after an injury such as stroke. We validated the use of direct Cb cortical neural activity in a neuroprosthetic task in healthy and stroke rodent models and also used this paradigm to study cortico-cerebellar interactions.

We recorded single-units and local-field potentials (LFPs) from drivable polytrodes in the Cb cortex as well as microelectrodes in M1 while adult healthy long-Evans rats (n = 11) performed a neuroprosthetic task using the M1 or Cb activity. Additionally, we conducted Cb BMI experiments in a cohort of M1-stroke injured animals (n = 5; photothrombotic stroke), to test the viability of Cb neural activity for BMI application with an injured M1. During the task, rats exerted control over the angular velocity of a water tube by modulating the activity of a subset of experimenter-defined Cb neurons, classified as ‘direct’ neurons and using a simple linear decoder (Gulati et al, 2017; Kim et al, 2019).

Our results show that efficient Cb-driven BMI control is possible, and it is as robust as M1-driven control. We observed that direct ‘decoder’ Cb neurons develop robust task-related modulation similar to the ones seen in M1-driven BMIs. Remarkably, robust neuroprosthetic learning was also seen in rats recovering from stroke that had their forelimb motor function impaired as assessed on a reach-to-grasp motor task. Furthermore, we observed extensive indirect task-related modulation in both Cb and M1. Using regression models, we found that Cb/M1 indirect activity predicted the Cb direct activity, but the timescale was different for local versus distant cross-region interactions. Cb BMI behavioral performance remained the same in M1-stroke injured versus healthy brain while cortico-cerebellar interactions were affected post-stroke.

Our work demonstrates the efficacy of direct BMI control using Cb neural activity when M1 is stroke-injured and elucidates the cortico-cerebellar neural mechanisms facilitating such control.

2-E-92 - Principles of reinforcement learning during continuous motor control

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Details

Reinforcement learning, the ability to learn from past outcomes, has been classically studied during decision-making, where agents use endpoint feedback after action selection to learn the value of potential options. Yet, there is now an increased recognition that reinforcement learning processes are also at play in other contexts such as during motor skill acquisition (e.g., learning to drive) or when patients have to re-learn fine motor skills through rehabilitation (e.g., manipulation of fragile objects). In such complex, continuous motor tasks, the potential of endpoint reinforcement feedback (RF) is limited as it lacks real-time information on which part of the movement needs correction. In contrast, providing RF in real-time, during movement, may be more efficient for control but also for future retention of the trained skill. Notably, recent rehabilitation technologies such as those incorporating serious games or extended reality applications now offer the means to provide real-time RF during therapy. Yet, the mechanisms underlying continuous reinforcement of motor skills remain largely unknown. To bridge this gap, we designed a continuous force-tracking task delivering personalized RF in real-time during ongoing motor control. Exp1 (n=24) revealed that the benefits of RF scaled with the level of visual uncertainty during the task, suggesting that the reliance on real-time RF depended on the quality of visual feedback. Information-theoretic analyses confirmed an increase in feedback corrections with RF specifically in contexts with high visual uncertainty. Dissection of kinematic profiles further revealed that RF-based increase in feedback corrections were related to a reduction of variability after success rather than an increase of variability after failure. These results were then replicated within the same subjects (Exp2) and another independent cohort (Exp3, n=24). Hence, real-time RF is particularly efficient when visual uncertainty is high and leads to direct improvements in motor control that are retained at later RF-free stages. In theory, improvements in motor control with high visual uncertainty could occur without somatosensory input, by reducing motor variability when movements are successful. To directly test this idea, we asked subjects (Exp4, n=40) to perform the same task with isometric EMG control of the cursor (limiting natural somatosensory feedback) and provided somatosensory feedback artificially, through a servo-motor. We found evidence that somatosensory input was not required for reinforcement gains in motor control. Intriguingly though, somatosensory information was necessary for reinforcement gains in motor memory retention, suggesting that reinforcement gains in motor control and retention rely on partially different mechanisms. Overall, this work characterizes key mechanisms underlying continuous reinforcement of motor skills, paving the way for the implementation of real-time reinforcement in rehabilitation.

F- Posture and Gait

2-F-74 - Assessing corticoreticular tract integrity in multiple sclerosis: implications for postural and gait deficits

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Details

The corticoreticular tract (CRT) is a prominent motor pathway that has been implicated as a key tract in motor control specifically influencing postural stability and gait. The CRT is thought to link various cortical regions to the pontomedullary reticular formation which projects to spinal interneurons and motoneurons via the reticulospinal tract. Several studies have identified associations between damage to the CRT due to stroke/traumatic brain injuries and postural and locomotion impairments, highlighting its pivotal role in maintaining balance and mobility. However, despite these insights, certain neurological conditions known to impact balance and mobility, such as multiple sclerosis, remain less explored.

Multiple Sclerosis (MS) is a debilitating neurological disease that currently affects 3 million people worldwide. In MS pathology, structural damage to neurons in the central nervous system leads to a range of symptoms that negatively impact quality of life. Specifically, balance and mobility impairments are the most commonly reported symptoms of MS and create a direct obstacle to independence in daily life. Despite this, our understanding of the genesis of these impairments and how to best treat them remains poor.

The present study uses diffusion magnetic resonance imaging (dMRI) to assess the integrity of the CRT in people with MS (PwMS). We further investigate the relationship between CRT integrity and various mobility and postural metrics, including gait speed, static balance, and lower limb power. For the study, we recruited 30 individuals diagnosed with relapsing-remitting MS and 30 age- and sex-matched controls. High-resolution dMRI scans were acquired with a 3.0 T Siemens MAGNETOM Prismafit MRI scanner equipped with a 32-channel head coil and parallel imaging to reconstruct the CRT and quantify white matter microstructural integrity. Behavioral metrics were acquired using six tri-axial Opal „¢ body-worn inertial sensors, a BTrackS portable force platform, and Bertec force platforms.

While data analysis is on-going, we anticipate that our findings will reveal significant differences in CRT integrity between PwMS and healthy controls. We hypothesize that PwMS will display decreased fractional anisotropy and increased radial diffusivity, indicating axonal loss and demyelination within the CRT. Further, we hypothesize that CRT integrity measures will significantly correlate with mobility and postural metrics, suggesting a direct association between corticoreticular tract damage and functional impairments in MS.

This study provides novel insights into the neuroanatomical substrates underlying postural and gait deficits in PwMS by associating CRT integrity and postural and gait metrics. By elucidating the role of the CRT in motor control for the MS population, we highlight the importance of targeted rehabilitation strategies aimed at preserving CRT integrity and improving functional outcomes in MS patients.

2-F-75 - Flexible and rapid modulation of gait control assessed by long-range autocorrelation

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Details

Gait variability of healthy adults displays Long-Range Autocorrelations (LRA), meaning that the stride interval at any time statistically depends on previous gait cycles; and this dependency spans over several hundreds of strides. Clinically, the presence of LRA in stride series is often considered as a marker of health, while its alteration has been associated with pathological conditions such as Parkinson's disease, and an increased risk of falling. Previous works suggested that LRA may result from a selective regulation of stride length and duration while maintaining a constant target speed. In this framework, constraining the stride time with a metronome would impedes the flexible regulation of this gait parameter, leading to a decrease of LRA in series of stride durations. However, while the decrease in LRA when gait is guided with a metronome has been widely documented, transitions between walking with and without a metronome (and vice-versa) have not been measured. It is therefore unclear how people adapt to such a change of task. Importantly our analyses were compared to a computational model allowing us to relate sudden changes in movement parameters to the LRA, which is typically measured over longer timescales. We first report the result of an experiment with 21 healthy adults. They were asked to walk overground and synchronize one foot with an isochronous metronome set to their average spontaneous pace, measured prior to the testing involving the metronome. Each participant performed two conditions of 15 minutes in which the metronome was activated during either the first or second half of the session to test both transitions. The LRA was assessed based on the Hurst exponent (H), computed with the Adaptive Fractal Analysis. This method was applied on successive overlapping subsets of the stride series to outline the evolution of the LRA. In healthy participants, results showed a clear transition in both conditions, with LRA of the series of stride duration gradually reduced when the metronome was turned on (difference in H = -0.34 +/- 0.15, $p < 10^{-4}$) and recovered when it was turned off (difference in H = 0.33 +/- 0.16, $p < 10^{-4}$). This change in LRA could be reproduced in the model by an instantaneous change of the parameter linked to the regulation of stride time. We then performed the same experiment involving patients with Parkinson's disease and age-matched healthy adults. Although the recruitment is still underway, our preliminary results already showed a significant decrease in LRA with the metronome, despite greater heterogeneity across patients compared to age-matched controls. Our results validate the hypothesis that LRA emerge from a flexible control that rapidly regulates timing and amplitude parameters according to task requirements. We interpret the adaptation in patients with Parkinson's disease in the framework of current theories associating the basal ganglia with a representation of motor costs.

2-F-76 - Stepping through fear: analysing postural adaptations in elderly women during transitional locomotor tasks

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Details

One of the primary factors influencing falls in the elderly is poor balance. These falls may occur during daily activities, the consequences of a fall might induce a loss of mobility, decreased independence and quality of life, or even increased mortality among the older population. Therefore, the purpose of our study was to identify postural changes that occur during a transitional task when the fear of falling is present. Eighty one females voluntarily participated in the study. Based on the falls efficacy scale-international (FES-I), participants were divided on the three groups with low concerns moderate concern high concern. The transitional task was measured by two force platforms. The procedure consisted of three phases: quiet standing, transfer onto a second platform, and quiet standing on the second platform. Four different conditions were applied: unperturbed transfer, obstacle crossing, step-up, and step-down. Double-support time, transit time, and stability time before and after the step task were analysed. The high concern group was characterized by a longer double support time, transit time and instability time during obstacle crossing, step-up, and step-down conditions compared other groups (p<0.05). There were no significant differences in time necessary to recover stability after taking a step (p>0.05). Fear of falling influences the time from exiting steady standing to stepping. However, it does not affect the time required to regain balance after taking a step. The transitional locomotor task might be useful for diagnosing postural impairment in individuals who report a fear of falling have no fall history.

2-F-77 - Dopamine intake improves cortico-muscular connectivity and gait coordination in Parkinson's disease

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Details

Introduction: Parkinson`s disease (PD) affects bilateral coordination of gait, reflecting impaired left-right stepping phase coordination. Underlying neurophysiological mechanisms may be related to defective cortico-muscular connectivity (measured via EMG-EEG coherences) due to impaired sensory feedback and sensorimotor integration in people with PD. Although not fully investigated, dopamine intake may improve sensory processing and integration, which may lead to better left-right step phase coordination. O**bjective:** We compared cortico-muscular connectivity and bilateral coordination of gait using the Phase Coordination Index (PCI, a measure of left-right stepping coordination) during walking in Parkinson's disease patients in ON (PD-ON) and OFF (PD-OFF) medication states and healthy older adults (OA). **Methods:** PD patients (n=14) and OA (n=9) walked back and forth in a 14m corridor. EEG, EMG, and gait events (heel strikes and toe-offs for identifying stance and swing periods) were measured. EEG-EMG coherences were computed for alpha, beta, and gamma bands between C3 and C4 channels (Ct) with right and left legs` muscles (vastus lateral -VL, biceps femoral -BF, gastrocnemius lateral -GL, tibial anterior -TA), respectively. We conducted ANOVAs with factors for Group (PD-ON & PD-OFF vs. OA) and Medication (PD-ON vs. PD-OFF). **Results:** Based on PCI, PD-OFF vs. PD-ON and PD-OFF vs. OA walked with lower coordination (ps<0.05). Based on cortico-muscular coherence, PD-ON vs. PD-OFF walked with higher Ct-VL, Ct-TA, and Ct-GL alpha during stance and Ct-VL alpha, Ct-BF and Ct-TA beta, and Ct-GL alpha, beta, and gamma coherences during the swing phase (ps<0.05). In contrast with OA, PD-ON walked with higher Ct-VL, CT-BF, and Ct-GL for alpha during the swing phase (ps<0.05). **Conclusion:** We interpreted that dopamine improves defective sensory feedback processing and sensorimotor integration, strengthening cortical-muscular connectivity and bilateral gait coordination in PD.

2-F-78 - Enhancing balance in the older adults: a tailored approach integrating postural training and proprioceptive stimulation

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Details

Efficient sensorimotor integration, involving visual, tactile, vestibular, and proprioceptive inputs, is crucial for maintaining upright posture. Dysfunction in proprioception, particularly in older adults, results in compromised balance and independence. Thus, inducing neural plasticity within proprioceptive pathways through targeted training and rehabilitation becomes imperative. This study investigates the impact of an 8-week balance training program, with and without superimposed proprioceptive stimulation, on balance and gait performance of older adults. Proprioceptive stimulation was applied through muscle vibration (MV), transcutaneous electrical nerve stimulation (TENS) or their combination, those stimulation modalities being known to target Ia afferent fibers from muscle spindles, crucial for sensorimotor integration.

A total of 49 healthy elderly participants (22 men and 27 women; 80 years ± 4; 166 cm ± 12; 66 kg ± 12) were randomly assigned into different groups: training (n = 8), training + local vibration (LV, n = 10), training + transcutaneous electrical nerve stimulation (TENS, n = 14), and training + LV and TENS (n = 17). All participants underwent baseline assessments followed by pre-intervention assessments 8 weeks later, this period acting as a control condition. This was followed by an 8-week intervention period, with two 1-hour sessions per week, and post-intervention assessments. The training sessions involved tailored postural exercises with variations in visual (i.e. eyes open vs closed), surface (i.e. stable vs unstable), and feet (e.g. monopodal vs bipodal) conditions. For LV and/or TENS groups, proprioceptive stimulation targeted the triceps surae and tibialis anterior muscles during exercises and resting periods. Outcome measures included the Berg Balance Scale (BBS), 6-minute walking test (6MWT), 10-meter walking test (10MWT), Time-Up and Go test (TUG), and Center of Pressure (CoP) variables during static postural tasks.

No significant differences were observed between baseline and pre-intervention values for all the outcome measurements, whatever the tested group. After training, all groups exhibited a significant improvement in BBS scores ($p<0.001$) and a decrease in TUG completion time ($p=0.006$), with no intergroup differences. The training interventions did not impact 6MWT ($p=0.434$) or 10MWT ($p=0.860$) performance. Static postural performance, as measured by CoP path length, improved significantly on an unstable surface ($p=0.020$) but not on a stable surface ($p=1$), with no differences between groups.

In conclusion, our findings suggest that tailored balance training effectively improves balance but does not significantly impact gait performance in older adults. Moreover, combining tailored balance training with proprioceptive stimulation through LV and/or TENS did not potentiate the observed benefits.

2-F-79 - Real-time analysis of gait through inertial sensors for optimization of epidural electrical stimulation

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Details

Segmentation of gait phases is a crucial initial step for all gait variable analyses. The ability to perform gait segmentation in clinical contexts is inherently valuable as it aids in characterizing and potentially diagnosing certain pathologies and their stages, or could support rehabilitation design. For instance, it could be employed to guide the development of epidural electrical stimulation protocols aimed at improving gait kinematics in patients with incomplete spinal cord injury. The integration of online processing could be useful for formulating data-driven frameworks to optimize electrical stimulation and provide real-time feedback to patients. In this context, development of easily applicable setups for the collection of gait data in clinical settings is crucial.

Typically, methods such as stereo-photogrammetry or insoles measuring ground reaction forces are employed, offering precise estimates through expensive sensor setups. In contrast, inertial measurement units, comprising a tri-axial gyroscope, accelerometer, and magnetometer, are a much more affordable way to estimate lower limb pose and thus to produce gait segmentation.

While offline gait analysis - including segmentation - does not poses particular challenges in healthy individuals, it becomes significantly more challenging in patients suffering from gait disorders and other pathologies, due to large deviations from standard gait parameter distributions and increased variability across several recordings of the same patient during therapy. Also, a difficulty arises in online analysis, where appropriate peak finding algorithms must be applied without knowledge of future signal behavior, raising difficulties even in the segmentation of healthy gait.

We demonstrate that signals from inertial measurement units placed on subjects' feet are adequate for reliable gait segmentation across various conditions (e.g., straight, backward, sideways walking) in healthy individuals, patients suffering from incomplete spinal cord injuries, Parkinson's disease, and hemiparetic patients. We outline the algorithms employed and present results in terms of gait segmentation and subsequent analysis of gait and electromyographic signals. Additionally, we illustrate how such segmentation can be conducted online in healthy subjects. Finally, we propose a framework for using these algorithms to facilitate online data-driven optimization of epidural electrical stimulation in clinical practice and promote feedback about motor performance.

2-F-80 - Cortical activity during reactive balance reflects perceptual-motor and cognitive-motor interactions

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Details

Our understanding of how human brain dynamics support complex whole-body behaviors that require cognitive and sensorimotor interactions remains limited. Prior research has been largely restricted to studying neural activity during relatively constrained tasks (supine or seated) and/or during tasks that dissociate perception from movement. Advances in mobile brain and body imaging using electroencephalography (EEG) now allow characterization of real-time cortical dynamics during ecologically-relevant balance task paradigms. This not only advances insight into the cortical control of balance, but enhances our understanding of circuit interactions between cognition, perception, and sensorimotor processing that may generalize across behaviors, from locomotion to upper limb movements. Here, we assessed EEG activity during external perturbations to standing balance to understand individual differences in cortical information processing in healthy adults and adults with neurological impairments (stroke, Parkinson's disease). EEG was recorded during a two-alternative forced choice task where participants judged whether pairs of backward support-surface perturbations during standing were in the "same" or "different" direction. Perceptual responses were fit to a psychometric curve to quantify perceptual ability. We also assessed cognitive set-shifting ability using the Trail Making Test and balance ability using the narrowing-beam walking test and the miniBEST. We focused on EEG activity originating from the supplementary motor area, as it serves as a hub for integrating cognitive, perceptual, and motor information necessary for complex whole-body behaviors. In younger adults, we found distinct neural correlates of perception and balance; pre-perturbation beta power, an index of sensorimotor processing, was associated with perception, consistent with prior findings of unimodal tactile perception in the upper limb. In contrast, evoked cortical activity modulation, an index of error assessment, was associated with balance function. In individuals with stroke and Parkinson's disease, cortical activity was less dynamic, particularly in individuals with cognitive set-shifting deficits; beta power was elevated, indicative of reduced sensorimotor processing, and evoked response modulation was attenuated. These findings suggest that reduced flexibility in cognitive processes may reflect a more global mechanism of less dynamic brain activity. The intersections across perceptual, cognitive, and motor domains may help identify complex mechanisms underlying whole-body behaviors in the real-world. Distinct neural correlates of perception and movement offers a unique opportunity to target different mechanisms in rehabilitation to optimize functional outcomes and improve our understanding of the neural control of movement.

2-F-81 - Human foot force reveals different balance control strategies between healthy younger and older adults

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Details

Aging can cause the decline of balance ability, which can increase fall risk and social isolation and decrease a person's quality of life. To understand the mechanisms behind compromised balance due to age, it is imperative to clarify any age-related changes in control strategies. The objective of this work was to determine if and how balance control strategies may differ between healthy older and younger adults. Although ground reaction forces are often measured to determine balance ability in subjects, only their point of application, the center of pressure, is usually considered. Previous work identified an intersection point of the lines of action of ground reaction forces that combines the information from the centers of pressure with the directions of those forces. This intersection point analysis incorporates the horizontal component of the ground reaction force that is proportional to the horizontal acceleration of the center of mass, adding important information about the dynamics of the system. Furthermore, previous studies of the intersection point on healthy young subjects in a variety of stance conditions showed a consistent behavior across all subjects when analyzed for different frequency components. When these experimental results were compared with simulated outcomes, the subjects' control strategy was best described by a controller that maintains minimal joint torque effort through the adjustment of relative ankle and hip torques. To determine whether this control strategy is maintained in healthy older subjects, the intersection point analysis was conducted on the ground reaction force data of 38 older subjects and 65 younger subjects from a previous study. To simulate balance, an optimal control method was used to control a double-inverted pendulum model with torque-actuated ankle and hip joints with white noise. First, it was shown that the intersection point analysis could distinguish between the two subject groups as effectively as the mean center of pressure speed, a measure that was previously shown to be effective in distinguishing between age groups. Second, the force data were compared to model predictions to identify best-fit controller parameter sets. The controller that minimized the overall torque effort in the ankle and hip produced the best fit for both subject groups. However, the relative use of these joints differed across the subject groups; older subjects' data required significantly more penalty on the hip torque than the ankle torque, compared to younger subjects' data. Further inspection of best-fit controller gains suggested a degradation of muscle that may be compensated for by increased neural activity in older adults. These results suggest that human balance strategies may evolve with age to compensate for decline in muscle stiffness and slower neural control systems. This work supports the applicability of the proposed method to identify the control strategies of quiet posture in various populations.

2-F-82 - Vestibular contributions to dynamic postural control in nonhuman primates

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Details

Maintaining stable posture is essential for animals moving in a dynamic world. It has long been appreciated that the vestibular system plays a vital role in postural control. For example, patients with profound bilateral vestibular loss (BVL) patients experience significant postural instability even following rehabilitation. Recent studies have demonstrated that vestibular afferents encode head motion in a context-independent manner, however neurons in the vestibular nuclei (VN) that generate vestibulo-spinal reflexes exhibit reafference suppression, attenuating their response to active self-generated motion.

Generating a well-tuned postural response to maintain stability requires distinguishing self-motion arising from an unexpected perturbation from that arising from active self-motion. Furthermore, postural compensation itself presents an additional source of self-motion that may be encoded as passive or active. Thus, whether and how neurons in the VN exhibit reafference suppression over the course of a postural perturbation will indicate whether the VN distinguishes between the passive perturbation and the active postural response.

Accordingly, here we test in a rhesus monkey model whether reafference suppression occurs during postural responses to support surface motion, and how these pathways adapt to vestibular loss. To determine whether vestibular signals are attenuated during postural responses, we first recorded behavioral responses to transient perturbations. Monkeys stood on a force plate and wore a head-mounted IMU. Roll tilts were delivered via a hexapod motion platform with the animal in a standard starting posture. While normal animals were able to compensate, BVL monkeys showed a characteristic maladaptive response to platform perturbations that was hypermetric and in the reverse direction of normal. Notably, this maladaptive response had a shorter latency than normal postural responses, indicating that vestibular feedback is required at every phase of the response.

Next we performed simultaneous neural recording from single units in the VN using a 32-channel linear probe and wireless neural logger to establish the mechanism underlying the maladaptive response generated in the absence of vestibular information. Despite the lack of vestibular input, vestibulo-spinal neurons were sensitive to head velocity opposite the normal direction. This is consistent with upweighting of somatosensory signals. Along with the absence of head-stabilizing neck muscle reflexes, this change in the tuning of the vestibulo-spinal neurons explains both the shorter latency and reversed response in BVL animals. Finally, our most recent work with vestibular prosthetic stimulation suggests that biomimetic stimulation can partially restore normal responses in vestibulo-spinal pathways. Taken together our results show that early postural responses are generated by spinal pathways, and vestibular feedback is required at all stages of the response.

G – Theoretical & Computational Motor Control

2-G-83 - Modeling proprioception with physics-informed neural networks

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Details

Proprioception is essential for planning and executing precise motor actions. It relies on sensory signals from mechanosensory neurons distributed within muscles, tendons, and joints. Muscle spindles convey information through sensory afferents to the central nervous system. While traditionally viewed as stretch receptors encoding muscle length and velocity, recent insights suggest they may function as adaptable signal-processing devices. Spinal gamma motor neurons are believed to drive this adaptability by modulating the responses of sensory afferent to task demands. However, the mechanisms by which this top-down modulation occurs are still unknown. To elucidate this, we propose a novel model of muscle spindles that merges structural fidelity with computational efficiency, leveraging the power of physics-informed neural networks (PINNs). The unique advantage of PINNs lies in their ability to incorporate physics knowledge, thereby enhancing model interpretability and predictive accuracy. By integrating principles of biomechanics and neural dynamics, our model captures the interplay of biomechanics and transduction processes within muscle spindles while maintaining computational tractability. Through validation across multiple experimental datasets and species, our model demonstrates superior performance in fitting experimental data and provides interpretability of the sources of variability in afferent responses including their top-down control. By bridging the gap between biomechanics and neural dynamics, our model offers a comprehensive understanding of muscle spindle function, shedding light on their role as adaptable signal processors in sensorimotor control. The proposed framework holds promise for advancing our understanding of proprioceptive mechanisms and functions along the sensorimotor pathway.

2-G-84 - The potential of neural avalanches to design innovative sensorimotor-based brain-computer interface

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Details

Brain-Computer Interface (BCI) research is a growing field not yet fully explored. The current features that are used in this context rely on local measurements disregarding the interconnected nature of brain functioning. To address these limitations, we proposed an original marker that captures the dynamic nature of the brain functioning: the neuronal avalanches, propagating cascades of bursts of activity among multiple brain regions. To assess their potential as BCI candidates, we tested neuronal avalanches using electroencephalography signals during resting state and a motor imagery task within a BCI protocol, both in sensor and source space.
Neuronal avalanche analysis entails identifying significant signal excursions beyond a threshold and clustering them based on temporal proximity. This process defines neuronal avalanches as periods of collective spatio-temporal organization, providing insights into rich functional connectivity dynamics. To track the probability that an avalanche would spread across any two channels/region we built an avalanche transition matrix (ATM) and we consider the brain as a network where nodes represent single channel/region and edges, linking two of them, their probability to be subsequently recruited by an avalanche.

Within the decoding framework relying on Support Vector Machine (SVM) classifiers, we compared classification performance resulting from the use of ATM (ATM+SVM) to the gold-standard approach, Common Spatial Patterns (CSP+SVM). In sensor-space, even if the averaged classification performance seemed comparable, CSP+SVM resulted in 6 subjects with performance below the chance level (58% here) compared to 1 subject with ATM+SVM. Besides, we observed a greater inter-subject variability in the case of CSP+SVM (standard deviation 15.55%) than with ATM+SVM (9.14%). Moreover, in source-space, ATM+SVM yielded significantly higher classification accuracy than CSP+SVM for 12 subjects, while the opposite was true for 3 subjects. These results show the potentially of ATM+SVM pipeline to be used in real-time experiments. Then, we investigated the interpretability of these findings by comparing the selected features for the decoding process and the set of edges where a significant condition effect was observed in most of the subjects, referred as “reliable”� edges. We observed an increased correspondence between “reliable’’ edges and the selected features induced an improved classification performance. Consistent patterns were observed over electrodes in motor areas (C5, CP3, and CP5) connected to parietal (P1, P3, and P8) and occipital (O2, O10, and PO9) areas, suggesting the involvement of multiple cognitive processes during a motor imagery task.

Our results propose integrating periodic and aperiodic features as a possible way to enhance task classification and neuronal avalanches as potential complementary/alternative features in BCI design.

2-G-85 - Modelling bilateral hemispheric control using neural networks

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Details

An important feature of our brains is the existence of two largely independent hemispheres, with the corpus callosum sending signals between them. The two hemispheres allow each side to be specialised in some functions - with a classic example being the differences between control of dominant and non-dominant hands. Neural-network models that mirror some of the key features of this control can help us better understand how this control takes place and model the effects of damage to the brain, mirroring damage due to brain injury. In this study, we examined the question by designing neural networks and selecting loss functions to achieve hemispheric specialisation in two tasks: accurate point-to-point movements (usually performed by the dominant hand/hemisphere), and maintaining a posture (usually performed by the non-dominant hand/hemisphere). We trained bilateral models with and without hemispheric specialisation, with and without inter-hemispheric connectivity (as a model of the corpus callosum), as well as unilateral models with and without specialisation. Additionally, we used virtual lesions in different parts of the network (cutting connections between layers/parts of the neural network). As expected, the networks trained on a particular task performed better than the non-favoured networks. A bilateral model was found to be better than the non-preferred hand in performing the relevant task, and as good or better than the preferred hand. The corpus callosum improved performance in some of the tasks. Further development of such neural network models can potentially help understand the purpose of handedness and provide potential training grounds for testing rehabilitation strategies due to brain damage.

2-G-86 - Investigating the modulation of muscular null space for the control of supernumerary degrees of freedom

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Details

Prior research has demonstrated the potential of muscular null space modulation for robotic augmentation, where the muscular null space, defined as muscle activation patterns not directly related to task-relevant forces, could be utilized to control supernumerary degrees of freedom. This approach would enable simultaneous control of both natural limbs and a supernumerary end-effector. In a previous study (Gurgone et al. 2022) we computed the null space from the matrix that approximates the mapping of EMG activations over 15 muscles onto isometric force, estimated by linear regression from EMGs and forces for multiple target directions. In this study, we aim to compare this method with a direct approach in which participants are instructed to activate specific muscles while minimizing the isometric force production. We compared these two approaches using the same EMG recording setup or a simpler configuration that only included data from six muscles, two of which used high-density electrode arrays. To compute the EMG-to-force matrix, participants performed a task where they had to reach and hold a cursor at various planar targets by generating forces on the horizontal plane. Participants were then asked to increase the EMG amplitude of targeted muscles while minimizing isometric force production. We then extracted a few components explaining most of the variation of the EMG patterns during the modulation of EMG amplitude for all muscles. We assessed the dimensionality of these components and their relationship with the null space obtained from the EMG-to-force matrix. The overall objective is to reveal the crucial parameters to optimise the setup for practical use and improve the identification of controllable null space dimensions.

2-G-87 - Using artificial neural networks to identify a neural basis of savings in motor learning

Mahdiyar Shahbazi [1], **Mehrdad Kashefi** [2], **Olivier Codol** [3], **Jonathan Michaels** [2], **Paul Gribble** [2]

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Details

Studies of motor learning consistently show “savings”, in which relearning a novel mechanical or visuomotor perturbation is faster than the initial learning even when an intervening no-perturbation washout session is used to return behavioural performance to pre-learning levels. There is debate about the mechanisms responsible for savings. Some have proposed that savings results from cognitive/strategic influences, e.g. through conscious recognition of the previously encountered perturbation. However recent electrophysiological studies (Sun*, O’Shea* et al., 2022; Losey et al., 2022) point to a potential neural basis of savings linked to changes in motor cortical neural activity that persist even after washout.

We tested this idea using MotorNet (Codol et al., 2022) by training a recurrent neural network (RNN) to control a mathematical model of the human upper limb and produce reaching movements in the presence or absence of velocity-dependent force-fields. Following initial training on point-to-point movements without perturbing forces (NF1), we then trained networks to compensate for the effects of a clockwise force-field (FF1). After learning we trained the network in a washout phase in which the FF was removed (NF2). Once the behavioural performance of the network was equivalent to the pre-learning baseline performance (as probed in NF1), we re-trained the network in the FF again (FF2). We report three main findings.

(1) The RNNs recapitulated the behavioural characteristics of savings. In the second encounter with the curl field (FF2), networks produced smaller reaching errors (as measured by lateral deviation from a straight line) and also re-adapted to the curl field faster than in the first exposure (FF1).

(2) Using an approach similar to Sun*, O’Shea* et al. (2022) we identified a component of RNN activity in the preparatory period prior to a go signal that is linked to learning—preparatory activity rotated in the direction opposite to the force field, as if the network was preparing for the neighboring target, and this change reverted after the washout. We also identified a component of RNN activity that can be linked to savings. This component of preparatory activity shifted in the same direction for all reaching targets, and did not fully revert after the washout, even after extensive training in NF2.

(3) We causally linked the uniform shift in preparatory activity to savings. After washout, we perturbed the preparatory activity of the RNN along the direction of the uniform shift on single trials and tested the effect on reaching performance upon re-exposure to the force-field (FF2). Perturbations in the same direction as the uniform shift enhanced savings and perturbations in the opposite direction reduced or abolished savings.

Our results point to a potential neural basis of motor memory retention that could underlie savings, even in the absence of cognitive/strategic components of learning, which were presumably absent in our RNN model.

2-G-88 - Identifying Essential Components of Proprioceptive Feedback with Task-Driven Deep Learning

Max Grogan [1], **Aldo Faisal** [1]

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Details

What information in proprioceptive feedback is essential and necessary for efficient control and adaptation of motor behaviours? It has been suggested that proprioceptive afferents encode a variety of muscle properties, such as length, velocity, force, and their derivatives. Meanwhile, previous investigations of cortical proprioceptive coding have found evidence for representations at the levels of single muscles, joint angles, and kinematics. Here we take a task-driven approach to elucidate this question, by optimising deep neural networks to control a biomechanically realistic arm across a series of tasks. We systematically explore varying combinations of input modality (i.e. varying muscle and joint angle properties) and quantify how the availability of each can impact the system's ability to efficiently control motor behaviours. We also evaluate their impact on adaptation, by imposing changes in movement parameters (e.g. muscle fatigue, force-field reaching) and comparing the training times required when differing forms of proprioceptive information are available. Our findings suggest that proprioceptive representations are as not as simply structured as some suggest, and sheds light on how such representations may be shaped by task requirements.

2-G-89 - Motor units recruitment and modulation patterns in variable-force single digit tasks

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Details

Previous attempts to achieve volitional control of individual motor units, critical for developing future neural interfaces, have primarily relied on visual feedback of motor units' spiking activity and subject-driven empirical control through trial and error. Enhancing control strategies at the motor unit level requires a deeper understanding of force-dependent motor unit activity. In this study, we seek to characterise motor units' behaviour during a variable-force task to inform improved motor unit control training protocols. We analysed a publicly available dataset consisting of 256 EMG channels over forearm flexor and extensor muscles (128 on each side) while participants (n=20) tracked a triangular force trace using individual finger isometric contractions. The force trace required variable forces in both finger flexion and extension directions, with 6 trials per finger for all 20 subjects, totalling 600 trials.

Motor unit decomposition, based on convolutive kernel compensation, was applied to all trials. On average, 79.9 ± 47.1 motor units were decoded per trial, showing significant inter-subject variability ($p<0.01$). Motor unit discharge rates were analysed after smoothing spike trains using a Hann window of 30ms. The coefficient of variation (CoV) of smoothed discharge rates served as a measure of modulation intensity for each motor unit in flexion or extension directions. Heatmaps of motor unit territories were generated based on discharge-weighted amplitude values of motor unit action potential waveforms.

Histogram analysis depicting motor units against their modulation values revealed a bimodal distribution, indicating two populations of motor neurons: one with high (CoV>0.5) and another with low (CoV ‰¤0.5) modulation, controlling variable-force tasks. Distinct differences were observed in the spread and activation intensities of motor unit territories covered by high- and low-modulation motor units during finger flexion or extension. Despite high-modulation motor units displayed greater temporal variability and correlation with force amplitude and direction, neither motor unit population nor all motor units together could be adequately modelled by a low number of synergies, highlighting the complexity of motor unit modulations in variable force scenarios. In conclusion, our study unveils critical insights into motor unit control, laying the groundwork for unlocking the full potential of neural interfaces. The identification of distinct modulation patterns by two motor unit populations sets the stage for targeted training strategies. Filtering only signals coming from previously identified sub-samples of motor units could lead to improved control of force-dependent or even force-independent motoneuron activity.

2-G-90 - A model of cerebellum contribution to visuomotor adaptation

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Details

The cerebellum has a key role in sensorimotor adaptation. For example, cerebellar patients are dramatically impaired when they encounter a sensorimotor discrepancy, e.g. under a rotation of visual feedback (VF) [1,2]. [2] trained participants (controls and patients) on a rotation task and tested them in 3 conditions: in feedback reaches (to obtain the perceived direction of movement in the presence of VF), in no-feedback reaches (to obtain the direction in the absence of VF), and in targeted reaches (to measure aftereffects). Compared to controls, cerebellar patients were unimpaired in the first condition, but strongly impaired in the last two conditions. The controls reported the perceived direction of their movement in the absence of VF to be half-way between the actual hand direction and the expected (rotated) visual direction whereas the patients reported this direction to be close to the actual hand direction and displayed no aftereffects. A precise computational description of these results is missing, which motivates a new computational model of adaptation.

This new model of adaptation to a visuomotor rotation is based on two interacting adaptive processes: one (prediction) which updates a VF prediction (*x*) and another (action) which updates the aiming angle of the hand (*y*). Noting *v* the actual VF direction, *T* the target direction, and *R* the rotation angle, the scenario is the following. In the baseline condition (*R=0*), the aiming angle, the actual VF and the VF prediction are all in the target direction (*y=x=v=T*). When a perturbation is first introduced (*R ‰ 0*), the aiming angle and the VF prediction are still in the target direction (*y=x=T*), but the actual VF is rotated by *R* (*v=y+R*). This creates a sensory prediction error *SPE=v-x*. The prediction process uses *SPE* as an error, and progressively drives the VF prediction toward the actual VF (*x=v*). This process has no influence on the actual aiming angle. The action process is based on a target error, the difference between the target direction and the predicted direction of hand, defined as a mixture of the VF prediction and the actual aiming angle (*kx+(1-k)y*), thus *TE=T-(kx+(1-k)y)*. The action process changes the aiming angle to progressively drive the predicted hand direction in the target direction [3]. The specific cerebellar deficit in [2] is explained in the model by a failure to update a VF prediction (prediction process), i.e. the baseline relationship *y=x=T* remains unchanged, the *SPE* is not reduced (*SPE=R*), and the target error remains null.

The present model describes a basic scenario for the involvement of the cerebellum in updating prediction during visuomotor adaptation which might give some new clues on the universal role of the cerebellum [4].

[1] Tseng et al. (2007) J Neurophysiol 98:54; [2] Synofzik et al. (2008) Curr Biol 18:814; [3] Tsay et al. (2022) Elife 11:e76639; [4] Diedrichsen et al. (2019) Neuron 102:918

2-G-91 - Biologically plausible neural dynamics for reaching emerge in reinforcement—not supervised—learning

Olivier Codol [1], **Guillaume Lajoie** [1], **Matthew Perich** [1]

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Details

The capacity of humans to learn complex motor skills to the point of virtuosity has long fascinated scientists and crowds alike. At its core, motor learning requires a teaching signal which informs the learner of the adequacy of their behavioral performance to drive improvements. Despite the centrality of this teaching signal to motor learning, its nature and origin remains unclear. Two competing theories can explain behavioral data. The first posits that the teaching signal is directly derived from moment-by-moment behavioral errors (supervised learning; SL). The second posits that it is derived from a surrogate reward function indicating whether or not the movement was successful (reinforcement learning; RL). Since both theories are consistent with behavioral data, it has been challenging to unequivocally determine which approach is used by the brain. Here, we directly address these competing theories at the neural level using recurrent neural networks (RNNs). We trained identical RNNs using either RL and SL to perform random planar reaches and compared the neural dynamics in each set of networks. First, we demonstrate that RL results in sparser, higher-dimensional latent activity than SL, underlining a discriminability that may be exploited to test both theories against neural data. We leveraged neural recordings of primary motor cortex (M1) and premotor cortex (PMd) of macaque monkeys performing an identical task to our models and observed that latent dynamics in RL networks more closely matched real neural activity. This difference could not be explained by a better correspondence between RL and monkey kinematics than SL. Thus, the RNNs allowed us to probe neural mechanisms of learning to show that RL, but not SL, produces representations matching motor cortical dynamics. This has broad implications for our understanding of motor learning and neurodevelopment, where our skills are shaped.

Poster Session 3

Thursday April 18, 2024

A – Adaptation & Plasticity in Motor Control

3-A-1 - Investigating view direction and perspective cues with varying perturbation profiles in dual visuomotor adaptations

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Details

Controlling multiple bodies with varying characteristics is a significant challenge in motor control, particularly when switching between bodies. To facilitate seamless switching between bodies' motor tasks, we rely on the framework of dual-adaptations studies. Here specifically, on adapting to 2 opposite visuomotor perturbations.

To adapt simultaneously to 2 perturbations, we need to identify their *context*. Related studies have shown that such context cues can contribute to motor adaptation in varying ways. While it seems that sensory cues related to the body state (e.g., arm position) primarily activate implicit motor adaptation, there are mixed results regarding the view direction cue (i.e, shifting workplace). Here, we explore the adaptive processes relying on the view direction cue, that is, switching between left/right workplace, or view perspective cue, that is, switching between left/right point of view (like if there was a camera looking from our left/right shoulder). We also explore different perturbation profiles (e.g., offset scheduling) to highlight better the context used by the participant.

We developed a "screen environment" and a "Virtual Reality environment" [VR], respectively, to study the view direction cue and the view perspective cue.

- In the screen env., online participants did a dual visuomotor task with their computer screen and mouse. The visual start and stop locations switched pseudo-randomly between the left and right sides of the screen.
- In the VR env., on-site participants were embodied into an avatar and used their right VR controller to reach the target. In our "3rd Person view Perspective", the view was located around the left/right shoulder and directed toward the workspace. Therefore, the participants were not required to move their eyes/head to see the target. The perspective switched pseudo-randomly.

We used perturbation profiles with gradual or abrupt changes and with/without offset scheduling between the 2 perturbations (e.g., with offset, the perturbation on one side will start 20 trials after the other).

We found that in the screen env., with the **gradual** perturbation profile, we observed 2 adaptations to the 2 perturbations if there was no offset. On the other hand, if there was an offset, we observed that both contexts used a similar adaptation for the 2 perturbations, resulting in a single motion profile for the 2 bodies. Yet, with the **abrupt** perturbation profiles, the offset introduced 2 adaptations to the 2 perturbations, resulting in 2 motion profiles for the 2 contexts.

In the VR env., with the **gradual** and **abrupt** perturbation profiles, in *1st person view*, we observed that both bodies used a single motion profile for the 2 contexts, whereas in *3rd person view*, both bodies used 2 motion profiles for the 2 contexts.

These findings shed light on how context generation influences the ability to adapt to dual visuomotor perturbations simultaneously.

3-A-2 - The high visibility of human locus coeruleus at ultra-high field MRI

Atsushi Yokoi [1], **Ikuhiro Kida** [1]

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Details

Testing the possible involvement of autonomic arousal in motor control and learning process is an interesting new endeavor. Although peripheral autonomic measures, such as heart rate and pupil diameter, can be a good proxy for central autonomic activities, measurement/manipulation of neural activity in central autonomic nuclei in humans is essential for further steps. Locus coeruleus (LC) is one of such structures, sending widespread noradrenergic projections throughout the brain. However, a critical issue here is that LC is a very small structure located in the brainstem, making it notoriously difficult to apply imaging/stimulation techniques. Here, using an LC-sensitive sequence (e.g., Sasaki et al., 2006; Dahl et al., 2023) in ultra-high field (UHF) MRI, we evaluated the structure of the locus coeruleus in humans. The LC structure showed greater spatial distinctiveness compared to previous 3T results. We also conducted motor learning experiments in part of these participants and compared the behavioral measures and LC structural integrity.

We scanned the brains of 38 healthy individuals (12 females and 26 males) using a 7T MRI scanner (Siemens, MAGNETOM Terra). LC-sensitive images were acquired with the turbo spin echo (TSE) imaging sequence (Hennig et al., 1986). Images covering the LC structure were oriented either perpendicular (13 slices with 2.3mm thickness) or parallel (9 slices with 1.5mm thickness) to the wall of the fourth ventricle with the in-plane resolution of $0.5x0.5mm^2$. We manually extracted the LC based on the contrast ratio (CR) image computed by the following formula at each slice: $CR(i,j)=(I(i,j) - R)/R$, with $I(i,j)$ being image intensity at pixel (i,j) and R being the average intensity within a reference region defined in the central pons.

The spatial distribution of peak CR in the LC showed a pattern consistent with previous histological studies, with areas of higher overlap across individuals in the central-rostral portion and caudal LC more spatially diffusive across individuals (German et al., 1998; Fernandes et al., 2012). The LC CR value was higher (0.25 ±0.05, mean ±SD) than the values reported in the previous 3T studies (0.15 ±0.04, Mather et al., 2017; 0.19 ±0.05, Clewett et al., 2018), confirming higher signal-to-noise ratio by UHF MRI.

Finally, we compared the extracted LC CR with behavioral data collected from a part of the participants (n=18). They participated in a single-trial adaptation experiment induced by various sizes of mechanical perturbation during reaching (e.g., Marko et al., 2012). At this point, we found no clear association of individual LC CR with the learning rate at small errors but some weak association with the learning rate at large errors.

Overall, the current results constitute the valuable first step to investigating the role of LC in motor learning and control.

3-A-3 - Impact of targets by human and object on accuracy in motor task

Ayane Kusafuka [1], **Rintaro Yamamoto** [2], **Taishi Okegawa** [2], **Daiki Yamasaki** [2], **Saki Takao** [2], **Kazutoshi Kudo** [2], **Katsumi Watanabe** [1]

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Details

The goal-criterions such as the size of the target implicitly influence perceptions of error and interpretations of success during goal-directed motor tasks. Previous studies reported such perceptions of error or success affected on motor performance from an affective aspect as well as information processing/cognitive aspect. This study focused on the effect of whether the target is human or object on accuracy in a high-speed throwing task.

Eleven healthy males (23-28 yr) without baseball experience participated in this study. They threw 20 four-seam fastballs each at a catcher's mitt and a mark on a board positioned 18.44m away. Both targets were about 0.2 m in width and length, whose center was placed 1.3 m above the ground. A high-speed camera placed on the participant's back was used to capture the ball movements. The ball arrival positions were obtained using the camera images in which the center of the ball at the moment of arrival was digitized and a direct linear transformation method. The mean absolute error and variable error of the ball arrival positions were compared between the two target conditions using a paired t-test.

The variable error in catcher's mitt condition was significantly smaller than that in mark condition only in the vertical direction (catcher's mitt: 0.59m, mark: 0.97m, $p < .05$). On the other hand, there was no significant difference in the variable error in the horizontal direction (catcher's mitt: 1.02m, mark: 1.14m, $p = .10$) and the mean absolute error (catcher's mitt: 0.56m, mark: 0.63m, $p = .07$).

These results showed that the human target increased accuracy in the vertical direction. It may be related to the depth perception of the target; if the target is perceived as far away, the ball arrival positions should shift upward, and if it is perceived as close, it should shift downward. Participants may have been able to perceive depth more easily due to the presence of people. In addition, psychological factors such as pressure to throw to a place where human can catch or a sense of relief that human catch the thrown balls may also be relevant. These suggest that target types have different information processing, cognitive, and affective effects on the throwing performance, which helps us understand human motor control.

3-A-4 - Cerebellar function in motor adaptation beyond spatial control: individuals with cerebellar ataxia exhibit impaired adaptation to perturbations of time and pitch in speech

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Details

Research in both limb control and speech production has shown that people with cerebellar ataxia (SCA) have impairments in sensorimotor adaptation. While these studies have established that the cerebellum plays a critical role in the adaptation of spatial dimensions of movement (e.g., visual perturbations of reaching angle or auditory perturbations of vowel formants), there is currently little evidence regarding cerebellar function in adaptation in other aspects of movement. Speech provides a unique window to examine cerebellar function in sensorimotor learning beyond spatial control in two domains: temporal duration and vocal pitch. Timing in speech is exquisitely precise, with differences as small as 10 ms causing the perception of a different speech sound (e.g., the duration of aspiration noise distinguishing “t” and “d”), and is critically reliant on predictive control as the durations of many speech sounds are shorter that the latency of measurable compensatory responses to auditory feedback errors in the motor output (~100-150 ms). Controlling vocal pitch differs from other motor behaviors in that it relies more on feedback control than predictive or feedforward control: pitch control has been shown to rely more on relative targets (higher or lower than the previous pitch) rather than absolute frequency targets, and control of vocal pitch deteriorates much more rapidly than control of supralaryngeal articulation in post-lingually deaf individuals.

We tested potential impairments in adaptation in individuals with ataxia in response to real-time perturbations of vowel duration (Exp 1) and vocal pitch (Exp 2). In Exp 1, the vowel duration of the word “best” was artificially lengthened, a perturbation which causes adaptive shortening in healthy individuals. Critically, as it is impossible to react online to a lengthened vowel by shortening it, any shortening observed must be driven by adaptation in predictive or feedforward control of speech timing, rather than within-trial compensation for perceived errors. In Exp 2, vocal pitch was externally shifted down by 100 cent, which causes healthy individuals to adapt by raising their pitch.

Results show that in both experiments, individuals with ataxia (n = 16/19) failed to adapt to the perturbations in either experiment, while a group of age-matched controls (n = 16/27) exhibited robust adaptation. Interestingly, adaptation in these tasks was totally absent in the ataxia group, contrasting with the reduced, but present, adaptive response typically seen in response to spatial sensory perturbations. These results strongly suggest that the cerebellum is critical for sensorimotor adaptation across all aspects of motor behavior, and is not limited to spatial aspects of movement. Clinically, these impairments are consistent with the idea that the motor deficits in individuals with ataxia may result from impairments in predictive control of movements in both space and time.

3-A-5 - Benefits of attentional focus on visuomotor adaptation are observed when paired with a perceptual pre-planned aiming task

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Details

It is accepted that cognitive processes contribute to motor learning. Attentional focus is one such process shown to benefit motor skill acquisition, while employing a reaching strategy has been shown to benefit visuomotor adaptation. Across two experiments, we sought to explore if attentional focus instructions alone benefit visuomotor adaptation (Experiment 1) or if also engaging in a pre-planned aiming strategy provide a benefit for visuomotor adaptation (Experiment 2). The task goal was to perform a shooting movement such that the cursor landed on the target (1) when a cursor accurately represented participants' hand motion (aligned cursor), (2) when a cursor was rotated 40 degrees clockwise relative to participants' hand motion (rotated cursor) and (3) in the absence of cursor feedback (no cursor). The process dissociation procedure was used to assess the contributions of explicit and implicit adaptation in the absence of cursor feedback when participants were to (1) engage in strategic reaching (i.e., assessment of explicit adaptation) and (2) reach directly to the target (i.e., assessment of implicit adaptation). In Experiment 1, an External focus group (EXT; n=27) was instructed to focus on the path taken by a cursor on the screen, while an Internal focus group (INT; n=27) was instructed to focus on the path taken by their hand. Attentional focus instructions were provided at the start and after every 40 rotated reach training trials (i.e., 4 times in total). In Experiment 2, a Direction group (DIR; n=16) were asked to report the direction their hand should aim prior to reaching, while the Endpoint group (END; n=16) were asked to report where their hand should end relative to the target. Reports on aiming strategy were assessed via a line orienting task, such that at the start of 25% of the reach training trials, a red line appeared and rotated around the start position (DIR) or target position (END). A Control group (CTL; n=51) were not provided with an attentional focus instruction and did not report anything at all prior to reaching. Analyses of reaching performance revealed that participants in the INT, END and DIR groups demonstrated similar visuomotor adaptation by the end of training (all $p>0.688$), which was greater than the EXT and CTL groups ($p<0.038$). Assessment of explicit adaptation revealed that participants in the DIR group engaged in strategic reaching to a greater extent than the EXT group ($p=0.06$). However, there was no difference in implicit adaptation across all groups (all $p>0.401$). The findings suggest the benefit of an internal focus of attention paired with a task-specific perceptual pre-planned aiming task for visuomotor adaptation. Conversely, an external focus of attention may impede visuomotor adaptation, potentially by disrupting strategic reaching processes. Together, these results challenge conventional wisdom in motor skill acquisition and highlight the distinct nature of visuomotor adaptation.

3-A-6 - Explicit sensorimotor strategies fail to launch in response to small perturbations

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Details

Sensorimotor adaptation tasks engage multiple learning processes in response to an experimentally imposed perturbation. The mismatch between predicted and expected sensory feedback engages an implicit process that serves to recalibrate the sensorimotor map. If the perturbation is large, the participant may strategically re-aim to counteract the perturbation. In this study, we examine strategy use in response to small, incremental perturbations and how this process is modulated by implicit recalibration.

Using a web-based platform, participants (n=50/group) were tested on a visuomotor rotation task in which the size of the rotation was incremented in small steps of 1.5 ° to reach an asymptotic value of 60 °. One group received endpoint feedback immediately after reaching, engaging both implicit and explicit processes. The second group received endpoint feedback after an 800 ms delay, a manipulation that essentially abolishes implicit adaptation, requiring explicit re-aiming to counteract the perturbation.

Consistent with this assumption, only the No-Delay group showed a significant aftereffect (No-Delay: 17.8 °; Delay: 4.2 °).

Turning to the strategy use question, we looked at performance changes early and late in response to the perturbation. During the early phase (perturbation size: 1.5 - 15 °), change in hand angle was reduced in the Delay group (1.0 °) compared to the No-Delay group (4.8 °). The negligible change in hand angle for the Delay group suggests explicit strategy use 'fails to launch' in response to an incremental perturbation, even when the perturbation size reached 27 °. When the perturbation reached 60 °, the change in hand angle for the Delay group nearly compensated for the error (55.0 °). Thus, when the perturbation became sufficiently large, participants in the Delay group had successfully identified a re-aiming strategy.

Interestingly, the No-Delay group showed a much smaller change in hand angle (34.2 °) at this phase of the experiment. As part of its operation, implicit recalibration may suppress strategy use. Alternatively, performance changes arising from implicit recalibration may be sufficient to preclude the launching of an aiming strategy. To evaluate these hypotheses, we focused on the data from individuals who demonstrated strategy engagement (N, Delay: 22, No-Delay: 29). There were no significant differences between Delay and No-Delay groups when the perturbation size reached 60 °, even though a substantial part of learning for the No-Delay group was implicit (evident by their aftereffect of 19.2 °). These results argue against the suppression hypothesis; rather, it appears that for a subset of participants in the No-Delay group, changes in performance from implicit recalibration were sufficient to preclude the deployment of a re-aiming strategy. We assume that strategies are used when there is sufficient information to confidently attribute a motor error to an external perturbation rather than noise in the sensorimotor system.

3-A-7 - Generalisation of motor skill learning with a hand augmentation device

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Details

The integration of robotic augmentation devices represents a frontier in enhancing human motor abilities. We investigated the behavioural aspects of motor learning, adaptability and resource allocation trade-offs in motor integration of a toe-controlled extra robotic thumb (the Third Thumb, Dani Clode Design) in hand skill. Over seven days, 30 individuals were trained - in laboratory and at-home sessions - to use the Thumb in tasks requiring both independent and collaborative movements with their natural fingers. Changes in augmented-hand motor skills, generalisation and alteration of lower limb abilities for these augmentation participants were evaluated against two control groups: an active control group (n=20) engaged in one-hand piano training to develop hand-toe coordination without using the Thumb, and a passive control group (n=18) that received no training.

Augmentation participants demonstrated clear improvements in motor skills, underscoring their ability to acquire novel motor skills using the Third Thumb and advocating for the success of at-home training. We also observed broad training-driven generalisation, where augmentation participants demonstrated the ability to transfer acquired motor skills to untrained tasks, even when using different body parts to control and wear the Thumb, and to untrained body postures, suggesting that the learning process involved might encompass aspects beyond traditional motor learning mechanisms.

We next examined whether this diverse new set of motor skill come with bodily costs. Therefore, we explored the effects of using the toe-controlled Thumb on balance, finding a modest but significant decrease in balance performance when participants used or wore the device, with no difference in impact between passive wearing and active control, and regardless of training. We also investigated the after-effects of Thumb use on participants' balance capabilities when not using the device. In this context, there appeared to be a tendency for a reduction in the ability to balance freely after Thumb training, while the Thumb was not being worn. Despite these preliminary evidences being not entirely conclusive yet, they underscore the need to understand the potential lasting effects of using augmentation devices on existing motor skills.

Overall, our results revealed the possibility of acquiring robotic augmentation specific motor skills, which resulted broadly generalisable beyond trained tasks and settings. However, they also highlighted potential trade-offs with regards to natural abilities of controlling toes. This highlights the complexity of integrating augmentation devices with the motor control of the human body, suggesting a need for further research on impacts and long-term effects on the biological body.

3-A-8 - Motor adaptation as an associative learning process

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Details

Implicit motor adaptation has traditionally been modeled from a control engineering perspective in which error information is used to update an internal model of a sensorimotor map. Here, we consider the utility of a simple associative learning framework, akin to that underlies eyeblink conditioning. Here, a neutral stimulus (conditioned stimulus, CS, e.g., a tone) is associated with an aversive unconditioned stimulus (US, an air puff) to produce a predictive, adaptive response (conditioned response, CR, a blink). Eyeblink conditioning shares important features with motor adaptation, including strict timing constraints for the CS-US interval and a strong dependency on the cerebellum.

We have reported a series of experiments illustrating that visuomotor adaptation adheres to basic principles of associative learning (Avraham et al. 2022). Using a reaching task, we paired tone and light cues (CS's) with either perturbed or unperturbed visual feedback (US's). After learning, we removed the feedback and examined changes in hand movement kinematics (CRs) in response to the cues. The behavior exhibited three key signatures of associative learning: 1) Associability: Cues that were paired with different movement outcomes yielded distinct movement trajectories; 2) Sensitivity to the CS-US interval: Increasing the time interval between the cues and the feedback diminished associability; 3) Additivity of competing CSs: Pairing a compound CS of the two cues presented simultaneously with a visuomotor error resulted in proportional responses to the elements of the compound.

These experiments demonstrate how neutral cues (tone and light) can modulate adaptation in a manner that follows the principles of classical conditioning. But how do these ideas apply to typical adaptation tasks? We propose that the onset of a target, which cues movement initiation, serves as the CS, one that becomes associated with the perturbed feedback (US). The repeated pairing of the CS and US will increase their associated strength, resulting in an adapted movement (CR) to that target even when the feedback is then removed (aftereffect). When viewed in this framework, we see that the target has CS-like features. For example, adaptation to nearby targets exhibits a generalization pattern similar to that observed in the conditioned eyeblink response to variations in the CS (e.g., tone frequency). As a more direct test of our hypothesis, we considered the phenomenon of latent inhibition. Latent inhibition refers to the finding that conditioning of a CS-US pair is weaker following prolonged exposure to the CS in the absence of the US. We find that latent inhibition is evident in adaptation: Repeated movements to a target without perturbed feedback result in attenuated adaptation when that target is then paired with perturbed feedback. In summary, this work highlights the potential of a simple associative framework for understanding motor adaptation.

3-A-9 - TMS-based neurofeedback facilitates motor imagery of different hand actions

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Details

Introduction: Non-invasive brain-computer interfaces (BCIs) allow the user to modulate brain activity patterns in a goal-directed manner. To date, most non-invasive BCIs can only decode gross movements but many daily-life tasks require much finer finger and hand control. We have developed a novel BCI using motor imagery (MI) and transcranial magnetic stimulation (TMS)-based neurofeedback (NF) training to reinforce representations of complex hand actions in the brain. In this proof-of-concept study, we aim to investigate the utility of such a new BCI for hand function training via MI.

Methods: We designed 2 experiments to study the effect of the TMS-based BCI on 3 hand actions (hold a bottle, turn a key and open your hand). In experiment 1, a deterministic approach was taken to guide healthy right-handed adults to modulate their brain activities with NF. In experiment 2, a more adaptive ensemble-based support vector machine (SVM) learning approach was used. To assess the participants' performance, an SVM classifier was used to decode target hand actions. Leave-one-trial-out cross-validation was used within training blocks ("Cross-validation test"). To understand the relationship between motor execution (ME) and MI, the first classifier trained on ME data in each ensemble was tested on each MI block ("Cross-condition test"). Here we report data from 8 participants (age 24 ±3 years, 5 females) in Exp. 1 and preliminary data from 4 participants (age 32 ±5 years, 2 females) in Exp. 2.

Results: The cross-validated classification accuracy of ME was 97 ±1 % (mean ±SD) for Exp. 1 and 84 ±2 % for Exp. 2. This indicates that participants could produce similar corticomotor excitability patterns within a hand action and distinct patterns between hand actions, suggesting that ME data could be used as “ground truth” for TMS-based BCI. The cross-validated classification accuracy of MI with NF showed 40 ±2% for Exp. 1 and significantly increased to 57 ±6% for Exp. 2 (t_{10}=-7.622, p<0.001). This supports that the adaptive approach worked better than the deterministic approach for training self-modulation of corticomotor excitability patterns of 3 finger muscles.

In Exp. 2, the cross-condition findings showed a progressive increase in median accuracy with training. By comparing ME and MI without NF, most participants could regulate the muscle-specific activities with given instruction and the patterns of MI became more similar to those of ME with training. This demonstrates that NF training could promote the modulation of corticomotor excitability.

Conclusions: A novel, personalized, and adaptive MI and TMS-based BCI for complex hand actions was developed and tested. Our findings suggest that healthy adults could simultaneously and selectively modulate brain activities for multiple fingers with the guidance of NF. This demonstrates that TMS-based BCI could be used for hand function training in individuals that are not able to produce overt motor output.

3-A-10 - Differential contributions of model-based and model-free learning to visuomotor adaptation

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Details

Separate conributions of model-based and model-free learning have been studied in the context of interlimb transfer, although their relative contributions to motor adaptation per se remain unclear. Here, we conducted two experiments, in which the contributions of varying degrees of model-based (exp. 1) and model-free (exp. 2) learning to visuomotor adaptation have been systematically investigated. Assuming that model-based learning is effector independent, we employed a visual observation method (i.e., watching a model who adapts to a novel visumotor rotation condition during reaching movements) to probe model-based learning; to probe model-free learning, we employed passive reaching movements. By employng visual observation and passive training, we minimized the possibility of the involvement of model-free and model-based learning, respectively. Each experiment comprised three sessions: baseline, training, and testing. In the training session, three groups of subjects performed different numbers (160, 64, or 32) of observation trials along with 160 passive reaching movement trials during visuomotor adaptation (exp. 1); and three groups of subjects performed different numbers (160, 64, or 32) of passive reaching movement trials along with 160 observation trials (exp. 2). A control group was included, who did not experience any observation or passive movement trials in the training session. In the testing session, all subjects adapted to the same rotation condition. Results showed that increasinig the number of observation trials reduced initial direction errors observed at the beginning of the testing session systematically, whereas the rate of learning was significantly higher than that of the control group only when 160 observation trials were experienced (exp. 1). Increasinig the number of passive movement trials also reduced initial direction errors observed at the beginning of the testing session systematically (exp. 2). However, the rate of learning was significantly higher than that of the control group in all groups who experienced passive trials (exp. 1). Comparing the effects of observation vs. passive trials, the difference was minimal in terms of direction errors observed at the beginning of the testing session. The difference, however, was significant in terms of learning rates, in that providing only 32 passive trials increased the rates significantly compared to the control group, whereas providing even 64 observation trials did not. These findings indicate that model-based and model-free learning make independent contributions to visuomotor adaptation. They further indicate that the contribution of model-free learning may be even greater than of model-based learning during the later phase of adaptation.

3-A-11 - EMG control of a hand augmentation technology

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Details

Wearable augmentation technologies hold a promise for improving motor control, not only in their functionality but also in their integration into daily life. The diverse applications, from enhanced productivity to improved healthcare outcomes, underscore the potential transformative impact of these technologies on human capabilities. Yet, one key bottleneck in the realization of these technologies is the control mechanism. Since augmentation technologies are designed to enhance motor abilities beyond the biological body, it is unclear how to best output motor control for precise and continuous use, without disrupting the biological body's motor abilities.

Electromyography (EMG) interprets muscles-generated electrical signals ancould offer a direct link between user intent and device response. The potential for seamless non-invasive integration with the human body places EMG as an intuitive and efficient control mechanism, paving the way for a more natural user experience. Nevertheless, EMG also presents challenges for device control. Specifically, the signal can be noisy even after processing, potentially impacting proportional control.

We aimed to evaluate the viability of EMG as a control method for augmentation technologies, using the Third Thumb (Dani Clode design) as a model. Currently, the Thumb is controlled through force sensitive resistors (FSRs) placed under the toes (one per DoF). We compared this validated control system against bipolar EMG surface electrodes. Participants performed a battery of tests, designed to probe Thumb motor control, emphasizing dexterity, cognitive load, proportional control and learning. To probe motor synergy between the Thumb and hand control, the tasks required either individuation, coordination, or collaboration between the Thumb and the biological hand. This series of tests was repeated twice, using the two different control methods: Toe-control FSR and Calf control EMG. For each run of the paradigm, the participants were not informed of the control method they are currently using. This allows an unbiased comparison of motor execution and learning between the two control methods. Further work will aim at isolating two degrees of freedom from the non-augmented arm to control the Thumb as an alternative means for EMG Thumb control using the same motor control paradigm.

Our results will allow us to determine whether EMG control provides a comparable level of motor dexterity and training to learn how to operate the Thumb at the level of traditional FSR control. This will not only exemplify the potential of EMG in enhancing user control but also highlights its potential challenges as an input method for hand augmentation. Overall, we aim to show how EMG-driven control aligns with the broader trajectory of wearable technologies, offering users a tangible extension of their physical abilities.

3-A-12 - Correcting cortical output: a distributed learning framework for motor adaptation

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Details

Learning is fundamental for interacting with a changing environment. Critical to this process is the ability to rapidly adapt previously acquired skills to external perturbations while avoiding catastrophic forgetting of previous tasks. Classic behavioral studies of motor control posited that the cerebellum encodes and continuously updates an internal model of the environment in order to adapt motor cortical command signals to external perturbations. However, the underlying mechanism is not well understood. More recently, recurrent neural networks (RNNs) have emerged as a new framework for how cortical dynamics generate temporally patterned motor outputs and learn from error feedback. Despite their distinct architectures and learning rules, the neocortex and cerebellum are densely interconnected through looped pathways. However, it is not clear how to integrate the view of the motor cortical pattern generator with classic cerebellar internal models. To address this gap, we propose that the cerebellum and motor cortex together form a distributed learning system, with supervised cerebellar learning guiding rapid adaptation, and slower consolidation of the new dynamical memory in the motor cortex through local plasticity. We demonstrate this hypothesis by training a modular cerebello-cortical RNN (CCNet) to control a motor plant while performing a visuomotor perturbation to a classic center-out reaching task. We show that CCNet is able to improve task performance in a few trials through rapid adaptation of the cerebellar module; on a slower timescale, cerebellar feedback guides local plasticity in the motor cortex, enabling the adapted dynamics to be stored in the cortical module. This two timescales approach allows CCNet to mitigate catastrophic forgetting by significantly modifying its dynamical memory only in the case of persistent changes in the environment or in the system itself. These results provide new insight for how distinct plasticity rules in different neural circuits could collaborate as part of a brain-wide distributed learning strategy.

3-A-13 - The developing homunculus: sensory body maps in children with and without upper limb differences

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Details

The aim of this study was to compare primary somatosensory cortex (S1) topography and activity in the missing hand hemisphere of congenital one-handed children (1h) and adults, relative to typically developed 2-handed (2h) children and adults. Congenital hand loss leads to large-scale neural adaptations in S1 that are not yet fully understood. Recent research in 1h adults indicates that the S1 territory corresponding to the missing hand shows increased activation (relative to 2h adults) when moving various body parts (Hahamy et al., 2017; 2019). It has been suggested that this remapping is facilitated by compensatory strategies - using other body parts to substitute the missing hand function could harness the freed-up hand resources. However, this theory has not yet been empirically validated. Within this theoretical framework, a key prediction is that the sensory representation of the body in one-handers is shaped by the compensatory use of multiple body parts during childhood. The developmental stages of childhood offer a favourable environment for use-dependent plasticity, as during this period, brain organisation is particularly sensitive to activity and experiences. Alternatively, these neural adaptations might be predetermined and thus already present from the onset of development.

We used fMRI to measure somatosensory activity in 1h and 2h children (5-8 years old) and adults (18-65 years old). We stimulated multiple body parts along the body ipsilateral to the missing hand, as well as the intact hand. We also measured compensatory behaviour by having the participants manipulate a controlled series of everyday objects (e.g. opening a book bag, using a toy screwdriver and putting on a glove), with a focus on body-part engagement during the different tasks.

Behavioural results suggest that one-handed children use their legs, torso and face more than both 2h children and 1h adults. Preliminary fMRI univariate results revealed somatosensory remapping of the residual arm representation in the deprived hand area in children as young as 6 years old. Qualitatively, both 1h adults and children show greater activity than two-handed adults and children, specifically in the deprived cortex. One-handed adults show larger responses and more distinct peaks, as do one-handed children. However, the deprived cortex contains less information about alternative body parts in children than in older one-handers. Taken together, the results could suggest continual development of the somatosensory homunculus in later childhood. This in line with the protracted development of manual motor skills. Multivariate representational similarity analysis suggests information about body parts is present in the deprived hand area, especially for the face. Further analysis and modelling will attempt to determine the relative contributions of different body parts based on the developmental period, and links with compensatory behaviour.

3-A-14 - Plasticity of sensorimotor confidence during motor adaptation

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Details

Humans are able to adapt to large and sudden perturbations of sensory feedback. For example, after plunging one’s hand into the water to retrieve a shell, there is an immediate mismatch between visual feedback and proprioceptively sensed location. Additionally, sensory-motor adaptation takes time, as anyone who has encountered an unexpected computer mouse sensitivity can attest. What sensory and motor-execution cues are used to determine confidence, and do the dynamics of confidence parallel those of ongoing sensorimotor adaptation? Participants sat at a table and performed reaches with a pen on a tablet. Stimuli were presented from above and reflected back toward the observer using a mirror positioned so that the stimuli appeared perceptually in the same plane as the tablet’s surface, and occluded the view of their true hand position. Targets were presented in a circle around the central starting location at randomly selected angles, with each quadrant of the tablet queried an equal number of times across the session. Participants made a slicing reach through a visual target with an unseen hand followed by a continuous judgment of confidence in the success of their reach. After the confidence response, visual feedback of hand position was shown at the same distance along the reach as the target. For the confidence judgment, participants adjusted the size of an arc centered on the target with a knob in their left hand. Larger arcs reflected lower confidence. Points were awarded if the subsequent visual feedback was within the arc, and fewer points were returned for larger arcs. This incentivized attentive reporting and minimizing feedback-target distance to maximize the score. A fixed, 20 º rotational perturbation (alternating CW/CCW across blocks) was applied to the feedback on trials 20-70 within each 100-trial block. We used least-squares cross validation to compare four Bayesian-inference models of sensorimotor confidence adaptation based on prospective cues (e.g., knowledge of motor noise and past performance), retrospective cues (e.g., proprioceptive measurements), or both sources of information to maximize expected gain (i.e., an ideal observer) with additional parameters for learning and bias. Proprioceptive uncertainty was separately fit for each participant during a control motor-awareness task, during which they repeatedly reached toward a target location and reported their perceived endpoint location using visual feedback. Models incorporating proprioception provided the best fit for all participants, indicating the use of proprioception when calculating sensorimotor confidence during motor adaptation. Notably, models that relied only on previous errors and did not take into account trial-specific proprioception did not provide the best fit for any participant. Over repeated blocks of exposure to the perturbation, participants' confidence recovered exponentially to pre-adaptation levels, but at a different rate than motor learning.

3-A-15 - Validating a low-density EEG device for Targeted Memory Reactivation (TMR) during sleep for stroke rehabilitation

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Details

Rehabilitation of movement impairment after stroke relies on motor learning. However, a component of motor learning that is often overlooked in the context of rehabilitation post-stroke is the consolidation of memory during sleep. Therefore, interventions that aim to boost learning and consolidation are of interest as potential adjunct therapies.

Targeted Memory Reactivation (TMR) is a form of brain activity modulation that involves delivering sensory stimuli (e.g. sounds) during learning and then re-presenting them during subsequent sleep to reactivate the associated memories. Its efficacy as a technique for promoting consolidation of motor learning has been well established for younger and older healthy adults. Notwithstanding, there is still a need to test the effectiveness of TMR following brain injury. Therefore, the main objective of this project is to determine if TMR can boost the memory consolidation processes underlying the motor learning required for movement rehabilitation after stroke.

To achieve this goal, we have developed (and are currently validating) a custom-built low-density EEG device for sleep stage detection, classification, and ultimately the delivery of auditory stimulation to be used with stroke survivors in a TMR protocol. Participants will wear our low-cost portable device alongside a polysomnography set up during overnight sleep. Our principal outcome measures are EEG Signal Quality and Sleep Stage Classification Similarity. We assess EEG signal quality between the two sleep recording methods using relative spectral power computed in our frequency bands of interest (1-4Hz, delta waves; 11-16Hz spindle range). To determine how similar the sleep staging is between the sleep recordings we will assess the percentage agreement for each 30 second epoch of staged sleep, calculated using Cohen's kappa (Îº) (Îº= 1 ˆ'P(e)/ P(a) ˆ'P(e)). Some participants will also be asked to perform a novel SRTT in the laboratory before and after a night of sleep to assess motor consolidation, which will be correlated with EEG metrics of interest.

Most sleep and memory research to date has taken place in laboratory settings, which places burdens and resource restrictions on both participants and researchers, while the unnaturalistic settings inside sleep laboratories may lead to findings that do not represent true patterns in target populations. As such, we hope to ultimately test the TMR protocol outside of the lab to examine its potential as a real-world clinical tool. The extent of patients' motor impairment and how this improves as a result of TMR will be our main variable of interest. We hope this research will pave the way for future large scale clinical trials to test the efficacy of TMR as an adjunct to motor rehabilitation after stroke.

3-A-16 - Delivering information to the cortical reach-to-grasp network with low-amplitude intracortical microstimulation

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Details

Bidirectional brain-machine interfaces (BMIs) both decode information from one cortical region (direction 1) and deliver information back to a different cortical region (direction 2). Common choices for decoding and delivering information include primary motor cortex (M1) and primary somatosensory cortex (S1), respectively. However, cortical control of movement involves many regions beyond M1 and S1. Posterior parietal and premotor cortex, for example, encode complex information about movement planning, reach trajectories, and object properties for grasping. BMIs have successfully decoded movement intent from these association cortical regions, but whether information can be delivered in these regions remains largely unknown. Considering the higher-level information relevant for reaching and grasping that potentially could be conveyed, the ability to deliver information into the premotor and/or posterior parietal cortex could substantially enhance the performance of bidirectional BMIs.

Here we investigated whether intracortical microstimulation (ICMS) could be used to deliver information in a variety of parietal and frontal association cortical regions: the anterior intraparietal area (AIP), dorsal posterior parietal cortex (dPPC), ventral premotor cortex (PMv), and dorsal premotor cortex (PMd). We investigated S1 as well for comparison. We first trained two rhesus monkeys to perform a center-out target task in which they had to move a cursor from a central target to 1 of 4 peripheral targets instructed with visual cues. Then, for each cortical region separately, we arbitrarily assigned a unique set of 4 electrodes to each of the 4 targets and delivered non-biomimetic, low-amplitude (subthreshold for evoking muscle contraction) ICMS on those electrodes in conjunction with the visual cues. We then gradually removed the visual cues until the ICMS served as the only instruction for the targets.

Both monkeys successfully learned to perform the task using only AIP-, PMv-, or S1-ICMS instructions, meaning the ICMS evoked distinguishable experiences in each of these areas, but neither monkey could learn the PMd- or dPPC-ICMS instructions. Further, in AIP, PMv, and S1, each instruction eventually could be delivered via a single electrode while maintaining success rates similar to those achieved with visual-cue instructions. Psychometric performance functions showed that sensitivity to changing ICMS amplitude, frequency, or pulse-train duration was remarkably similar among AIP-, PMv-, and S1-ICMS instructions. We conclude that, in addition to S1, AIP and PMv may also provide effective cortical territory for delivering information to the brain as part of a bidirectional BMI. Delivering information with ICMS in PMd or dPPC may be comparatively ineffective.

3-A-17 - Finger-specific representations are sharpened during a fatiguing motor task

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Details

Introduction

Motor fatigability is a frequent symptom in neurological disorders. It can be quantified by the decrease in movement speed, when low-force movements are performed repeatedly with maximal speed. In this study, we measure motor fatigability in healthy with fast finger tapping. Previous research has shown that the decrease in movement speed, or motor slowing, is associated with a rise in BOLD activity and a reduction in surround inhibition in the primary sensorimotor cortex (SM1). However, it remains an open question of whether motor slowing and the associated release of inhibition causes a reduction of signal-to-noise ratio for movement-specific information. Here, we aim to answer this question by assessing finger representations using representational similarity analysis (RSA) when participants perform fatiguing index or middle finger tapping. We hypothesized that a reduction of movement-specific information would be associated with the finger representations in SM1 getting blurred over time due to a gradual breakdown of surround inhibition. Thus, if the signal-to-noise ratio of movement-specific information decreases in parallel with motor slowing, we would expect finger representations to become more overlapping. Vice-versa, if the signal-to-noise ratio of movement-specific information increases despite motor slowing, we would expect sharper finger representation.

Method

26 participants performed a 30s motor slowing finger tapping task during fMRI with index and middle finger. For the first-level general linear model, the fingers were regressed separately and split into 3x10s regressors (time bin 1-3). We performed RSA on each time bin for M1 and S1 (regions of interest, ROI). A mixed effects model was used to test whether dissimilarity changed over time. Since this change might purely be explained by changes in BOLD activity, we extracted an estimate for BOLD activity for each time bin and tested whether activity increased over time. We then predicted expected dissimilarities for bin 2 and bin 3 based on the changes in activity. Using a mixed effects model with the factor dissimilarity type (predicted, actual) and time (bin 2, bin 3), we tested whether the predicted and actual dissimilarities differed. These analyses were done separately for each ROI.

Results

Tapping speed significantly decreased in each finger ($F(1,85)<=10.67$, $p<=.001$), while BOLD activity increased in both ROI ($F(2,50)<=20.09$, $p<.001$). Comparison of the predicted versus the actual dissimilarity revealed a significant difference in both ROI ($F(1,75)<=37.62$, $p<.001$) for time bin 2 and 3 (post-hoc tests, $p<.005$).

Conclusion

We conclude that the finger representations in the sensorimotor cortex become more distinct with motor slowing, even when correcting for the increase in activity. This suggests that the signal-to-noise ratio of movement-specific information is increased, potentially to compensate for supraspinal changes caused by fatigability.

3-A-18 - External feedback signals in oculomotor learning

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Details

Efficiently aligning our fovea with objects of interest requires accurate saccadic eye movements. Whether a saccade is accurate and has reached the target object cannot be evaluated during its execution. Instead, post-saccadic feedback is required to assess accuracy. If the eye has missed the target object, a secondary corrective saccade has to be made to align the fovea with the target. If a systematic post-saccadic error occurs repeatedly, adaptive changes to the oculomotor behavior are made, such as shortening or lengthening the saccade amplitude. Systematic post-saccadic errors are typically attributed internally to erroneous motor commands. The corresponding adaptive changes to the motor command reduce the post-saccadic error and the need for secondary corrective saccades, and, in doing so, restore accuracy and efficiency. However, adaptive changes to the oculomotor behavior also occur if a change in saccade amplitude is beneficial for task performance, or if the shortening or lengthening of the saccade amplitude is rewarded. Oculomotor learning thus is more complex than reducing a post-saccadic position error through adaptive changes to the motor command. In the current study, we used a novel oculomotor learning paradigm and investigated whether human participants are able to adapt their oculomotor behavior to improve task performance. The task was to communicate the intended target object among several objects to a simulated human-machine interface by making saccadic eye movements. The participants were informed that the system itself could make errors. The selection process depended on a distorted landing point of the executed saccade, which led to selection errors. Two different types of visual feedback were added to the post-saccadic scene, each in a separate recording session. We compared how participants used the different feedback types to adjust their oculomotor behavior to avoid errors. We found that task performance improved over time, regardless of the type of feedback. Thus, error feedback from the simulated human-machine interface was used for post-saccadic error evaluation. This indicates that 1) artificial visual feedback signals and 2) externally caused errors, for example by faulty behavior of a simulated system, might drive adaptive changes to oculomotor behavior.

3-A-19 - Unveiling the gradual formation of stable functional representation of muscle synergies during infant locomotor development through kinematic-muscular synergies and personalized neuromusculoskeletal modeling

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Details

Primates may generate a wide range of motor behaviors by combining a manageable number of discrete motor-control units representable as time-invariant muscle synergies (MS). However, the exact process through which the motor cortex determines the optimal strategy for activating a limited set of MS from among the redundant solutions remains unknown. Several studies have suggested that MS are responsible for executing specific biomechanical functions. For instance, each MS is believed to be associated with a particular phase of human gait cycles. Expanding on this notion, we propose that the MS possess inherent functional representations upon which the motor cortex relies to select and activate the most suitable MS for specific tasks in a feasible and efficient manner. The presence of a stable functional representation of MS has been observed in the mature behaviors of adults, where a causal relationship between MS and kinematic synergies (KS) has been established. KS describes the coordinated variation of joint angles during movement and is considered a result of muscle synergy activation. However, in the case of human children, this stable functional relationship has not yet been established. This raises questions about how children develop the functional representation of MS during their growth, and what the dynamic and adaptable processes through which they construct a mature control network for the mature MS may be.

We rely on the kinematic-muscular synergies (KMS), originally proposed by Scano and d'Avella (*J. Neurophysiol.*, 2022), which combines MS and KS into single vectors. Our objective is to characterize the changes in human lower-limb KMS during locomotor development. To achieve this, we longitudinally recorded surface electromyography signals (EMGs) from 14 muscles as well as hip, knee, and ankle kinematics with 9 degrees of freedom for each limb. These recordings were collected from typically developing infants (n=11) at four different developmental stages: weight-supported walking, hand-support walking, early independent walking, and mature independent walking . Additionally, we recruited two separate groups of younger adults (n=7) and older adults (n=7) who performed independent walking to serve as comparison groups for the infant group. Through our longitudinal and cross-sectional comparisons of KMS, we discovered that while MS remained consistent across different stages, subjects, and limbs, their associated KS exhibited variability across stages. This finding suggests that the early, inborn MS for infants may be "generic" in that in any individual, the MS are not fine-tuned and tailored to the biomechanical properties of the individual's limbs to execute the biomechanical functions needed for stable gait. As the individual ages and gains sufficient experience, the functional associations of the MS tend to become more stable.

3-A-20 - Rapid implicit learning of temporal context in a cerebellar task

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Details

In motor neuroscience, implicit learning is characterized as a slow process, whereas explicit learning is expected to occur over more rapid timescales. In cognitive neuroscience, however, implicit processes are believed to be rapid and automatic, and explicit processes are considered slow and deliberate. Implicit processes are often believed to rely on associative learning and have been ascribed to subcortical regions like the cerebellum, whereas, explicit processes are generally ascribed to the frontal cerebral cortex. Recent work has revealed that these areas are connected in disynaptic functional loops, raising the question of how implicit and explicit processes are acquired in interconnected brain-wide circuits. We investigated a novel context-dependent human sensorimotor timing paradigm, which contained both explicit and implicit learning motor readouts that were previously shown to originate in frontal cortical and cerebellar circuits, respectively. Participants learned to associate different contextual cues with delayed interval responses using a manual response. Error feedback, however, was provided by a periocular airpuff, inviting the possibility of conditioned eyelid responses as an implicit readout of contextual learning. Conditioned eyeblink behaviors have been well-studied in cerebellar circuits, are considered implicit behaviors, and are generally believed to be inflexible and rudimentary motor processes. We found that participants were able to learn context-dependent responses for the explicit manual response task but more surprisingly, we found that predictive eyeblink also exhibited a flexible context-dependent character such that the eye would preemptively close at different time intervals based on the context cue at the start of each trial. Moreover, we found that well-timed implicit eyelid responses were acquired faster than well-timed explicit manual press responses. We also examined the influence of cognitive strategy on the performance of this task based on previous work. We found that cognitive strategy served to accelerate the learning rate of both manual and eyelid readouts. Finally, we provide a computational model to explain how rapid and flexible implicit learning can be implemented in cerebellar circuits. Our model and behavioral findings generate testable predictions for cortical and cerebellar systems neuroscientists and suggest that implicit learning associated with cerebellar circuitry may be more sophisticated than previously believed.

3-A-21 - Unravelling motor adaptation: insights from EEG and post-movement beta rebound

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Details

Motor learning results from several interacting learning mechanisms. These include learning via cognitive strategies and implicit adaptation. While strategy-based and implicit learning can be dissociated at a behavioural level, their underlying systems-level physiology is poorly understood. In this talk, I report data from a series of electroencephalography (EEG) studies, which provide evidence that the post-movement beta rebound (PMBR), a prominent EEG signal that follows movements, and which decreases during motor adaptation, indexes neural processes associated with strategy-based learning.

We measured brain activity using EEG while healthy participants performed reaching movements towards a target, with online visual feedback replacing the view of their moving hand. In a first experiment, the feedback was sometimes rotated, either relative to their movements (visuomotor rotation), or relative to the target (clamped feedback), always for two consecutive reaches interspersed between non-rotated reaches. In both rotation conditions, the first reach with a rotation was unpredictable. For the second reach, the task was either to re-aim, and thereby compensate for the rotation experienced during the first reach (visuomotor rotation; Compensate condition), or to ignore the rotation and keep on aiming at the target (clamped feedback; Ignore condition). Importantly, PMBR power following the first rotated reach decreased in both conditions, but this effect was larger when participants had to prepare to re-aim.

We examined if this effect was caused by different types of rotated feedback or by the behavioural relevance of an error signal. In a second experiment, the feedback was always rotated relative to the hand; however, participants were informed if a rotation would occur only for one reach (Once condition) or for two consecutive reaches (Twice condition). In both conditions, the first rotated reach was unpredictable. For the next reach, participants were instructed to keep aiming at the target (as feedback would be veridical again, Once condition) or to compensate for the rotation during the first reach (repeated on the next, Twice condition). We found a stronger decrease of PMBR following the first rotated reach when the perceived error was informative for re-aiming, i.e., in the Twice condition.

In an ongoing third experiment, we are currently examining whether the observed beta modulation during learning is bound to movement offset, possibly reflecting a conflict between vision and proprioception, or generalises to visual feedback that is dissociated in time from the movement, i.e., delayed.

Our findings could have implications for a better understanding of various neurological and psychiatric disorders in which the PMBR is altered. For example, the reduced PMBR in patients with obsessive-compulsive disorder could indicate that they continuously perceive their movements as incorrect, and therefore repeat them as part of the compulsion.

3-A-22 - The error signals for sensorimotor adaptation with visuomotor rotation perturbations

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Details

Though sensorimotor adaptation is primarily error-based learning, what error signals are is still under heated debate after decades of research. While performance error (TE) underlies explicit adaptation, the error signal for implicit adaptation divides the field: while sensory prediction error (SPE) remains its conceptual importance, most if not all computational models use TE. Previous theorizations have conveniently defined both SPE and TE in visual terms, possibly due to the wide use of visual perturbations, and overlooked one dispensable need of the motor system, i.e., locating the effector before every movement. Using perceptual error (PE) for hand localization, which incorporates multiple movement cues including visual ones, we proposed a theoretical model that can account for isolated implicit adaptation elicited by the error clamp paradigm. Here, we extend our theory to the motor adaptation regime with co-existing explicit and implicit adaptation to resolve the error-source debate. We performed six independent adaptation experiments with the classical visuomotor rotation (VMR) paradigm and compared three competing models (TE, SPE, and PE). Exp1 replicated but extended the widely-observed perturbation size-dependency in VMR: explicit adaptation increases, but implicit adaptation stagnates over perturbation size. By model fitting and cross-validation, TE and SPE models failed to predict implicit adaptation's nonlinear size dependency. PE model could simultaneously explain both learning patterns. Exp2 tackled an intriguing finding in VMR: a stepwise-increased perturbation can effectively boost implicit adaptation compared to an abruptly-applied perturbation. PE model can parsimoniously explain both conditions and demonstrates that the stepwise perturbation incrementally increases perceptual error and thus boosts implicit adaptation. Exp3 used random perturbations to suppress explicit adaptation to isolate implicit adaptation in VMR. We found the isolated implicit adaptation followed a nonlinear pattern, as accurately predicted by our PE model with similar parameters obtained from Exp1's blocked adaptation. Exp4 addressed one most-cited behavioral evidence for SPE-driven implicit adaptation, i.e., unintentional drift caused by re-aiming at a secondary target, which both SPE and TE have been suggested to account for. We manipulated the size and timing of the re-aiming. We found the drift remained unchanged when re-aiming was re-directed within (Exp4) or at the end (Exp5) of the adaptation and decreased with a larger perturbation size (Exp6). Only our PE model could capture these diverse patterns. In sum, our behavioral and modeling work provides converging evidence that TE or SPE, defined in visual metrics, cannot account for the learning dynamics of implicit adaptation in classical adaptation paradigms. The explaining power of perceptual error highlights the central role of multisensory cue integration in procedural learning.

B – Control of Eye & Head Movement

3-B-23 - Extraretinal information contributes to manual tracking

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Details

When tracking or reaching a visual target with the hand, retinal information is key to guide the hand. Although the contribution of extraretinal signals (eye efference copy and ocular proprioception) associated with saccades is established for reaching movements, little is known about that contribution during manual tracking in which smooth pursuit dominates. The goal of this study was to fill this gap. We hypothesized that, in addition to retinal information, smooth pursuit provides extraretinal information that can benefit to manual tracking accuracy. To test this possibility, manual tracking performance was compared in 10 participants under three conditions where eye and hand movements were both recorded. In the *1-Target* condition (baseline), participants had to track a single target that followed a smooth but rather unpredictable trajectory with both the eyes and the hand. In the *1-TargetFix* condition, participants had also to track the same target trajectories with the hand but this time while keeping the eyes fixed about 10 deg away from the target (ruling out the contribution of extra retinal signals, while imposing to rely on peripheral vision). Finally, in the *2-Target* condition, participants were required to track one target with the hand and another one with the eyes that, both following the same trajectory but simply spread

10 cm apart (imposing to rely on peripheral vision while preserving access to congruent extraretinal signals). We reasoned that if extraretinal information is key for hand tracking, compared to the *1-Target* condition, manual tracking should be less altered in the *2-Target* condition than in the *1-TargetFix* condition.Our results confirmed this line of reasoning. Indeed, not only manual tracking in *2-Target* was better than *1-TargetFix*, but it was as accurate as in the *1-Target* condition (as revealed by the analyses of cursor-target error and lag). Additional tests reveal that the latter finding does not hold when eyes and hand must follow uncorrelated trajectories. These results suggest that manual tracking can remain precise in the absence of target foveation as long as the eyes move congruently with the target that the hand is tracking. Taken together, these results extend the contribution of extraretinal signals beyond the control of hand reaching movements.

3-B-24 - Spatial transformations underlying saccadic eye movements to tactile and visual target stimuli

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Details

Different spatial transformations are required to make saccadic eye movements to tactile and visual stimuli on our body. When we feel a touch, our brain must combine the location of the touch on our skin with our body's current posture to determine the saccade target location in external space. In contrast, when we see a visual stimulus on our body, our brain can prepare the saccade based on just the retinotopic location of the visual stimulus. Nevertheless, some studies suggest that visual stimuli are encoded relative to the body position in frontoparietal brain regions. In the present study, we directly compared the brain networks involved in tactile and visual sensorimotor transformation to determine whether there is shared, multisensory coding of these sensory stimuli in anatomical or external-spatial reference frames, and/or a common coding of the saccade target location regardless of the sensory modality.

Participants made eye movements to visual and tactile stimuli presented on their hands, while we recorded their brain activity using fMRI. Participants were positioned with their arms in uncrossed and crossed postures, such that the right hand was positioned in the left side of space when the arms were crossed. This allowed us to distinguish between coding of sensory stimuli in an anatomical reference frame (relative to the hands) and an external-spatial reference frame (relative to the position in external-space). We further distinguished brain responses involved with sensory processing and saccade planning using a delayed anti-saccade paradigm, where participants only learned the final saccade target location (towards or away from the sensory stimulus) after a delay.

We could decode the anatomical location of tactile stimuli (left vs right hand, regardless of side of space) from bilateral somatosensory, motor and insular cortex, and right interior frontal cortex. We could not decode visual stimuli relative to the hands from any regions. External-spatial tactile location (left vs right side of space, regardless of stimulated hand) could be decoded from a medial region extending from posterior parietal to occipital cortex, and from bilateral lateral occipital cortical regions. External-spatial visual stimulus location could also be decoded from these regions, and classifiers trained to decode external-spatial tactile location could generalise to external-spatial visual location, and vice versa, suggesting a shared multisensory coding. Once the saccade movement goal was specified, a broad network of occipital, parietal and frontal brain regions encoded the saccade target location, in a common coding regardless of whether the movement target was tactually or visually defined.

Altogether, our results demonstrate that both tactile and visual stimulus locations are recoded by parietal cortex into common, modality-independent saccade movement goal locations.

3-B-25 - Failure of reafference: movement induced visual loss secondary to infantile nystagmus. It is not just the VOR

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Details

Introduction: Patients with infantile nystagmus syndrome (IN) complain of significant vision loss, despite the fact that static visual acuity in such patients is often relatively normal. When tested in the clinic, such patients do not complain of oscillopsia. In the real world, they note that they must stop to see. When moving, they experience oscillopsia and poor vision. To evaluate the challenges of movement within the visual world in such subjects under controlled laboratory conditions, we examined a range of eye movements and acuity in a group of patients diagnosed with IN.

Methods: Using two-dimensional video-oculography, we recorded eye movements during binocular viewing of point targets, square wave gratings, and a wandering E optotype. Gaze holding was assessed in the dark and in multiple target locations. Optokinetic responses were recorded during viewing of high contrast square wave gratings. Smooth pursuit was elicited by sinusoidally moving point targets. Vestibulo-ocular reflex (VOR) was elicited during en-bloc rotation in the dark. Functional VOR was evaluated by comparing static and dynamic acuity. Minimum perception time was assessed with timed presentation of visual targets.

Results: The eye movements of patients with IN changed dramatically with age and viewing context. Young patients showed symmetric pendular eye movements when fixating central targets, while older patients showed predominately jerk nystagmus. Waveforms at all ages changed with context. Gaze holding in eccentric locations changed the velocity, waveform type, and direction of the nystagmus. Smooth pursuit was severely impaired. Optokinetic nystagmus gains were well below normal even when the stimulus motion was perpendicular to the underlying nystagmus. Saccades were also inaccurate with long latencies, independent of the direction of the movement relative to the direction of the IN. Saccadic velocities were largely normal. Vestibulo-ocular reflex function was intact in the dark, however in the light, dynamic acuity was significantly impaired as was minimum perception time.

Discussion: This work indicates that there is significant impairment of visual function and eye movement in response to self-motion and moving visual stimuli in IN patients. These deficits are consistent with patient reports of visual loss despite mild loss of acuity in clinical measurements. We hypothesize that the loss of acuity and the emergence of oscillopsia in patients with IN during movement is a consequence of a suppression of sensory feedback from visual motion and predictive compensation for static IN waveforms. The visual system no longer provides the necessary inputs to motor and perceptual systems to stabilize or track images, or to calibrate reflexes, with the added dimensions of self motion and motion of objects in the visual world.

3-B-26 - Dissociation of smooth and saccadic pursuit while tracking moving motion patterns

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Details

Often when we track a moving object it is with a combination of smooth pursuit and saccades and the two subsystems are considered to be closely linked in a shared control system. Here we report a strong dissociation of the pursuit and saccade system while tracking moving motion patterns. We presented three different motion patterns: a simple motion border, a natural vortex, and an artificial square motion pattern. Despite their differences, each pattern exhibited a motion border causing local curl in the motion field and moved independently of its first-order motion. Participants, instructed to pursue the motion patterns, were unable to perform smooth pursuit, for all three motion patterns the pursuit gain was close to zero. This was compensated by frequent catch-up saccades which landed accurately on target. Thus, there was no motion signal that could be used for pursuit, but there was a motion signal that could be used by the saccade system to predict the movement of the motion patterns during saccade planning and execution. To test whether only pursuit initiation was impeded, we added a red dot that moved along with the motion patterns to initiate a successful pursuit and measured if pursuit gain could be maintained when the red dot was shut off. Results showed that after switching off the red dot the pursuit gain decreased as fast as when both the red dot and the motion patterns were switched off together. Therefore, the pursuit could not be maintained by the movement of the motion patterns, even if it was successfully initiated. In a second experiment we investigated whether the dissociation of catch-up saccades and pursuit also holds for intercepting saccades and pursuit. Although smooth pursuit of this motion type is impeded, we observed an increased pursuit gain in the first 200 milliseconds following an intercepting saccade. Afterwards the pursuit gain diminished close to zero once more. The initial gain correlated with the saccade's error magnitude, and the cumulative pursuit in the initial 200 milliseconds typically compensated for this error. We propose that even in the absence of any motion signal in the pursuit system, the saccade system can activate the pursuit system to compensate for its shortcomings.

C- Disorders of Motor Control

3-C-27 - Does postural training combined with proprioceptive stimulation modulate further muscle spindles pathway in old adults?

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Details

Alteration in sensorimotor integration of different sensory inputs (visual, tactile, vestibular, proprioceptive) can modify postural control in older adults. In such a case, intervention should be designed to restore proprioceptive efficacy by inducing neural plasticity. This could be done by stimulating proprioceptors with local vibration (LV) or their afferent fibers with transcutaneous electrical nerve stimulation (TENS). An even more effective intervention would be to combine these techniques with an on-going proprioceptive input induced by balance exercises. At the spinal level, neural plasticity could indirectly be investigated with the Hoffmann (H) reflex, which assesses the efficacy of Ia afferents to discharge motor neurons. For instance, down-modulation of soleus H-reflex from seated to standing position is assumed to reduce the risk of unexpected reflex activity that may impair balance control. The aim of this study was to evaluate the impact of an 8-week balance (two 1-hour sessions/week) training program with or without proprioceptive stimulation (LV and TENS) on the modulation of the H reflex from seated to standing posture in old adults. A total of 32 old adults (mean ±SD; 18 women, age=80 ±3, BMI=23 ±2) were randomly assigned into 4 different groups: the LV group (n=7) trained with the vibrators applied to the triceps surae and tibialis anterior muscle, the TENS group (n=8) trained with electrodes placed to the same muscles using TENS currents, the group trained using both techniques (LV+TENS (n=10), and the control group (CON, n = 7) trained with no proprioceptive stimulation. All participants underwent baseline assessment followed by pre-intervention assessments 8 weeks later, this period acting as a control condition. This was followed by an 8-week intervention period, with two 1-hour sessions per week, and post-intervention assessments. The training sessions involved tailored balance exercises, with each exercise being a combination of four variables: vision (eyes open/closed), surface (rigid/foam/Bosu), feet position (comfortable/together/1 foot/tandem) and movement such as heel to toe. The outcomes were soleus H-reflex to maximal M-wave ratio triggered by electrical stimulation of the posterior tibial nerve in both seated and standing positions. Results showed that the H-reflex amplitude was not significantly down-modulated from seated to standing position before training ($p=0.54$) nor after ($p=0.16$). Furthermore, the intervention did not induce changes in the normalized H-reflex amplitude in both standing (mean for all sessions: 15.1 ±8.9%) and seated (mean for all sessions: 22.3 ±14.1%) positions. This absence of balance intervention effects on the muscle spindles afferences effectiveness to discharge on motor neurons in old adults might be due to the decrease of automatic control (i.e, spinal loops) and the increase of controlled processing (i.e, basal ganglia-cortical loops) of upright standing in old adults.

3-C-28 - Quantitative assessments of reaching after focal ischaemic lesions in non-human primates

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Details

Immediately after a stroke, survivors transition through a stereotyped sequence of recovery. Within days to weeks, initial weakness and loss of dexterity (negative motor signs) are replaced with spasticity and highly stereotyped muscle coactivation patterns called ‘synergies’ (positive motor signs). Flexor synergy is the most common abnormal post-stroke synergy, whereby elbow flexors are obligatorily recruited relative to the degree of shoulder abduction, regardless of the motor goal. Most survivors eventually suppress intrusive synergies to regain strength and coordination of the affected upper limb; however, some survivors become ‘stuck’ in this state, making reaching and grasping near impossible. Despite this, no animal study has ever attempted to investigate the neural source of post-stroke synergies separate from weakness. **Our aim was to dissociate quantitatively the relative contributions of different divisions of the primary motor cortex (M1) to the positive and negative motor signs after stroke, and how this is changed after combined lesions of the cortex and magnocellular red nucleus (RNm).** 8 rhesus macaques were trained on a reach and grasp task between a handle and a baited cup. Handle and cup positions were reconfigured for flexion vs extension reach performance, repeated with and without arm support. Comparison of these task conditions ensured a discrimination between impairments caused by synergies versus weakness. When fully trained, wires for electromyography (EMG) recording were implanted into 12 right upper limb muscles. High speed videos and EMG were recorded while the monkeys made rapid reaching movements. Videos were analysed using DeepLabCut for markerless tracking of the hand. After a baseline recording period, endothelin-1 infusions produced focal ischaemic lesions of the upper limb representations in each cortical area of interest: the anterior (n=2) and posterior (n=2) subdivisions of ‘Old’ M1, and ‘New’ M1 (n=2). These areas were defined according to anatomical studies which suggest differences in their cortico-motoneuronal and cortico-reticular connections. Additional monkeys (n=2) also received RNm lesions preceding a cortical lesion. Kinematics and EMG were analysed over 15 weeks after each cortical lesion. Our results show that unlike human stroke survivors, none of the macaques developed flexor synergy, only weakness. Maximal recovery in all animals was reached within two months post-lesion. We identified quantitative differences using our reaching assessments, dependant on the lesion area and whether the animal had received a RNm lesion preceding a M1 lesion. This research suggests positive motor signs are not caused by the loss of a specific M1 subregion, regardless of having a RNm lesion beforehand.

3-C-29 - Pathogenesis of freezing of gait in a neuromusculoskeletal model

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Details

The ability to start and stop locomotion in response to different situations is an essential survival strategy in mammals. This flexibility of locomotion is thought to be mainly regulated by the brainstem and spinal cord. Although freezing of gait (FOG), a pathological phenomenon seen in conditions such as Parkinson's disease, deprives individuals of flexible locomotion and increases the risk of falls, its pathogenesis remains unclear. In this study, we investigated the pathogenesis of FOG and its subtypes using a two-dimensional neuromusculoskeletal model. This model consisted of a body with seven links and 18 muscles, as well as a neural system including the brainstem and spinal cord. Following internal parameter optimization, using standard genetic algorithms, the model was able to walk successfully. Under abnormal brainstem activity conditions, we investigated whether FOG could be observed by modifying the parameters of the pedunculopontine nucleus (PPN) and cuneiform nucleus (CnF) models in the brainstem during the initial 3 seconds of walking. Using an FOG-identifying algorithm, we detected 156 FOG events among the generated 40,000 parameter sets. Hierarchical cluster analysis of FOG instances identified four clusters of parameters, and comparisons of physical movements during instances revealed differences among the clusters. These results suggest that modifications in PPN and CnF activity may be responsible for the pathogenesis of FOG and its subtypes, providing potential objective criteria for the qualitative clinical classification of FOG.

3-C-30 - The neural basis of motor sequence control in individuals with Developmental coordination disorder (DCD)

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Details

Behavioural research suggests that motor deficits in Dyspraxia/Developmental coordination disorder (DCD) are related to alterations in the planning of movement sequences, but it is unclear which neuro-functional mechanisms of motor sequence control are affected. Motor sequence planning and execution are associated with movement-related desynchronisation in the Î² band (MRBD), a marker of excitation of the motor system, followed by a Î² rebound (PMBR) immediately after the movement ceases. Further, neurophysiological and behavioural findings in controls show that movements in a sequence are internally pre-ordered in parallel during planning and predict quality of subsequent performance. We set out to study whether individuals with DCD show reduced excitatory and inhibitory neural modulation and sequence pre-ordering during the peri-movement phase. 4 participants with reported DCD diagnosis and 11 healthy controls took part in a sequence learning study where they performed two 4 element finger sequences from memory after a 1s delay (delayed sequence production task) over three sessions and were scanned in the Magnetoencephalography (MEG) scanner after a refresher of the delayed sequence production task. During training DCD were affected in the sequence accuracy rate (p<.001), as well initiation speed (p=.004) and movement duration (p=.003) in trials with correct sequence production. In addition, they showed behavioural markers of reduced preordering of movement in the upcoming sequence for RT (p=.026) and error (p=.014) for press probes associated with different positions in the sequences during planning. Our preliminary MEG findings (N=11 out of target 16 age-matched controls and N=4 out of target 16 participants with clinically diagnosed DCD) suggest that individuals with DCD have a less pronounced modulation of the motor system in the peri-movement phase compared to controls when they produce correct sequences from memory. In particular, we observed less excitation (movement-related *Î¼* desynchronisation) -700 before to 950ms after the first movement (p=0.003) and a less pronounced inhibition (movement-related Î² rebound) 300 to 1250ms after the last movement (p=0.04) over contralateral M1. This was accompanied by a less contralateral and more widely distributed modulation of *Î¼* and Î² during sequence planning in DCD participants. Multivariate pattern decoding will be utilised to examine the neural preordering of movements during planning and its relationship to the oscillatory markers in the peri-movement phase. Our results suggest that individuals with DCD modulate primary motor areas less and engage a broader set of neural resources outside the contralateral primary motor network in skilled sequence production from memory. This work advances our understanding of the neural and informational control of motor sequences in DCD and may provide entry points for future interventions.

3-C-31 - Does imagery influence movement during dance in people with Parkinson’s disease?

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Details

Dance and music can improve motor outcomes for people with Parkinson's disease (PD) as well as older adults without a neurological condition. Although behavioural evidence indicates that dance can improve motor symptoms of PD and specific outcomes such as gait, little is known about the neural mechanisms underlying effects of dance for PD. Motor simulation through action observation and motor imagery is widely used within dance. These strategies can enhance motor performance and learning in different populations, and have been explored as techniques for neurorehabilitation in conditions such as PD. It has been proposed that motor simulation (observing and imagining movement) may contribute to beneficial outcomes of dance for people with PD, but so far this is only evidenced through qualitative and self-report data. The present study examines the influence of motor imagery on quantitative measures of movement in a group dance setting for people with and without PD.

Individuals with PD (N=8) and without PD (N=12) watched and performed a series of seated dance movement sequences. The dance was performed first without, and then with, motor imagery instructions and an imagery-evoking narrative. Participants' movement was recorded with a markerless motion capture system.

Kinematic data will be analyzed to examine differences in aspects of movement such as smoothness and velocity when performing the dance movements with and without imagery. Kinematics will also be compared between participants with and without PD. The results will provide insights into the role of motor simulation in influencing movement within dance, as well as the potential to enhance therapeutic outcomes of dance and other activities.

3-C-32 - Ventral motor cortex activity supports neural cursor control by a person with paralysis

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Details

Intracortical brain-computer interfaces (iBCIs) offer the potential to restore communication capabilities for people with paralysis due to neurological disease or injury such as ALS or stroke. While computer control via cursor movement and discrete gestures has been a staple application of iBCIs for over a decade, recently speech-based iBCIs have progressed rapidly, achieving levels of word accuracy necessary for practical usage. Typically, cursor iBCIs are driven by neural activity recorded from electrodes in the predominantly hand-related dorsal precentral gyrus (dPCG), whereas speech iBCIs are driven by electrodes in the predominantly speech- and orofacial-related ventral precentral gyrus (vPCG). Because the cortical coverage of an iBCI is currently limited by constraints on the number of electrodes that can be implanted and on the craniotomy size, a decision must be made per user as to which brain area(s) to target. It was unknown whether an iBCI can enable both cursor and speech functionality if all the electrodes were implanted in vPCG (to maximize speech decoding accuracy).

In this study, we demonstrate for the first time cursor and click control driven by neural activity recorded from intracortical microelectrodes (four 64-electrode Utah arrays) in vPCG. This cursor iBCI was used by participant T15, a 45-year old man with ALS enrolled in the BrainGate2 clinical trial, who has previously operated a speech iBCI [Card et al. 2023, medRxiv]. In his very first usage of a cursor iBCI, T15 successfully gained closed-loop control of the cursor within 41 seconds of beginning calibration. In a later session, T15 achieved a bitrate as high as 1.83 bits per second (average 1.68 bps) in a target grid selection task. This result suggests that iBCI users may be able to have arrays placed in vPCG (speech motor cortex) in order to operate both a cursor iBCI and a speech iBCI, instead of having to split arrays between ventral and dorsal areas. This offers additional flexibility to communication neuroprostheses to provide multimodal BCI functionality while still having sufficiently high channel counts in ventral areas to support accurate speech decoding.

One observation warranting further investigation is that speech production-related neural activity in vPCG transiently interfered with cursor control, in contrast to a previous finding that speech production-related neural activity in dPCG did not interfere with cursor control. Future work is required to explore whether vPCG neural activity contains orthogonal speech-related and cursor-related neural subspaces which decoders can utilize in order to provide simultaneous speech and cursor control. In the meantime, current multimodal cursor and speech iBCIs driven by vPCG neural activity may be limited to sequential cursor and speech use when high-precision cursor control is required.

3-C-33 - Subthalamic neurons of patients with early onset Parkinson's disease are more sensitive to voluntary movements

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Details

The prevalence of early-onset Parkinson's disease (PD) in clinical practice has increased significantly in recent years, yet little is still known about the characteristics of "early" PD and the associated electrophysiological parameters. In this study, we examined the activity of single units associated with movement in a group with early onset PD and a control group.

We performed microelectrode recording of single unit activity of subthalamic nucleus (STN) in 8 Parkinson’s disease patients with early onset and 8 patients with late onset (control group) during neurosurgery DSB procedure. During recording we asked patients to perform voluntary motor tests. In total, we performed recording of 328 subthalamic neurons, 93 of which were associated with movement. We analyzed the firing rate and spike pattern parameters of the selected sensitive neurons and divided them into 3 groups - burst, pause, and tonic by means of an unsupervised clusterization.

Analysis of evoked activity showed the similar unit responses: activation or inhibition, which advanced or lagged behind voluntary movements in both groups of patients. Wherein we found twice as many sensitive neurons (37% vs 18%) in patients with early onset. We also found that in early-onset patients, neurons were characterized by significantly lower firing rate and higher coefficient of variance and percentage of bursting spikes. These differences may result from a larger percentage of pause neurons (60% vs 40%) and lower percentage of tonic cells (9% vs 30%) in the early-onset group.

Thus, we showed that subthalamic cells in the early-onset parkinsonian patients were more movement sensitive and characterized by a more pause pattern of activity. Further study is needed to find electrophysiological features of PD patients with early onset which could be useful in DBS programming.

The study was funded by the Russian Science Foundation (22-15-00344).

3-C-34 - Epidural stimulation with viral BDNF therapy and robot training after SCI improves recovery of function, delays the onset of viral side effects, and maintains observed hindlimb muscle synergies and motor modularity

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Details

Some interneuronal circuits in the spinal cord that synapse directly onto motor neurons may be organized for modular muscle control, as synergy groups, rather than individually. Electromyogram (EMG) recordings reflect the premotor network drives and potential modular network structures, allowing inferences of modular spinal circuits and any changes after spinal cord injury (SCI) and rehab. Using dimensionality reduction techniques (i.e., ICA) on hindlimb EMG, our lab has reported modular spinal circuit structures in neonatal, adult, injured and uninjured rats. Here, we used ICA to study changes in spinal circuits throughout rehab when using combination therapies for SCI in rats. Although each therapy modality, rehab robotics, biological, and epidural stimulation (ES), improves function individually, we understand little about their synergistic interactions functionally. We also have limited knowledge of the effects of combination therapies on muscle activation patterns and their underlying neuronal circuits, which may reflect different neuronal control strategies for motor coordination through recovery. Our lab demonstrated enhanced locomotor outcomes in rats with complete T9/10 SCI after combining robot training with viral BDNF and ES. Prior work revealed a potential critical period during the initial two weeks of training, when ES likely attenuates some spasticity development that can be an effect of the BDNF treatment on motor function. Spasticity can result in the eventual collapse of gained motor function in 40% of rats. Broad-current spread ES centered at L2 and S1 prevented collapse over 6 weeks when combined with viral BDNF and robot rehab. Here, we tested if combined therapies with ES can prevent collapse beyond 6 weeks and if more selective ES can further improve stepping. We hypothesized that the combined treatment using localized ES would selectively target the central pattern generators at L2 and S1, resulting in improvement in weight-supported stepping. We also hypothesized modularity analysis of the hindlimb muscles will reveal patterns of spinal circuit reorganization and preservation of spatial synergy structure across rehab treatments and outcomes. Our data show that the combined therapy can improve stepping after injury, but the tested ES parameters may only delay the onset of viral spastic collapse rather than prevent it. However, ICA of the hindlimb

EMGs supports conservation of the spatial synergies in modular control of locomotion in intact rats, after SCI, and throughout rehab, regardless of outcomes. The high post-SCI correlation values of the weighting matrices and synergy matching in all groups suggest preservation of spatial synergies after SCI and rehab, regardless of collapse outcome. Future analysis will explore the differences in activation patterns and temporal organization of the drives to these conserved spatial synergies to better understand the progression of rehab, of collapse, and its mitigation by ES.

D – Fundamentals of Motor Control

Poster Cluster (3-D-35 to 3-G-37)

3-D-35 - Targeting a specific motor control process reveals an age-related compensation that adapts movement to gravity environment

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Details

As the global population ages, it is crucial to understand sensorimotor compensation mechanisms that allow older adults to remain in good physical health, i.e. underlying successful aging. Although age-related compensation has long been conceptualized and despite important research efforts in varied gerontological subfields, behavioral compensatory processes and their underlying neural mechanisms remain essentially chimeras. This study investigates age-related compensation at the behavioral level. It tests the hypothesis that age-related compensatory processes may correspond to an adaption process that changes movement strategy. More specifically, we focused on the ability of younger (n = 20; mean age = 23.6 years) and older adults (n = 24; mean age = 72 years) to generate energetically efficient movements in the gravitational environment. Previous results, from separate studies, suggest that aging differently alters energy efficieny in arm movement and whole-body movement tasks. With aging, energy efficiency seems to remain highly functional in arm movements but was shown to decrease in whole-body movements. Here we built on recent theoretical and experimental results demonstrating a behavioral process that optimally adapts human arm movements to the gravitational environment. Analyzing phasic muscle activation patterns, previous studies provided electromyographic measurements that quantified the output of an optimal strategy using gravity effects to discount muscle effort. Using these measurements, we probed the effort-minimization process in younger and older adults during arm movement and whole-body movement tasks. The key finding demonstrates that aging differently alters motor strategies for arm movements vs whole-body movements (= 5.48, P=2.44E-02, =0.120). Older adults used gravity effects to a similar extent as younger ones when performing arm movements (older adults, mean ± SD: -10.7 ± 5.6, 95% CI: [-8.4;-13.0]; younger adults, -11.4 ± 3.6, [-9.8;-13.0]), but to a lesser extent when performing whole body movements (older adults, -9.7 ± 3.2, [-8.0;-11.5]; younger adults, -15.6 ± 3.3, [-14.1;-17.0]). These results provide clear experimental support for an adaptation strategy that down-regulates effort minimization in older adults.

3-D-36 - Metabolic cost demonstrates gravity-related effort minimisation

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Details

The Central Nervous System (CNS) is thought to select movement trajectories that optimize certain criteria within the environment. For example, previous work revealed that young adults' arm movements are tuned to harvest gravity effects and reduce muscle effort, as supported by kinematic and electromyographic (EMG) parameters (Gaveau et al., 2016, 2021). This is supported by the results of model simulations using the optimal control theory (Berret 2008, Gaveau 2016). The present study aims to further test gravity optimization theory by examining energy consumption through exhaled gas analysis. Hitherto, support for the optimal integration of gravity are either indirect (kinematics), or only concerns some specific movement phases, i.e. muscle activation during the acceleration of a downward movement and the deceleration of an upward movement. A more direct and global support is lacking and could be provided by metabolic analyses.

20 young adults (10 females; 22.8 years old) performed four blocks of horizontal movements and four block of vertical movements with their right dominant arm. One block consists of 120 consecutive single degree of freedom arm movements. Visual and audio signals were used to time movements. The **energy consumption** was measured using a Cosmed K5 portable metabolic system using breath-by-breath mode (BxB). Then, we computed the net metabolic power using the Brockway equation (Brockway, 1987) from the VO2 and the VCO2 and by subtracting the baseline metabolic power. We also recorded **EMG** signals from 4 shoulder muscles (Anterior and posterior deltoids for vertical movements and major pectoral as well as infraspinous for horizontal movements) using bipolar surface electrodes (1000Hz) and the **kinematics** of 10 markers using a custom model from a Vicon motion capture system (200Hz). The total torque was computed from the kinematic data using the finger and the shoulder markers.

A slight torque difference was found between horizontal and vertical movements, where vertical movements were more torque-costly than horizontal ones. Therefore, we used this variable as covariate in the statistic model. Classic kinematic and electromyographic analyses confirmed the results of previous studies supporting the hypothesis that the brain minimizes muscle effort by harvesting gravity effects. In terms of net metabolic power, vertical movements proved less energy-consuming than horizontal ones (Repeated Measures Anova ; P=3.61E-02, η^2 =0.222 ; vertical: 0.498 ± 0.35 ; and horizontal: -0.626 ± 0.37). These new results provide strong support for the effort-optimization theory, assuming that an internal model of gravity is used to leverage its effects instead of compensating for them.

3-G-37 - Deactivation and collective phasic muscular tuning for pointing direction: insights from machine learning

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Details

Arm movements in our daily lives have to be adjusted for several factors in response to the demands of the environment, for example, speed, direction or distance. Previously, we had shown that arm movement kinematics is optimally tuned to take advantage of gravity effects and minimize muscle effort in various pointing directions and gravity contexts (Gaveau et al. 2016). Here we build upon these results and focus on muscular adjustments. We used Machine Learning to analyze the ensemble activities of multiple muscles recorded during pointing in various directions. The advantage of such a technique would be the observation of patterns in collective muscular activity that may not be noticed using univariate statistics. By providing an index of multimuscle activity, the Machine Learning (ML) analysis brought to light several features of tuning for pointing direction. In attempting to trace tuning curves, all comparisons were done with respects to pointing in the horizontal, gravity free plane. We demonstrated that tuning for direction does not take place in a uniform fashion but in a modular manner in which some muscle groups play a primary role. The antigravity muscles were more finely tuned to pointing direction than the gravity muscles. Of note, was their tuning during the first half of downward pointing. As the antigravity muscles were deactivated during this phase, it supported the idea that deactivation is not an on-off function but is tuned to pointing direction. Further support for the tuning of the portions of the phasic EMG containing only negative activity was provided by progressively improving classification accuracies with increasing angular distance from the horizontal. Overall, these results show that the motor system tunes muscle commands to exploit gravity effects and reduce muscular effort. It quantitatively demonstrates that phasic EMG negativity is an essential feature of muscle control. The ML analysis was done using Linear Discriminant analysis (LDA) and Support Vector Machines (SVM). The two led to the same conclusions concerning the movements being investigated, hence showing that the former, computationally inexpensive technique is a viable tool for regular investigation of motor control

3-D-38 - Deepening understanding and practical application of neural control with high-density electromyography

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Details

Recent research indicates that many individuals with complete paralysis can activate motor units (MUs) below their spinal cord injury (SCI), which can be detected using electromyography (EMG). Using high-density electromyography (HDEMG), we detected MU activity in the forearm as the subject attempted gestures with their paralyzed hand. Despite no visible movement, distinct patterns of muscle activity were identified corresponding to the attempted movement of individual digits, showcasing the potential to extract voluntary control signals from paralyzed muscles. This advancement paves the way for novel applications and control of assistive devices, enabling individuals to engage with games and activities in ways not possible previously.

The **ultimate goal** of this study is to leverage HDEMG to enable individuals with paralyzed hands to master motor-unit control for enhanced engagement in various immersive activities like gaming and occupational tasks that were previously inaccessible.

Our poster outlines muscle activation mapping during finger and wrist movements using four 64-channel HDEMG arrays on the dominant forearm. We analyzed movement patterns and quantified voluntary degrees of freedom (DoF) in the HDEMG signals, comparing them with able-bodied participant data. These results inform practical applications, such as optimizing control strategies. Participants used myoelectric activity from specific movements to navigate through custom video game levels with varying degrees of difficulty.

The study involved two participants: *one able-bodied participant and the other with an SCI classified as AIS B C5 motor complete, C6 sensory incomplete*. A marker-based motion capture system tracked their movements, and ultrasound identified muscle boundaries under the HDEMG electrodes. Participants attempted prompted movements displayed as animated hands on a screen, involving isometric flexion and extension of each digit and the wrist.

Distinct myoelectric activity patterns and motor unit firing were observed during attempted wrist and finger movements for both participants. The participant with SCI showed the highest EMG activity during wrist movements, which could be performed overtly due to the residual function of the wrist extensors, and exhibited no voluntary motion in any digits compared to the healthy participant. However, attempted movements of the thumb, index, and middle fingers produced clear EMG modulation on the extensor side and weaker signals on the flexor side. Attempted ring and pinky finger movements resulted in minimal extensor activity and barely visible signals on the flexor side. Using this data, we developed and implemented optimized control strategies for participants to interact with a 1DoF Unity custom game solely using their HDEMG activity. **These tailored strategies capitalize on observed muscle activity patterns, demonstrating the technology's potential for enabling functional control in individuals with motor impairments.**

3-D-39 - Differential roles of low- and high-beta band cortico-subcortical coherence in movement inhibition and expectation

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Details

Beta band oscillations in sensorimotor cortex and subcortical structures such as the subthalamic nucleus (STN) and internal pallidum (GPi) are closely associated with motor control. Recent work suggests that low-beta (14.5-23.5 Hz) and high-beta (23.5-35 Hz) cortico-STN coherence arise through distinct networks, possibly reflecting indirect and hyperdirect pathways. Here, we sought to probe whether low- and high-beta coherence also exhibit different functional roles in facilitating and inhibiting movement. Twenty Parkinson's disease patients with deep brain stimulation electrodes in either STN or GPi performed a classical go/nogo task while magnetoencephalography and local field potentials were simultaneously recorded. Subjects' expectation was manipulated by presenting go- and nogo-trials with different probabilities. We identified a lateral source in sensorimotor cortex for low-beta coherence and a medial source near supplementary motor area for high-beta coherence. Task-related coherence time courses for both sources revealed that low-beta coherence was more strongly implicated than high-beta coherence in the performance of go-trials. Accordingly, subjects' average pre-stimulus low-beta but not high-beta coherence correlated with overall reaction time. Unexpected nogo-trials led to a brief increase in low-beta coherence shortly after stimulus presentation and at a longer latency for high-beta coherence. Neither low- or high-beta coherence showed a significant correlation with patients' symptom severity. While low-beta cortico-subcortical coherence seems related to motor output, the role of high-beta coherence remains elusive.

3-D-40 - Discerning state estimation and sensory gating, two presumptive predictive signals in mouse barrel cortex

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Details

We studied two neuronal, presumptive predictive systems, sensory gating (SG) and state estimation (SE) in the somatosensory cortex (S1) of mice. Both have almost identical effects in attenuating sensory signal flow. Recording their respective effects on S1-spiking in the same experiment, we were able for the first time, to delineate the two systems on the neuronal level. To do this we translated the classical paradigm of 'open loop approach', developed by Curtis Bell in 1981 in fish, to mammals, namely head fixed mice trained on a whisker reaching task. The success in separating the two systems was based on regarding their temporal relationship to movement and its sensory consequences. SG attenuation can be active for longer (~500 ms) after movement onset than SE (~200 ms). SG is present after training the animal to reach movements, while SE can be learned within one session after presenting a change in sensory consequences. Currently we test the dependencies of the system to cerebellar blockade. We hypothesize that SE likely serves sensorimotor control, assuring smooth movements, while SG may be located on a higher hierarchical level, e.g. directing attentional processes, or predicting the availability of reward.

3-D-41 - The effects of inherent and incidental constraints on bimanual force control in parabolic flight

Deanna Kennedy [1], **Osmar Pinto Neto** [2], **Madison Weinrich** [1], **Renee Abbott** [1], **Nathan Keller** [3], **Traver Wright** [4], **Bonnie Dunbar** [1], **Ana Diaz Artiles** [1]

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Details

The ability to coordinate actions between the limbs is important for many operationally relevant tasks associated with space exploration (e.g., controlling a rover, landing a spacecraft). Recent research has indicated that bimanual control differs between simulated microgravity (0 g) and Earth (1 g). However, little is known about the impact of partial g-levels on bimanual control. A significant milestone in space exploration is the planned return of humans to the moon and the establishment of the groundwork for crewed mission to Mars. Therefore, understanding constraints that can influence operational performance of bimanual tasks in altered gravity is of practical and theoretical importance. The current experiment was designed to determine the effects of gravity on coordination dynamics. Parabolic flight was used to deliver g-levels of 0, 0.25, 0.5, and 0.75 g. Right limb-dominant participants (N=12) were required to coordinate patterns of isometric forces in 1:1 in-phase and 1:2 multi-frequency patterns by exerting force with their right and left triceps brachii muscles. Lissajous plots and force templates were provided to guide performance. Muscle activity from the triceps brachii muscles were recorded. EMG-EMG coherence between the two EMG signals was calculated using wavelet coherence. Results indicated effective temporal performance of the goal coordination patterns in all gravity conditions. However, force production was less harmonic in 0 g than in 0.75 g, indicating that more force distortions (adjustments, hesitations, and/or perturbations) occurred in the 0 g condition than in 0.75 g. No differences between gravity conditions for EMG-EMG coherence measures were observed in the 1:1 task while differences were observed in the 1:2 task. During the 1:2 task significantly higher coherence was observed in the Beta bands during microgravity compared to 0.75 g. Higher levels of coherence in the Beta band during 0 g than 0.75 g suggest greater cortical influences are acting on the central nervous system in microgravity than in partial gravity. Results are consistent with previous research attributing manual control deficits in altered gravity environments to cognitive and perceptual constraints. Future work will continue to investigate inherent (neuromuscular) and incidental (environmental) constraints that facilitate or interfere with the neural control of bimanual actions in altered gravity environments using tilt paradigms and centrifugation. This research effort is supported by the NASA Human Research Program, Grant number 80NSSC20K1499.

3-D-42 - Deliberative processes within the sensorimotor cortex: the effect of choice uncertainty on beta-band activity in a free-choice task

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Details

A central question in motor neuroscience is how the brain selects amongst many potential movements to achieve a goal. An influential model posits that decisions involve a competition between multiple movements being prepared simultaneously in sensorimotor regions, which are then biased by decisional variables from higher-order regions. In support, several lines of evidence have revealed that neural activity in sensorimotor regions depends upon the number of alternative possibilities, with greater preparatory activity when more options are possible. However, most previous studies have used instructed-choice tasks, in which decisions are based on abstract selection rules (i.e., stimulus-response mappings), leaving open whether such competitive interactions also subtend internally-guided decisions that mediate natural interactive behavior, like choosing to go left or right of an obstacle. Here we aimed to investigate the effect of choice uncertainty on action selection in a free-choice task involving decisions about actions directed toward a single goal. To do so we used electroencephalography and measured beta-band activity (15-30 Hz) over contralateral sensorimotor cortex, which is known to desynchronize (Î²-ERD) prior to movement as a reflection of motor preparatory processes. We developed an obstacle avoidance task in which healthy human participants (n = 23) reached toward a centrally located target using their right (dominant) hand. On every trial, an obstacle appeared on the path to the target. Participants were free to avoid it to its left or right, but had to initiate their movement within 600ms of obstacle presentation. Uncertainty was manipulated by placing either a small obstacle on the direct path to the target, which could be equally well avoided from the left or the right (high uncertainty condition; 100 trials), or a larger obstacle shifted laterally, which could only easily be avoided on one side (low uncertainty condition; 50

trials for both left and right). Critically, this setup equated movement trajectories across conditions, allowing us to isolate the influence of uncertainty on Î²-ERD. We hypothesized that Î²-ERD would be greater in the high than low uncertainty condition, indexing greater preparatory activity when more trajectories are possible. Behavioral results revealed that reaction times (RT) were significantly longer when uncertainty was high ($p<0.001$), suggestive of longer deliberation. Strikingly, however, and contrary to the hypothesis, Î²-ERD was smaller in the high uncertainty condition ($p=0.010$). This finding suggests that higher uncertainty led to weaker preparatory activity, possibly underlying the longer RTs. Together, these data suggest that deliberation between actions evolves differently in the sensorimotor cortex when participants freely choose which movement to make as compared to when choices are instructed.

3-D-43 - The cellular encoding of passive forelimb movement in mouse forelimb primary somatosensory and motor cortex

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Details

Cortical processing of proprioceptive information is thought to generate an internal body schema for perception and accurate motor control. While prior work in primates has shown responses to passive limb movement in both primary somatosensory and in primary motor cortex, differences between the two regions in the cellular encoding of limb movement and position and in the afferent sources of input remain unclear. Because of the possibility of combining intersectional genetics with single cell resolution recordings, mice are an ideal model system to address these questions, but, to our knowledge, only one study has investigated passive limb movement encoding in mouse forelimb somatosensory cortex (fS1) and forelimb motor cortex (fM1) (Alonso et al., 2023). Using multi-electrode probes, we recorded limb movement responses simultaneously in fS1 and fM1 and characterised single-unit directional and velocity encoding of mainly deeper layer cortical neurons. We show that the representation of passive movement is distributed across fS1 and fM1 with single neurons tuned to different horizontal movement directions. Moreover, responses to limb movement in fS1 and fM1 are more strongly driven by higher movement velocities, though fS1 units remaining more sensitive to lower amplitude velocities than fM1 units. We further attempt to assess afferent-specific drive by comparing movement responses to vibrotactile stimulation with different frequencies. Low-frequency cutaneous vibrotactile stimulation drove only weak responses in fM1 but a stronger activation in fS1 which showed a larger proportion of units responsive to both vibrotactile and limb movements than fM1. We next performed recordings in *Pvalb-Cre;Piezo2^{cKO}* mice, which have a phenotype of uncoordinated limb movement resulting from a proprioceptor-targeting knockout of Piezo2 (Woo et al., 2015). We report a larger reduction of passive limb movement responses in fM1 neurons than in fS1. Together these data support the hypothesis that there is a higher relative contribution of proprioceptor afferent drive in fM1 than in fS1 and support the mouse as an intersectional model system for the mechanistic understanding of cortical limb proprioception.

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3-D-44 - Does arm performance under different visual conditions explain related arm selection?

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Details

In everyday life, we regularly perform multiple tasks (e.g., reaching for a glass, flicking a light switch) requiring movement of one upper limb or the other. Either limb may easily accomplish such tasks but our strong preference for selecting the dominant limb typically ensures a marked asymmetry in limb selection. The demands of any given movement (e.g. the workspace to be acted in) may modulate limb selection. The availability of vision may also have a marked effect; for example, Przybyla et al. (2013) found removing visual guidance of movement increased selection of the non-dominant limb. The concurrent finding showing superior precision of the non-dominant limb under these conditions provided some explanation for the accompanying limb selection effects. We conducted a similar study. In response to a semicircular array of 15 targets presented on a touchscreen monitor, 132 unimpaired right-handed participants each made 300 speeded reaching movements with their left and/or right upper limbs. Participants were in one of four groups; (i) choice vision (n=31), (ii) choice no-vision (n=37), (iii) predetermined vision (n=32), and (iv) predetermined no-vision (n=32). Participants in the choice groups selected which limb to use on each trial whereas the those in the predetermined groups completed blocks of reaching movements always using the same limb. For the no-vision groups, movement onset (release of the start key) triggered the removal of vision via occlusion spectacles, vision returning once the screen was touched. Presentation order of the 15 target locations was random. All participants received visual feedback in the form of the touch position superimposed on the target following each trial. Reaching frequency data were derived from the choice groups while performance data (i.e. precision and movement time for each limb) were derived from the predetermined groups. Like Przybyla et al., we also found more equal limb selection in the choice no-vision group compared with the choice vision group. However, we found no concurrent evidence of superior left limb performance; indeed, the right limb remained more precise in the presence and absence of vision. Nevertheless, movement times for the right hand were significantly shorter than those for the left hand in the vision group, whereas movement times were comparable in the no vision group. Our data are supportive of Przybyla et al.'s finding of more equal limb selection in the absence of vision; and they also provide further support for the superiority of the dominant limb in visually guiding reaching movements. In our task at least, the relatively modest impact of vision on limb selection appeared to be best-explained by the modest levelling of performance between the limbs in the absence of vision.

3-D-45 - Emergence of crystallized neural patterns during vocal learning

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Details

Motor skills are acquired by learning new repertoires of motor actions and refining those actions through sensorimotor feedback. Young songbirds undergo this process whereby its undifferentiated, babbling-like vocalizations develop into categorical vocalizations (syllables) which form a highly precise and stereotyped crystallized song that mimics the song of its adult “tutor”. During this weeks-long period of motor skill acquisition, neural activity patterns are dramatically reshaped, becoming precisely timed and syllable-specific during adult crystallized song; however, it remains poorly understood how changes in neural activity patterns enable skill learning. To examine whether and how the neural control of song vocal behavior changes during learning, we recorded spiking activity from individual units in the premotor nucleus of the arcopallium (RA) in Bengalese finches during song learning and quantified changes in the neural vocabulary (the unique spike patterns produced) as well as in the motor code (how spike patterns influence behavior). Our chronic neural recordings span multiple weeks of vocal learning in individual animals, which we then examine with novel mathematical tools. This unique approach advantages us with new insights into the individuality of motor codes used across animals as well as changes in motor codes within animals during skill learning. We first implemented a new pipeline for analyzing vocal behavior which uses unsupervised methods to identify the emergence of new syllables and analyzes the dynamics of the latent representations of syllable acoustics to characterize the evolution of individual syllables across weeks of song learning. Our preliminary results show changes in the statistics of spike pattern vocabularies as song syllables mature into acoustically distinct and refined syllables. We also ask whether and how the timescale of motor coding changes during learning -that is, whether developing song is impacted by variations in spike patterns on the scale of 1-millisecond, as our group has demonstrated in adult song, or by variations on slower timescales. Furthermore, we examine whether changes in the motor code is dissociable, even at the level of a single neuron’s activity, into factors like age and amount of sensorimotor practice. Broadly, our study provides a framework for investigating how transformations in spike patterns drive learning across different species.

3-D-46 - Force matching: motor effects that are not perceived by the actor

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Details

We investigated unintentional force drifts and their effects on a force matching task. Based on earlier studies, we hypothesized that the force drift would stop during force matching by the contralateral hand. Twelve young, healthy individuals participated in this experiment. The task was consisted of production of a constant force magnitude (20% of MVC) using one hand (the “task hand”), by pressing with the index and ring fingers and matching the force magnitude with the other hand (“match hand”) at different time (4, 8 and 15 s after the initiation of force production). Furthermore, we also investigated possible drifts in the unintentional forces (‘enslaving’) and instructed participants to place their middle fingers on force sensors without using them during the task. During the first 5 s of each trial, participants got visual feedback on the force level produced by the task hand. No feedback was ever provided for the match hand’s force. Turning the visual feedback off led to a consistent drift in the task hand force to lower magnitudes. Initiating force matching by the other hand led to an accelerated force drift in the task hand

followed by a force plateau. The total amount of the force drift was about the same in trials with and without force matching. The participants were unaware of those effects and reported that they performed accurately at all times. The force generated by the non-instructed middle finger showed a consistent increase over all conditions. Force drifts toward lower magnitudes were also evident in the match hand. The mentioned effects suggest strong interactions between the hands, which are not perceived by the actor. We interpret obtained results based on the theory of control with spatial referent coordinates. The results support the hypothesis that unintentional force drift is primarily due to a drift in the coactivation command, and it is limited by its initial magnitude.

3-D-47 - Volitional control of movement interacts with proprioceptive feedback in motor cortex during brain-computer interface control in humans

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Details

Vision and proprioception regulate motor output during reaching. To study the effects of sensory input on motor control, brain computer interfaces (BCIs) offer particular advantages. As part of a long-term clinical BCI trial, we implanted two 96-channel microelectrode arrays into M1 of a person who was completely paralyzed below the neck but retained intact somatosensation. Neural recordings from M1 were transformed into a 2-dimensional velocity control signal for a robotic arm using an optimal linear estimator decoder that was calibrated while the participant imagined performing movements demonstrated by a virtual arm. Once the decoder was calibrated, we asked the participant to move the robotic arm left and right past a pair of lines as many times as possible in one minute. We examined how visual and proprioceptive feedback were incorporated into BCI control during this task by providing the participant with either visual or proprioceptive feedback, both, or neither. Proprioceptive feedback was provided by moving the participant’s own arm to match the movement of the robotic arm. Task performance with vision or proprioception alone was better than when neither were provided. However, providing proprioceptive feedback impaired performance relative to visual feedback alone, unless the decoder was calibrated with neural data collected while both visual and proprioceptive feedback were provided. Providing proprioceptive feedback during decoder calibration rescued performance because it better captured M1's neural activity during BCI control with proprioceptive feedback. In general, BCI performance was positively correlated with how well the decoder captured variance in neural activity during the task. In summary, we found that while the BCI participant was able to use proprioceptive feedback regardless of whether the decoder was trained with vision only or vision and proprioception, training the decoder with both visual and proprioceptive feedback made performance more robust to the addition or removal of visual or proprioceptive feedback. This was because training a decoder with proprioceptive feedback allows the decoder to take advantage of proprioception-driven activity in M1. Overall, we demonstrated that natural sensation can be effectively combined with BCI to improve performance in humans.

3-D-48 - Grasp posture in ambiguous settings is sensitive to prior object motion

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Details

The wrist posture chosen to grasp an object is normally consistent, determined by the optimal, most efficient strategy learnt from previous experience. Yet in certain settings, despite object properties remaining constant and intention the same, the action chosen by an individual can vary with a lack of clear preference for one posture over another. This is referred to as motor ambiguity. Here, we investigate the influence of preceding dynamically changing visual information on participants' choice between two possible wrist postures when grasping an object at various orientations. We found that the decision is influenced by the participant observing rapid object rotation. Surprisingly, rather than being biased to choose the grasp that would have been appropriate for the initial position before object rotation, participants become more likely to use the alternate wrist posture. When object rotation is blocked from view, the bias effect is abolished. Furthermore, the bias strength was found to be independent of the motion magnitude, and persists even when greater decision time is allowed. We suggest that the influence of motion on ambiguous grasping could be attributed to participants overestimating the object's final position when its motion is observed, preparing them to use the grasp appropriate for the upcoming region of certainty. The overestimation may be due to miscalculations in the cerebellar internal model or the gain computation induced by the pairing of rapid motion with the uncertainty of the ambiguous context.

3-D-49 - Visual activity modulates population dynamics during the initiation of identical grasp movements

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Details

An important objective in systems neuroscience is to comprehend how different movements are initiated and controlled in the neural network of the brain. In recent years, it was proposed that the neural population response at the onset of movement determines the subsequent movement-related neural dynamics independent of time and context, known as the optimal subspace hypothesis. In contrast, two studies have shown that the neural response at movement onset of the same movement can vary considerably between immediate and delayed movements. Furthermore, there is increasing evidence that neural activity in motor areas is not only modulated by movement preparation and execution, but also by active vision. We hypothesize that the differences in the neural response at movement onset for the same movement can be explained - at least partially - by differences in the timing of visual processing.

To investigate the visual-, preparatory- and movement-related dynamics in the fronto-parietal grasping network, we recorded neural data from AIP, F5 and M1 of two monkeys performing a mixed immediate and withheld (delayed) grasping task. By utilizing a targeted dimensionality reduction, we identified different orthogonal population subspaces for visual, preparatory and movement execution related activity. Neural subspaces were identified only based on the delayed trials, for which visual, preparatory and execution related activity is temporally separated by the task design. Yet, the identified subspaces captured equal amounts of variance also for immediate movements, confirming the validity of the subspace decomposition. For delayed trials, visual-related processing of the cue signal was already completed at the time of movement onset, whereas for immediate trials, visual activity was also present at the time of movement onset. Interestingly, preparatory subspace occupancy at movement onset was similar for immediate and withheld movements, irrespective of the amount of visual activity. These results suggest that only the preparatory response at the time of movement onset determines the subsequent movement, but not the entire neural population response. Consequently, these findings indicate that visual activity is transformed into preparatory activity, and only preparatory activity into execution activity, even if visual activity is still present at the time of movement.

Our results therefore refine the optimal subspace hypothesis for the presence of different population responses at movement onset.

3-D-50 - Combining visual and proprioceptive information in fast motor decisions

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Details

We often make hand movements to visual targets and can adjust our movement once a target moves. Movement planning is not only based on visual information of the hand and target, but also on somatosensory information of the hand: efferent and proprioceptive afferent information. How are these information sources combined for fast motor decisions, for which you may not have time to combine the information? Proprioception and vision have different biases and precision. This may affect the late movement planning depending on availability of the different information sources. In a fast target-directed reaching task in which participants have to replan, we “forced” 34 participants to choose by presenting target splits after movement onset. We assessed the late planning decisions on the chosen target in terms of choice bias and precision in a condition with and without vision of the hand by plotting the probability of choosing a target against the hand distance to that target at the moment of a target split. We hypothesized that both vision and proprioception contributes to late movement planning. If only vision is used to determine which target is closest to the hand, hand distance to each target should be unrelated to the movement decision. If only proprioception is used, decision-making will be unaffected by removing vision of the hand. If a combination of vision and proprioception is used, decision-making precision should be better with vision of the hand, and we predicted that the bias should then differ idiosyncratically between the vision conditions. We could fit psychometric curves for each participants’ graph of the chosen target over hand distance to that target. We found that removing vision did not decrease choice precision. We also found that removing vision significantly affected choice bias for most participants, but in an idiosyncratic way. We thus conclude that fast motor decisions are based on a combination of vision and proprioceptive information.

3-D-51 - Effects of tool use on differences between dominant and non-dominant hands in right-handed and left-handed individuals

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Details

"Handedness" is a phenomenon that occurs in 96% of humans (Annett 1998). Regardless of race or nationality, ~90% of humans are right-handed and only ~10% are left-handed (Goble & Brown 2008). However, the mechanisms of handedness are largely unknown. Many previous studies have reported that the dominant hand has motor skills superior to those of the non-dominant hand, yet in which motor tasks the differences between the dominant and non-dominant hand are most distinct remains unclear. Here, we compared the ability of both the dominant and non-dominant hands to use familiar versus unfamiliar tools. Furthermore, because being left-handed is not simply the inverse of being right-handed, we examined the use of familiar and unfamiliar tools in both right-handed and left-handed individuals.

We explored tasks in which healthy subjects took hold of and moved a lightweight object from a starting position to a target position with two digits (no tool), chopsticks (familiar tool), or a hemostat (unfamiliar tool). We used both small and large targets for each task. Three-axis force sensors were used to determine the time expended and maximum force exerted in moving the object.

The time taken to move the object was fastest for the digits conditions and slowest for the chopsticks conditions with the non-dominant hands in both right-handed and left-handed subjects. The time for the digits condition was significantly faster than for either the chopsticks or hemostat condition in both right- and left-handed subject. On the other hand, no significant differences in movement duration were found among the tool conditions when using the dominant hand.

Peak grip forces were higher for the hemostat condition than for the digit or chopsticks condition regardless of the hand used or the target size. The forces used in the hemostat condition were significantly higher than in the digits or the chopsticks condition in both right- and left-handed subjects. In the left-handed subjects, significantly higher forces were exerted by the dominant hand than the non-dominant hand for all tool conditions.

In both right- and left-handed subjects, subjective difficulty, scored on a 5-point scale, was significantly higher for the non-dominant hand than for the dominant hand in the chopsticks and hemostat conditions, while significant differences in subjective difficulty were not found in the digits condition.

In summary, in both right- and left-handed individuals, the results of the time and subjective difficulty reflect differences in the motor abilities of the dominant versus non-dominant hands when people use tools. Higher grip forces may be due to the unfamiliarity of the hemostat.

3-D-52 - Jaw muscle spindle afferents as multiplexed channels for sensing and guiding orofacial movement

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Details

Muscle spindle afferents (MSAs) are stretch-sensitive neurons that provide critical real-time feedback to the nervous system about body position and movement. While classic models proposed that MSAs are ‘kinematic encoder’ sensory neurons, more recent models highlight the dynamic tuning of these neurons and propose they instead serve task-specific motor control functions. Here, we record from MSAs innervating the jaw musculature (located in the mesencephalic trigeminal nucleus, MEV) in behaving mice to test these competing hypotheses. In our task, head fixed mice lick a moving ‘port’ through an arc of seven locations surrounding the mouse’s face to receive a water reward. The sequence progresses in opposite directions on alternating trials. MSA ensemble activity is complex, evolving over single lick cycles as well as over entire licking sequences. While some MSA ensemble activity is correlated with jaw kinematics, other activity shows clear decoupling from the kinematics. We find that (1) encoding of kinematics varies across the MSA ensemble, with a small fraction of single MSAs showing strong kinematic coupling in a manner consistent with classic models, (2) MSAs innervating jaw synergist muscles show distinct activity based on muscle of innervation, with MSAs from one muscle (temporalis) showing the strongest kinematic encoding, and (3) MSAs show patterns of activity modulated by sequence progression but poorly explained by the kinematics (e.g. firing at the start of the trial regardless of sequence direction), suggesting task-linked active modulation of MSA activity. Ongoing research is aimed at understanding how active modulation of MSAs may facilitate performance of the lick sequence task.

3-D-53 - Neural dynamics of macaque motor cortex during flexible manual interception

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Details

Summary. Although motor cortex, is widely known to a central brain region for generating movement, it is unclear how the motor cortex works during predictive interception in changing environments. Here we simultaneously recorded neural activity from M1 and PMd demonstrates differential temporal coding properties and directional tuning modulated by target motion. **Methods.** Two monkeys were well trained to perform this delayed manual interception task. After monkeys holding the center at the beginning of a trial, a peripheral target turned on (TO), either stationary or rotating around the center at a constant angular speed. There were five target-motion conditions, consisting of clockwise and counterclockwise at 120 °/s and 240 °/s, and a 0 °/s (static). Monkeys were instructed to wait during a random delay (400 to 800 ms) until the central dot went dark (GO) and then to immediately reach for the target. Once monkeys touched the screen, the target stopped and another dot showed the touching location. We implanted Utah arrays in dorsal premotor cortex (PMd) and primary motor cortex (M1) of two monkeys, and recorded 11 sessions (M1 90 ±17 units, PMd 36 ±8 units, mean ±s.d.). **Results.** 1. Motor cortex showed a rich activity pattern in different task periods. PMd is mainly involved in motor planning, and 42 ±10% of neurons had peak activity during delay period (TO-GO), and 46 ±12% of neurons had target direction selection (TO +200ms, two-way ANOVA, $p<0.05$). A small fraction of M1 neurons (7 ±1%) had peak activity before GO, and 39 ±12% of neurons responded to target direction. After GO, the motor cortex mainly encoded the reach direction (50 ±9% M1 and 40 ±8% PMd). 2. Does the neural activity of motor cortex during preparatory period encode target location? We tried to fit the single-trial firing rate to target direction by introducing a series of time lags. Delay response of M1 could be well explained by future target direction (time delay: 200ms) with cosine function (43% M1 $R^2>0.1$, $R^2=0.22 \pm 0.09$), and they a had stable preferred direction (PD) and persisted until GO, then switched to encode reach direction (74% M1 $R^2>0.1$, $R^2 = 0.29 \pm 0.15$). However, PMd neuron couldn't be easily explained by a uniform latency (26% PMd $R^2>0.1$, $R^2 = 0.19 \pm 0.08$) and their PDs were substantially different in different target speed conditions. 3. Population neural state results were consistent with single-unit finding. We performed targeted dimensionality reduction (TDR, Mante et al., Nature 2013) to obtain the neural state representing the target direction, and the direction of neural state was highly correlated with the future target direction (circular correlation coefficient of M1 0.6 ±0.2 and PMd 0.4 ±0.1, mean ±s.d.). In conclusion, motor cortex not only predicts the target position during the delay period, but also has a target-speed modulation on the directional tuning.

3-D-54 - Clustering patterns in multiunit LFP recordings in the monkey motor cortex during a reach and grasp task

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Details

The capacity to move in an optimal manner requires not only efficient muscular contractions but also their correct timing with respects to each other. This is especially clear in view of several movement deficiencies caused by altered muscular correlations. An example of this would be the poor capacity to move isolated body segments as seen in the post stroke extensor or flexor synergies [1]. For hands, the power grip requiring less finger individuation is often favored in post stroke conditions [2]. Given the importance of the appropriate coupling and decoupling patterns of muscular contractions, the aim of this study is to analyze correlations in neuronal activities of the motor cortex as the task of reach and grasp unfolds. This was done by analyzing local field potentials (LFP) from a previous study [3] in which multiunit arrays containing upto 256 electrodes collected data as monkeys reached for an object with horizontal and vertical orientation. The recordings were done in the premotor and primary motor cortex of the left and right hemispheres. We found very robust changes in the correlations of the LFP recordings corresponding to task epochs. They decreased significantly during reaching and then increased during grasp. A hierarchical cluster analysis gave results that went in the same direction - a decrease in cluster number during reach and an increase during grasp. Monitoring cluster numbers also provided useful indicators on upcoming events. Machine learning applied to the evolving cluster numbers was able to predict the start of hand exit and the start of grasp within 10ms of occurrence with a success rate of greater than 90%. Some previous studies have also demonstrated the presence of correlated neuronal activity during the reach and grasp movement [4,5]. Unlike the current study the focus for these two previous studies was the description of low dimensional descriptors of neuronal activity in keeping with the idea of synergies for motor control. They did not carry out a detailed analysis of cluster evolution as the task progressed. Another important difference of the current study is the use of LFPs for studying neuronal correlations during the task. As a low frequency, extracellular signal, they are known to be relatively robust and less subject to factors such as electrode position [6], hence holding out the promise for greater ease in studying movement disorders involving neuronal clustering.

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3-D-55 - Neural dynamics of sensorimotor decision-making in freely walking rhesus macaques

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Details

For many animal species, the ability to take decisions during ongoing actions is pivotal for survival. Behavioral studies have shown that ongoing actions can influence our decisions, leading to the hypothesis that action selection and execution share the same neural substrate: the sensorimotor cortex. Neurophysiological testing of chair-seated animals supports this idea, but how action selection and execution are integrated in the sensorimotor cortex while acting remains unclear.

Here, we investigate the neural basis of decision-making during goal-directed, full-body movements. Four monkeys learned to choose between two targets while (go-before-you-know, GBYK) or before (know-before-you-go KBYG) walking towards them. To induce mid-movement choices in GBYK trials, we revealed the value of both targets at a variable latency after movement start. Neural activity was recorded from primary motor cortex (M1), dorsal premotor cortex (PMd) and dorsolateral prefrontal cortex (dlPFC).

We found a strong correlation between single channel activity and walking pattern, observed predominantly in M1. When the reward contingencies were disclosed during walking (GBYK trials), the activity in PMd and dlPFC was modulated by the target choice (left or right). A similar modulation was observed when the information was disclosed before walking (KBYK trials). Neural state space analyses confirmed these results, showing circular trajectories in the PCA space for M1, and splitting trajectories for left and right choices in PMd and dlPFC. The neural dynamics of all three brain areas split based on target choice when the monkeys were instructed while idling (KBYG trials).

Our results support the notion that M1 and PMd are both involved in action selection and execution. However, it seems that when choosing while walking, compared to choosing while sitting, M1 is engaged primarily in the stepping behavior, leaving to PMd and higher-level areas, such as dlPFC, the task of representing and selecting between alternative action goals.

3-D-56 - The influence of object weight on handover actions in young and old adults

Lena Kopnarski [1], **Claudia Voelcker-Rehage** [1], **Julian Rudisch** [1]

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Details

Handovers are joint actions describing the transfer of an object between two persons. Accurate anticipatory knowledge of object properties (such as its weight) might facilitate handover actions as this information can inform response-planning by the receiver. Older adults show different movement profiles in object lifting tasks than young adults. Furthermore, it is also known that older participants scale their grip forces less accurately to the objects weight than young adults. Our aims were, thus, to investigate I.) whether receivers can anticipate the weight of an object from observing the movement kinematics of a giver and II.) whether there is a difference between young (20-30 years) and old (> 80 years) adults.
Twenty dyads comprising of 40 healthy young participants aged 22.6 ± 2.5 years and 20 dyads of 40 healthy old participants aged 81.9 ± 2.3 years completed the experiment. A 3D motion capture system, as well as a self-constructed test object for grip force measurement were used to record the participants' motion data and their applied grip forces. Two different object sizes (small, big) and three different object weights (light, medium, heavy) were used. The experiment was divided into four blocks, with the condition *size* varied between blocks and the condition *weight* varied pseudo-randomly within blocks. Participants had no knowledge about the object weight before each trial. Thirty handover actions were performed per block, with the giver/receiver role being switched after the half of the trials. The parameter maximum wrist velocity (MWV) was analyzed for the givers and peak grip force rate (PGFR) for the receivers. The analyses were completed for the 20 young dyads and 12 old dyads.
The MWV was significantly lower for heavier objects than for lighter objects. Additionally, we found that the differences between the weight classes were greater for the old participants than for the young participants. Further, higher object weights led to significant higher receiver's PGFR. We also found an age-size interaction effect, whereby older participants, in contrast to young participants, grasp the small object with a higher PGFR than the big object.
The difference in the MWV between the objects weights was greater in the older participants than in the younger participants. We argue that this might be related to the fact that the older participants need longer for the feedback-controlled scaling to the object weight than the young participants. Furthermore, we could show that the object weight has an influence on the receiver's PGFR. This indicates that the receiver uses the information from the giver kinematics for anticipatory grip force scaling. Young participants seem to primarily use the giver kinematics for anticipatory grip force scaling, while older participants seem to additionally use object size as a cue, although this does not provide valid cues for object weight.

3-D-57 - The interaction between visual position and visual motion for moving targets and self-controlled cursors explained through a multisensory LQG model

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Details

When interacting with the world we heavily rely on vision for estimating the position and velocity of moving targets. For such targets, it is known that visual position and visual motion tend to interact. For instance, the Motion Induced Position Shift (MIPS) arises from a conflict between an object's position and texture motion on the object's surface. This results in an apparent shift of the object's position in the direction of texture motion.

In contrast, for self-movement, e.g., moving our hand or a cursor, it is less clear how position and velocity estimates might interact since multiple senses are at play. For proprioception there is evidence that position and movement sensing are governed through separate processes. However, we often also see the cursor and thus also have access to visual position and velocity information.

Here, we used the MIPS effect to investigate how visual position and motion estimates may differently influence perception of a moving target and the perception of our own movements. Participants tracked a moving target with a cursor controlled by moving a stylus over a graphics tablet. In half the trials, the MIPS stimulus was the target and the cursor a simple dot, and vice versa for the other half of the trials. The trajectory of the target and the texture motion within the MIPS stimulus were varied independently. The reliabilities of visual position and texture motion were varied through changing the size of the MIPS stimulus or the motion coherence of the texture, respectively.

For the MIPS target our results confirmed previous findings of texture motion leading to a perceived shift of the target, which increased for less reliable position, and decreased for less reliable motion information. For the MIPS cursor we also found a small effect of the visual motion on the sensed position, which decreased with decreased reliability of the motion. However, decreasing the visual reliability of the position did not lead to a significant increase of the MIPS effect in the cursor.

To model these results a mix of Linear-Quadratic-Gaussian (LQG) control and reliability-based multisensory integration was used. Vision and proprioception for the cursor were included as separate state estimates, and information from vision and proprioception was integrated only at the sensory feedback stage and separately for the position and velocity estimates. This way both the interaction between position and motion in vision as well as their relative independence in proprioception could be left intact, whilst still integrating the estimates across the senses. This model accounts for the differences observed in our current data.

In short, we found that visual position and motion estimates interact for both target and cursor objects to some degree. However, for cursor objects this interaction can be less obvious as the visual information is integrated with proprioceptive information at the sensory level.

3-D-58 - Inter-participant similarity of muscle synergies is not increasing with external constraints during walking but is influenced by extraction algorithms and the chosen number of synergies

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Details

Background: The motor equivalence theory posits that similar tasks can be controlled with diverse motor strategies, and vice versa. This also implies that individuals use either similar, or different motor strategies to control movements with similar outcomes. Muscle synergy analyses are widely used to enhance our understanding of human motor control. Whether individuals employ similar synergies for comparable tasks, remains unclear. Previous studies found high inter-participant similarities (IPS) for cycling (Hug et al. 2010) and backward giant swings (Frere et al. 2012), but high variability for barely restricted hand grasps (Zhao et al. 2021), indicating a potential influence of external constraints. This study investigates if external constraints during walking alter IPS of synergy vectors, and if different synergy extraction algorithms or the number of chosen synergies influence these results.

Methods: Nine participants underwent normal walking (NORM) and walking with external constraints: metronome paced (-20% cadence, MET), ground-mark-guided (-20% step length, MARK), or a combination (-20% cadence and step length or all equal: 100 steps/min, 65cm step length). Surface electromyography signals (Cometa, Italy) of 5 muscles/leg were high-pass filtered, demeaned, rectified, low-pass filtered, amplitude normalized (max across all conditions) and time normalized to gait cycles of the right leg. Processed signals (10 cycles/condition) were concatenated, and synergies were extracted per condition via non-negative-matrix-factorization, initialized by random- (RAND), single-value-decompensation- (SVD), or sparse- (SPARSE) inputs (Turpin et al. 2021). To avoid local minima, the algorithm was repeated 50 times, and outputs with the highest total variance accounted for were analyzed. K-means clustering identified the most similar vectors within conditions, across participants. IPS for every pairwise comparison of participants in each condition was determined using the mean Pearson correlation coefficient of clustered vectors. A two-way repeated measures ANOVA assessed if IPS varied between conditions and initialization methods for 4 to 6 extracted synergies.

Results: 4 synergies: SVD exhibited higher similarity than RAND and SPARSE. MET and MARK had lower similarities than the other conditions. 5 synergies: Only NORM-SVD had lower similarity than NORM-RAND and NORM-SPARSE. 6 synergies: SVD had lower similarity than RAND and SPARSE. NORM had higher similarity than all other conditions and MET than MARK.

Discussion: Our study emphasizes the influence of algorithm choice and synergy number on IPS analyses. Moreover, our results suggest that external constraints do not increase IPS of synergies during walking. Hence, NORM similarity was equal or higher than the constraint conditions. These insights provide crucial methodological considerations for interpreting inter-participant variability in prior and future studies.

3-D-59 - Muscle dynamics follow typical movement trajectories in persons with limb amputation

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Details

It has been shown humans follow typical minimum jerk trajectories (MJTs) during a variety of tasks, such as arm reaching (Flash & Hogan, 1985). This behavior has been well documented for reaching tasks using multi-joint coordinated limb movement. But it was unknown if the muscles, or muscle compartments also hold similar control properties. To demonstrate this, we used a target acquisition task where the control signals were derived from muscle movement (i.e., not the resulting movement of the end-effector). Results from those experiments by our group (Patwardhan, 2023) have demonstrated that virtual target acquisition task performance can also show MJTs like coordinated multi-joint movements. In order to drive the virtual cursor, we utilized a human machine interface controller based on sonomyography - continuous real-time ultrasound imaging of forearm muscles (Dhawan et al., 2019), which extracts a control signal that scales with the extent of muscle flexion exerted by the participant. However, it was unclear if the MJTs demonstrated by participants while using sonomyography were a result of motor control policies at the muscle level, or a consequence of participants having visuospatial feedback of their virtual cursor during the task. To answer this question, we designed an experiment similar to our prior work, but where visual feedback of the cursor was removed during certain trials. We recruited ten able bodied individuals as well as one person with limb amputation. To assess the performance of subjects, the trajectory of each trial was compared to the MJT. For every target position, we computed the average time to target and used this time to compute the MJT for that target position. The time series root mean square error was computed between the average position trace and the MJT, termed as position error. Three separate two-way Scheirer-Ray-Hare tests were conducted to test the effect of movement distance and visual feedback condition, on the position error, peak velocity, and time to target. We found that visual feedback did not have a significant impact on the participant demonstrating an MJT even though the final acquired position had a significantly higher error when visual feedback was removed. The average position error, peak velocity, as well as time to target increased significantly with respect to increase in movement distance ($p<0.05$) but were not significantly different between the two visual feedback conditions. Three separate linear regressions showed that these outcomes increased linearly with respect to movement distance. All these results were consistent across all the able-bodied individuals as well as the individual with limb loss. We have shown that participants demonstrate MJTs even in the absence of a limb, fully utilizing position control over the end-effector. These results hold significance with respect to the design of future rehabilitation and assistive devices, such as prosthetic limbs.

3-D-92 - Motivation upregulates the adaptive response in sensorimotor learning

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Details

Being in a heightened motivational state can drive more vigorous motor response, increase effortful exertion, and reduce reaction times. Recent studies of motor learning have begun to examine how rewards, contingent on motor performance, influence motor adaptation and skill learning. However, motivational state in these studies was confounded by the performance-contingent outcomes. To decouple these factors and make them statistically independent, we stochastically presented participants with different motivational cues and perturbations during arm-reaching movements. Participants held a robotic manipulandum, and made rapid reaching movements toward a single target, and performed a baseline and adaptation phase. In adaptation, participants were exposed to pseudo-random velocity-dependent force-field, in both the clockwise (CW, +) and counterclockwise (CCW, -) directions. Critically, some perturbation trials were associated with monetary cues that were uniformly sampled, but statistically independent from the perturbation schedule, with value of ,ª10 and ,ª100, for low and high motivational state, respectively. In experiment 1 (n=12, aged 22.3 ±2.1 years, mean ±std), we tested the effect of motivation on adaptive response. We quantified the trial-by-trial adaptation by measuring the motor output before and after each force-field perturbation trial. We pseudorandomly presented groups of three trials (i.e., triples) in which a force-field perturbation trial (P) was presented between force channel trials (C_1-->P-->C_2). Participants were presented with three different types of triples C_1PC_2, $C_1PC_2^{low}$, and $C_1PC_2^{high}$. In C_1PC_2, no motivational cue was presented and, therefore, the change in force from C_1 to C_2 was due solely to the error experienced in trial P. In $C_1PC_2^{low}$ and $C_1PC_2^{high}$, low and high motivational cues were presented in the second force channel trial, so the change in force from C_1 to C_2 was not only due to the error experienced in trial P, but also the motivational cue presented in C_2. We used a computational state-space model to estimate the adaptive response and the sensitivity measure (i.e., rate of the adaptive response). In experiment 2 (n=12, 26.4 ±3.1 years), we directly tested the potential effect of motivation on retention, where we used a similar protocol as in the experience 1 but with modified version of triples. We found that a higher motivational state was associated with increased adaptive responses ($F_{1,12}$= 25.24, p<0.0001). Post-hoc analysis revealed that sensitivity in the high motivational state was significantly larger than the sensitivity in low motivation state (t_{12}= 5.84, p=0.0003). Motivation, however, had little to no effect on retention of adapted state ($F_{1,12}$= 1.30, p=0.29). Our finding provide evidence for a mechanism through which motivation shapes error-based motor learning.

E – Integrative Control of Movement

Poster Cluster (3-E-60 and 3-E-61)

3-E-60 - Central projection to the hand region of primate cuneate nuclei

Moeko Kudo [1], **Shinji Kubota** [2], **Satomi Kikuta** [1], **Junichiro Yoshida** [1], **Saeka Tomatsu** [3], **Tatsuya Umeda** [4], **Kazuhiko Seki** [1]

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Details

Voluntary movements are critical for survival, as animals forage in and navigate through the complex environments. However, such movements create an additional challenge for the sensory system as the sensory consequences of self-motion need to be dissociated to enable perception of the external sensory environment. The central question is how the central nervous system accomplishes this dissociation. We have previously demonstrated that sensory afferent signal, in the wrist and hand movement of nonhuman primates, was flexibly and dynamically modulated in the sensorimotor cortexes (Seki & Fetz. 2012). Here, we addressed the anatomical correlate of the sensory gain modulation in the volitional movement, by examining the top-down and bottom-up projections to the earliest relay of somatosensory signals in the ascending pathway, i.e. cuneate nucleus. Under deep anesthesia, we exposed the brainstem in three macaque monkeys and recorded field potentials evoked by the electrical stimulation applied to the cutaneous (superficial radial nerve) and muscle afferent (deep radial nerve) in the forearm, and established the 3D maps of the cutaneous and muscle representation of hand/forearm. Then, we injected retrograde neuronal tracers (CTB, cholera toxin subunit B; BDA, biotinylated dextran amine: FB, fast blue) to the core of the main (pars rotunda) and the external cuneate nuclei based on the 3D maps, respectively. Three to five weeks after the tracer injection, monkeys were perfused and the brainstem, cervical spinal cord, and cerebral cortex were sampled to find the neurons that make a direct projection (projection neuron) to the cuneate nuclei and the spinal cord by the histological analysis. Serial sections were cut into 50- µm thicknesses and processed for visualization of CTB, BDA, and FB. Separately, a series of adjacent sections were mounted, and Nissl was stained with Cresyl violet. In the cerebral cortex, both retrograde labeling neurons from the main and extra cuneate were found. A predominant (40-50%) number of projection neurons (to the main cuneate) were labeled in the primary sensory area (Areas 3a, 3b, 1, 2), but it is also present in Area 4, Area 5, Area 7, and the secondary sensory cortex. In contrast, many projection neurons (to the external cuneate) were located in Areas 2, 5, and 7. In the spinal cord, projection neurons (to the main cuneate), possibly mediating postsynaptic dorsal column pathway, were mostly localized in the Rexed's laminae IV-VI of C6-T1 segments. These results will be discussed for their potential contribution to the sensory gain modulation at the cuneate nucleus.

3-E-61 - Projections from the primary motor and sensory cortex to the subcortical somatosensory relay neurons in non-human primates

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Details

Peripheral somatosensory signals are suppressed during voluntary movement in the primate spinal cord (Seki et al., 2003) and cuneate nucleus (Kubota et al., 2024), these are the first relay sites in the ascending lemniscus pathway. We proposed that the efference copy signal of motor command could be a potential source of the suppression at these subcortical relays, given its coincident occurrence with the movement initiation and execution. Several areas in the sensorimotor cortices are known to have direct projections to the cuneate nucleus ("cortico-cuneate") and spinal cord ("cortico-spinal") (see companion poster presentation by Kudo et. al.). Therefore, we could assume that these cortical projections are the potential source of the efference copy signal that generates the sensory attenuation at the subcortical relays. However, little is known about which sub-areas in the sensorimotor cortex are involved and how the somatosensory signal is suppressed in the local neuronal circuits within the cuneate nucleus and spinal cord. To address this issue, we injected AVV vectors (AAV2-CaMKIIa-mClover) to the subregions of sensorimotor cortices (Broca's area 4, 3, and 2) in monkeys (n=3), and characterized the neuronal populations in their target of projection in the cuneate nucleus and spinal cord. Specifically, we performed the in-situ hybridization analysis to characterize the excitatory and inhibitory neurons of their target areas. Our results revealed the Area 2 neurons showed strong projection to both the external cuneate and the rostral part of the main cuneate nucleus, whereas the

Area 4 neurons project preferentially to the caudal part of the cuneate, where the relay neurons mediating postsynaptic dorsal column neurons are localized. In the spinal cord, Area 2 and 3 neurons projected mainly to the medial part of the lamina V and VI, and this trend was also observed in Area 4 neurons together with the ventral projection. Preliminary findings from in-situ hybridization indicate sparse labeling of GAD67, a marker for GABAergic neurons, in the caudal region of the cuneate nucleus. This suggests a possible site for the sensory gating of peripheral sensory signals through the integration of descending cortical inputs.

3-E-62 - The role of visuomotor experience in attenuation of visual evoked responses

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Details

To successfully interact with the environment, it is essential to discriminate external events from those that are a result of our actions. Indeed, voluntary actions modulate neural responses to their sensory consequences, relative to responses evoked by identical stimuli from an external source (sensory modulations). One potential type of information associated with such modulations is the agentic source of the stimulus (self/other), suggesting a general difference in signal gain between active stimulus generation and passive observation. Another possible type of associated information is specific expectation of sensory outcome. In the current study, we examined how learning of new action-visual contingencies modifies visual evoked responses. To this end, we used an EEG paradigm in which participants learn the coupling between a cue (button press / tone) and a specific visual stimulus (pictures of faces or objects). To avoid potential prediction advantage in the button press condition, we introduced a constant 500ms delay between predictor (press/tone) and visual outcome. Preliminary results (n=9), indicate that participants successfully learnt the mapping between cues and outcome equally well across conditions (98% / 95% correct responses in press/tone conditions respectively). At the neural level, P100 amplitudes in the visuomotor condition were smaller than in the audiovisual condition in posterior electrodes. Notably, we see a difference in amplitude between cue conditions even on the first repetition of cue-outcome presentation, when no specific expectation of sensory outcome has been formed. In addition, we find an effect of learning such that the magnitude of the P100 decreases across repetitions, as the mapping between presses/tones and pictures is strengthened. Examining the EEG signal during the delay period between cue (press/tone) and visual outcome, we find more negative signals in the first repetition compared to the last repetition, with no evident differences between cue conditions. However, examining this time window using a time-frequency analysis reveals independent differences between cue types and differences between learning repetitions. Our results so far suggest that the P100 evoked response is independently sensitive to both agency and expectation level. This may imply that the P100 contains an expectancy component that is not specific to motor commands, in addition to an agency component that is invariant to the degree of mapping between actions and expected visual outcome. This conclusion is further supported by examining the effects of cue condition and repetition on signal at the delay period between cue and sensory outcome. Our results provide critical information constraining neural models of visuomotor interactions.

3-E-63 - Repetition of coordinated digit force control disrupts switching between motor plans

Catherine Sager [1], **Ian Greenhouse** [1], **Michelle Marneweck** [1]

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Details

During early sensorimotor learning, motor plans to generate force are context-specific and susceptible to anterograde interference. Learning to minimize the tilt of an object with a left center of mass (CoM) via a compensatory torque countering the external torque will not initially transfer to success when the object is rotated such that the CoM is on the right. Instead, digit force and digit positioning contributing to compensatory torque are copied from the trial preceding the object rotation, resulting in task failure. Growing behavioral evidence suggests that repeatedly generating the same motor plan for force control can magnify this anterograde disruption on the ability to switch flexibly to a new motor plan. We and others have shown that repeatedly lifting an object with a given CoM to minimize its tilt magnifies errors when the CoM is switched. In this study, we selectively dissociated the reach and object contact phase from the lift phase of object manipulation to examine their susceptibility to the deleterious effects of repetition on switching between motor plans. We manipulated the number of times young adults (*n* = 20) reached and pressed on one of two grasping surfaces of an inverted T-shaped object, before switching the grasp surface side to be pressed. In a separate experimental block, with the order of blocks counterbalanced, we manipulated the number of times participants reached, grasped, and lifted the inverted T-shaped object with a CoM on one side before switching the CoM to the other side. Preliminary results replicated the significant deleterious effects of pre-switch trial repeats on performance after the switch requiring a new motor plan on the object lifting task, but not on the reach-to-press task. These results suggest that repetition hampers flexibly switching between motor plans that require feedforward coordination of lift force between digits.

3-E-64 - Corticospinal excitability reflects unfolding decisions during ongoing actions

Cesar Canaveral [1], **Louis-Phillipe Tremblay** [1], **Andrea Green** [1], **Paul Cisek** [1]

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Details

Many studies in monkeys have suggested that while we make decisions about actions, the unfolding deliberation process continuously influences - and perhaps involves - the frontoparietal sensorimotor regions that control those actions. In humans, decision-related processes have even been shown to influence the preparatory state of the motor system, as measured in corticospinal excitability (CSE) and reflex gains. Notably, in all of these studies subjects made decisions prior to initiating movement, but that is often not the case during natural behavior. During natural behavior, we often make decisions while we're already engaged in an action, such as while walking through a crowd, playing a sport, or escaping from a predator in the wild. Do decision-related processes influence the motor system even in such decide-while-acting scenarios? If so, how is it that they don't disrupt the accurate execution of the ongoing action? Here, we address the first question by using transcranial magnetic stimulation (TMS) to measure CSE in human participants (N=18) performing a continuous manual tracking task. In 33% of trials ("No Choice") participants simply tracked a target moving smoothly across the workspace. In 67%

of trials, halfway through the tracking action an alternative target appeared, either to the left or the right of the current tracking trajectory, and participants were free to either switch to it (“Switch” trials) or continue tracking (“No Switch” trials). In 72% of all trials, single-pulse TMS was applied to the primary motor cortex at target onset or after 150, 200, 250, or 300ms. EMG activity was recorded from an elbow flexor (biceps) and extensor (triceps lateral). When an alternative target was presented, subjects switched to it approximately 47% of the time. As expected, we found that within 200ms after target presentation and before the time of trajectory change, CSE in Switch trials was significantly higher in the agonist muscle to a given target (biceps for left, triceps for right) as compared to No Switch or No Choice trials. Most interestingly, however, we also found that between 200-250ms, the CSE for the agonist was higher in No Switch trials than in No Choice trials, as if the motor system was transiently engaging specific muscles as a target option was being considered, even if it was ultimately rejected. This suggests that deliberation processes continuously influence the motor system even during ongoing actions, possibly in preparation for a fast response in case circumstances suddenly demand it. These findings raise questions about how such covert changes avoid disrupting ongoing movement control, and how the concept of a “threshold” for decisions or for action initiation can be generalized to scenarios of continuous embodied decision-making.

3-E-65 - Neural activity in the cortico-basal ganglia network of non-human primates: integration of context information and coordination of behavior during foraging

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Details

Recent behavioral work in human and non-human primates suggests that decisions and actions are coordinated to optimize success rate. In support of such integrated view, neurophysiological studies have long revealed an anatomical overlap between the circuits of decision-making and those controlling movements. These circuits include the sensorimotor cortex and the basal ganglia. Yet, a unified view about the functioning of the cortico-basal ganglia loop as a whole is missing. In particular, it is currently unknown how some of the most crucial determinants of interactive behavior, namely reward and motor costs, are handled in this network.

To address this question, one monkey was trained to perform a reaching-based foraging task in which she had to move a lever into one of two circles to receive rewards at a decreasing rate (exploitation). She was then free to either stay in the depleting circle or leave it (i.e. explore) to reach the other circle and start another period of exploitation. Reward rates were varied from trial to trial, and the size of the circles as well as their distance were varied in blocks of trials, allowing to manipulate motor costs during exploration. Simultaneous, multi-electrode neural recordings were conducted in the animal dorsal premotor cortex (PMd), in the dorsal striatum as well as in the globus pallidus while she was performing this task.

Analysis of the animal's behavior indicates that in most sessions, the longer the duration of the decision to end an exploitation, the greater the vigor of the movement executed to explore the other source of reward. Moreover, both reward rates and motor costs influenced decision durations, as exploitation duration was often shortened when the rate of reward was high and when the required motor accuracy was high.

At the neural level, we found that both cortical and basal ganglia activities show a strong relationship with exploitation duration and exploration speed. Population analysis indeed indicates that the two processes are represented in the same sub-space of the neural state, especially in PMd and in the striatum. We also found a significant proportion of neurons in each area whose activity is significantly modulated by motor costs, both during the exploitation and movement phases. Interestingly, this integration of motor contextual information appears to be clustered within specific subpopulations of cells in each structure. Finally, we found that reward rate has a smaller impact on neuronal activity compared to motor costs, including in the dorsal striatum.

Together, these data indicate that the cortico-striatal-pallidal loop plays a key role in determining and coordinating the vigor of behavior by combining and processing important determinants of interactive behavior, most notably motor costs.

3-E-66 - Unveiling the role of cutaneous feedback in voluntary movement control: Insights from conflicting visual-somatosensory inputs

Maria Evangelia Vlachou [1], **Juliette Legros** [2], **Cécile Sellin** [2], **Dany Paleressompoulle** [2], **Francesco Massi** [3], **Martin Simoneau** [4], **Laurence Mouchnino** [5], **Jean Blouin** [6]

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Details

The sense of touch operates as a multifaceted sensory system, transcending from a simple interface with the external world to a component of proprioceptive processing. Activation of cutaneous mechanoreceptors allows us to perceive the relative motion between our hand and a surface. Previous work highlights the tactile impact on hand movements (Moscatelli et al., 2019). However, the dynamic interplay between visual, proprioceptive, and cutaneous feedback in movement control remains unexplored, especially in active tasks with visual input on hand location. To address this gap, we employed a motor task wherein the processing of somatosensory information is detrimental to movement accuracy. We hypothesized that reducing tactile feedback would reverse this effect. Participants traced with their index finger the outline of an irregular polygon engraved on a 3D-printed surface fixed on a force platform. Made of spiral patterns, the surface enhances the transmission of cutaneous inputs compared to smooth or grooved surfaces (Sutter et al.,2023). Participants performed tracing under two visual conditions: looking both at the polygon and their hand directly (NoConflict) or through an inclined mirror (Conflict). Subjects of the Cutaneous group (N=16) were in direct contact with the surface using the pulp of the index finger, while the NoCutaneous group (N=15) executed the same tasks wearing a finger splint reducing tactile stimulation. We evaluated the efficacy of the finger splint as a tactile attenuator by comparing the power spectrum density of the vertical acceleration, measured on the fingernail, and the friction coefficient, evoked by the finger surface interaction, between the two groups. Indeed, the NoCutaneous group exhibited significantly lower values in both parameters ($ps<0.05$), indicating diminished tactile finger stimulation. We assessed tracing performance by computing the jerk, a smoothness metric calculated from the derivative of the shear force along the X and Y axes. The jerk was significantly smaller in the NoCutaneous compared to the Cutaneous group, but only in the Conflict condition (significant Group x Vision, $p<0.05$). This result is consistent with our hypothesis that, in a conflicting sensory environment, tactile cues attenuation would improve tracing performance. At the neurophysiological level, a substantial gating of somatosensory inputs has been observed while tracing with mirror-reversed vision, possibly serving as a dynamic mechanism to resolve the visuo-somatosensory conflict (Bernier et al., 2009). The EEG source analyses revealed that this sensory gating occurred only in the Cutaneous group, implying that successful movement control during a visuo-somatosensory discrepancy requires suppression of tactile feedback. Collectively, our results provide compelling evidence for a pivotal contribution of cutaneous feedback to motion control and shed new light on the interplay between vision and touch in active tasks.

3-E-67 - Active movement encoding in motor working memory

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Details

Previous research has found evidence for distinct sensory-based (effector-specific) and abstract (effector-independent) representational codes in nonvisual "motor working memory". This work was conducted by having participants encode passively guided movements for later active recall with the same or opposite arm. Recalling a movement with the same arm afforded the participant both representational codes, but when they recalled with the opposite arm, they could only rely upon the effector-independent information. Importantly, this passive task lacks some ecological validity - do these results hold in more naturalistic volitional movements? Here we build on previous work through a similar task, but critically, instead of encoding passive movements, participants made active voluntary reaching movements of their choosing. Strikingly, the results mirrored those observed in the passive study, suggesting that concurrently maintained codes in motor working memory are present in the context of naturalistic active movements. With these results in hand, in a second experiment we explored the extent to which these codes may reflect explicit and implicit motor learning processes, which were here measured through a visuomotor rotation task. These experiments will help us understand the relationship between explicit short term memory processes and deliberate aspects of motor learning.

3-E-68 - Impact of EMG signal processing on accuracy and latency of motor intention prediction

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Details

In the context of robot-aided rehabilitation and assistance, myoelectric control has emerged as a promising avenue to integrate the user’s neural command in a non-invasive way. However, EMG-based control is often subject to substantial latency and uncertainties. This raises important questions regarding how the central nervous system may adapt to such intricate interaction loops. This preliminary study aims to evaluate the delays and uncertainties in joint torques induced by various signal processing methods for myoelectric control. Most EMG-driven methods use linear or nonlinear mappings and/or neuromusculoskeletal models to estimate the efforts produced by the user and reinject this knowledge in the control loop. However, before being used, the EMG signal undergoes a feature extraction process, applying signal processing methods to extract information. This translates in a variety of candidate methods and metrics: infinite impulse response filters, time-domain features such as the root mean square and the waveform length, or frequency-domain features such as the total power and the spectral moment. Although these features have been compared regarding classification accuracy for discrete human intention detection, few studies have addressed their performance in a continuous paradigm. Furthermore, these studies did not consider the latency induced by the extraction process: each feature, being a non-linear filter, generates a phase lag. We based our EMG feature regression accuracy and latency analysis on a previously established dataset of 17 participants (11 M, age 28.2 $\pm$ 7 years, height 175.4 $\pm$ 7 cm, weight 70 $\pm$ 11 kg). Experiments included ten elbow flexion/extension trajectory tracking trials in a visco-resistive exoskeleton with EMG signals, joint dynamics, and interaction forces recordings. We used a non-linear EMG-to-torque mapping model to measure accuracy, and the correlation with a baseline zero-phase filtered signal to measure latency. Following a statistical analysis, our results show that the choice of feature and extraction window significantly impacts both latency and accuracy ($p < 0.01$). More precisely, for an equivalent accuracy, time-domain features significantly improved latency by a factor of two compared to frequency-domain features ($p < 0.01$). Likewise, for a comparable latency, accuracy was enhanced by using time-domain features. Overall, higher accuracy was associated with higher latency, underlying the Pareto front that human-machine interaction systems face: control accuracy and system reactivity cannot be increased simultaneously. Future work will focus on the motor adaptations resulting from such EMG-driven force fields induced by an exoskeleton.

3-E-69 - Decoding hand movements with optomyography

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Details

Muscle contractions are often used as control signals to wearable assistive devices such as prostheses and exoskeletons. Non-invasive myography is of particular interest for such applications because of its ease of implementation and the possibility of individual adjustments. Electromyography has been widely used for sensing muscle activity. Yet, electromyography recordings have limitations, including changes in skin-electrode contact, mechanical artifacts, interference from power supply and interference from other muscles. To overcome these problems, new types of myography have been proposed, particularly optomyography which utilizes optical sensors placed on the skin to measure displacement and tension in the underlying tissue. In optomyography, optical data are collected using an infrared light that passes through the skin. Here we introduced an optomyography-based approach for decoding hand movements. Optomyographic signals were recorded in five participants performing hand movements. The data were classified to extract hand configuration and movement direction. We suggest that this approach could enrich the capacity of wearable devices.

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3-E-70 - The effect of cortical inhibition on behavior and motor unit activity with and without visual feedback

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Details

Visual feedback is a powerful tool used to update our internal dynamics with sensory information, commonly investigated by employing an isometric force tracking task. The removal of visual feedback often results in force drift, with an individual either gradually increasing or decreasing their force output compared to movement goal. Force drift demonstrates the importance of visual feedback in the interplay between sensory information, motor planning, and action execution. However, it remains largely unknown how the differing brain areas are involved in modulating motor unit activity with or without visual feedback. Using advanced electromyography sensory arrays and low frequency (1-Hz) online inhibitory repetitive transcranial magnetic stimulation, we examined the impact of the motor cortex, somatosensory cortex, and supplementary motor area on motor performance and motor unit activity when completing an isometric force tracking task. Our preliminary studies have found that the removal of visual feedback increases force drift in all groups, with a significantly greater reduction observed in the stimulation groups compared to the sham group. Additionally, when inhibiting the primary motor cortex, motor unit firing rate exhibits a larger decrease than the sham group - suggesting the motor cortex plays a pivotal role in updating internal dynamics via limited sensory information during the task. To our knowledge, we are the first to investigate how inhibition of different cortical areas disrupts updating downstream components of the motor pathway while attempting to control force with or without visual feedback. Our examination of motor unit activity in response to varying internal and external dynamics can help vertically elevate the field by understanding how motoneurons react to internal and external changes.

3-E-71 - A multivariate analysis of central-peripheral communication during a precision grip task reveals indications of a non-cortical bidirectional connectivity in the high gamma band

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Details

Introduction: The neural communication in sensorimotor pathways across the central/peripheral nervous system (CNS/PNS) gives rise to motor tasks in daily activities; yet, this communication remains poorly understood at a network level. Cortico-muscular coherence, estimated by the spectral coherence between the electroencephalography (EEG) and electromyography (EMG), examines cortical engagement during the motor tasks. However, assessing the contribution of non-cortical regions in broader sensorimotor networks remains challenging. We, therefore, used EEG recordings with extended electrodes to capture the neural activity from cortical and non-cortical sources in the CNS and used Generalized Partial Directed Coherence (GPDC) to estimate the non-symmetric causal/directed interactions between these sources and the muscles. We hypothesized that non-cortical neural sources act as an intermediate hub, playing a crucial role in the communications between CNS and PNS.

Objective: To find the directional influences between the cortical motor regions, non-cortical sources in CNS, and effector muscle activity during motor execution**.**

Methodology: 4 right-handed healthy participants attended an experimental session and performed a precision visuomotor task in 30 trials, each including a 5-second isometric pinching grip. EEG was recorded from the brain and extended electrodes over the neck areas. EMG was recorded from a right-hand effector muscle, abductor pollicis brevis (APB). Three signals were standardized for subsequent network analysis by GPDC after artefact removal: 1. EEG over the primary contralateral motor cortex (C3). the non-cortical sources identified in CNS by spatial filtering of extended EEG recordings (back-projected to cervical sensor level), and 3. the bipolar EMG from APB. Null distributions from surrogate data and rank-based statistics were used to evaluate the statistical significance.

Results: The primary motor cortex was found to be a driver in the alpha and beta bands, whereas the non-cortical activity in CNS and EMG were found to act as driver in the high gamma band for EEG. Strong directed influences were observed between the non-cortical CNS source and EMG in both directions in the same high gamma band.

Discussion: The causal interaction in the sensorimotor system could be highly asymmetric which confirms the rational for using the directed connectivity measures. These asymmetric interactions can originate from the activities in the afferent and efferent pathways and various other directional effects in neural assemblies. Furthermore, the non-cortical regions in CNS were shown to play a crucial role in the sensorimotor networks presented by bidirectional influences in high gamma band. Overall, the findings suggest that neural networks controlling precision grip tasks may be organized at multiple-levels, where the non-cortical control might be characterised by communication in distinct frequency bands.

3-E-72 - The effect of reward and punishment on learning, memory and transfer of real-world motor skill learning

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Details

It has long been known that reward and punishment are powerful modulators of human and animal behavior. However, until only recently, the ways in which reward and punishment specifically influence human motor learning have not been extensively studied. Particularly in the area of sports training, although sports couches have identified reward and punishment as having important but dissociable effects on optimizing motor skill learning, the scientific basis for these effects is largely unknown. In the present study, we investigated the effect of reward and punishment on learning, memory and transfer of real-world motor skill learning.

Specifically, three groups of participants were trained and tested on a ping-pang ball bouncing task for three days. The training and testing sessions were identical across the three days: during the training session, participants trained with their right (dominant) hand each day under conditions of either reward, punishment, or a neutral control condition (neither). Before and after the training session, participants were tested with their right hand and then with their left hand without any feedback.

All groups of participants started at a similar level and improved their performance over the three days of training. However, their performance differed among the three groups: on the first day, the punishment group showed better motor learning than the other two groups, while on the last day, the reward group showed better learning than the control group. For short-term memory, measured by the difference between the pre- and post-training tests, all groups improved their performance on the first day. However, for the last two days, only the reward group showed significant improvement. Only the control group showed a long-term memory gain from the post-test on day one to the pre-test on day two. Although the participants' left hand was never trained, all groups showed improvement between the two tests within the first two days. However, only the reward group maintained the improvement on the last day. Both the reward group and the control group showed a long-term offline gain from the second to the third day, but only the reward group showed the gain from the first to the second day.

The results suggest that although punishment resulted in immediate superior learning, the effect was not sustained. Reward could have a lasting motivational effect on both short-term memory and motor transfer. However, both reward and punishment feedback could have a detrimental effect on long-term memory gain. These results suggest that reward and punishment may engage different neural mechanisms during real-world motor skill learning, with important implications for sports training.

3-E-73 - The decoding of extensive samples of motor units in human muscles reveals the rate coding of entire motoneuron pools

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Details

Movements are performed by motoneurons transforming synaptic input into an activation signal that controls muscle force. The control signal is not linearly related to the net synaptic input, but instead emerges from interactions between ionotropic and neuromodulatory inputs to motoneurons. To advance our understanding of the neural control of muscle, we decoded the firing activity of extensive samples of motor units in the Tibialis Anterior (129 ±44 per participant; n=8) and the Vastus Lateralis (130 ±63 per participant; n=8) during isometric contractions of up to 80% of maximal force.

From this unique dataset, we characterised the rate coding of each motor unit as the relation between its instantaneous firing rate and the muscle force, with the assumption that the linear increase in isometric force reflects a proportional increase in the net synaptic excitatory inputs received by the motoneuron.

This relation was characterised with a natural logarithm function that comprised two phases. The initial phase was marked by a steep acceleration of firing rate, which was greater for low- than medium- and high-threshold motor units. The second phase comprised a linear increase in firing rate, which was greater for high- than medium- and low-threshold motor units. Changes in firing rate were largely non-linear during the ramp-up and ramp-down phases of the task, but with significant prolonged firing activity only evident for medium-threshold motor units.

Contrary to what is usually assumed, our results demonstrate that the firing rate of each motor unit can follow a large variety of trends with force across the pool. From a neural control perspective, these findings indicate how motor unit pools use gain control to transform inputs with limited bandwidths into an intended muscle force. We will show how these results can help to design linear or non-linear decoders that aim to predict muscle activation or muscle force from descending inputs recorded in supraspinal centres, with the will to generalise their performance across movements.

F – Posture and Gait

3-F-74 - Early manifestation of muscle activity during passive and spontaneous movements in preterm and full-term infants

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Details

Early infancy is a critical period for the development of sensorimotor circuits and the generation of appropriate muscle tone. Sensory feedback resulting from interactive and spontaneous movements is instrumental for developing sensorimotor circuits in early infancy, and shorter gestational periods (preterm infants) may have compromised muscle strength and functionality. Here, we examined potential differences between the behavior (movement-related muscle activity) of preterm infants and that of full-term infants.

We evaluated early manifestations of muscle tone by measuring muscle responses to passive stretching (StR) and shortening (ShR) in both upper and lower limbs in preterm infants (at the corrected age from 0 to 12 months), and compared them to those in full-term infants. Passive movements were recorded in a supine position, were periodic (typically 4-7 consecutive cycles of flexion/extension) and relatively slow. In a subgroup of participants, we also assessed spontaneous muscle activity during episodes of relatively large active limb movements either during non-restricted limb movements or when one of the limbs was blocked.

The results showed very frequent StR and ShR, and also responses in muscles not being primarily stretched/shortened, in both preterm and full-term infants. The majority of muscles exhibited a significant decline in the expression of reactions with age. For active (spontaneous) movements, the appearances of selected episodes of relatively large limb movements were in general similar in full-term and preterm infants. However, the age-related increments in correlations of antagonist muscle activity were notable only in full-terms.

Overall, postterm development of muscular activity during passive movements was not much different in full-term and preterm infants. A reduction of sensorimotor responses with age suggests a reduction in excitability, and/or the acquisition of functionally appropriate muscle tone during the first year of life.

However, the preterm infants showed higher rates of muscle responses to passive movements at 3-6 mo corrected age and a lack of age-related changes in correlations of antagonist muscle activity. Atypical responses in preterm infants were mostly noticeable in the first months, perhaps reflecting temporal changes in the excitability of the sensorimotor networks.

3-F-75 - Complexity and variability of neuromuscular control during human locomotor development

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Details

When does modular control of locomotion emerge during human development? Two related concepts have attracted considerable interest in neuroscience and evolutionary developmental biology, modularity and complexity. Modularity refers to the existence of decomposable processes with stereotypical functions. We studied this issue in the context of locomotor development. One view is that modularity is not innate, being learnt over several months of experience. Alternatively, the basic motor modules are present at birth, but are subsequently reconfigured due to changing brain-body-environment interactions.

One problem in identifying modular structures in stepping infants is the presence of noise. Here, using both simulated and experimental muscle activity data from stepping neonates, infants, and adults, we dissected the influence of noise, and identified modular structures in all individuals. We recorded the EMG activity of 8 bilateral lower limb muscles during stepping/walking in 11 neonates, 53 infants, and 15 adults.

First, we examined the features of EMG activity of individual muscles by analizing the power spectral density (PSD) of the EMG data. For each muscle, the features of both the periodic and aperiodic components of PSD and the spectral entropy were significantly different between neonates and adults, the patterns being more complex in adults relative to neonates.

For multi-muscle coordination, we evaluated the dimensionality of the EMG data using different factorization algorithms. The traditional way to assess dimensionality (complexity) consists in measuring the Variance Accounted For by the extracted modules, but this procedure may be affected by the presence of noise, especially in the neonatal data. Therefore, here we combined traditional measures with new consistency measures that consider the potential variability of motor modules across strides. We tested this approach on different sets of both simulated and experimental EMG data. The results showed that the values of the inter-stride consistency measures were much less affected by the amount of noise, thus representing a better way of estimating the actual dimensionality, and clearly demonstrated a systematic trend toward increasing dimensionality of the modules with increasing age.

We conclude that complexity increases from the neonatal stage to adulthood at multiple levels of the motor infrastructure, from the intrinsic rhythmicity measured at the level of individual muscles activities, to the level of muscle synergies and of bilateral intermuscular network connectivity.

3-F-76 - Simulating plantar cutaneous afferent responses to behaviorally relevant forces

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Details

The foot sole is the primary interface between the body and environment, carrying information about the surface upon which we are standing or walking on, and contributing to balance maintenance. Existing research into the responses of tactile afferents at the foot sole has used carefully controlled low-amplitude stimuli to identify afferent firing thresholds and characterise response properties. However, such stimuli are not reflective of those experienced by the foot sole during everyday behaviour, limiting the generalisability of current experimental results to real-world behaviour. To fill this gap, we presented novel stimuli with load profiles comparable to those experienced during gait, with forces of up to 35 N/cm^2, and recorded afferent responses using microneurography. Stimuli included both slow ramps and fast ramps to reflect different loading patterns experienced during everyday behaviour. We found that during slower ramps, greater forces and slower rates of loading influence afferent classes to different extents: slowly adapting afferents exhibit greater firing rates to high force-low derivative stimuli, whereas fast adapting afferents respond more to low force-high derivative stimuli. Additionally, fast ramp stimuli applied to SA2 receptors led to very high firing rates, much higher than those elicited from vibrational stimuli, suggesting that these slowly adapting receptors may contribute more to balance maintenance than previously thought. We next fitted a computational model of foot sole cutaneous afferents to the experimental electrophysiological data and simulated tactile responses to spatiotemporal pressure patterns during balance and gait. These simulations allow for responses during dynamic stimulation to be predicted, building on the current limitations of microneurography. Combining experimental and computational methods affords the opportunity to provide new-found insight into the role that tactile feedback plays during natural behaviours, such as standing balance and gait.

3-F-77 - Interpersonal coordination during walking of adults and children with hand contact

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Details

Handholding can naturally occur between two walkers. When people walk side by side, with or without hand contact, they frequently synchronize their steps. Despite the significance of haptic engagement in general and the natural use of hand touch between humans during walking, few studies have examined the forces resulting from physical interactions. Here, we studied how interpersonal coordination acts through interaction forces during side-by-side walking in adult-adult, adult-child and child-child dyads.

Eleven couples participated in this study (sixteen healthy volunteers,7 adults and 9 children): 2 adult-adult, 5 adult-child and 4 child-child. Each couple was asked to reach 3 different targets (located at a distance of ~6 m straight, left, right from a start position) walking in 4 different conditions. In the two conditions ("no role"), they walked with eyes open either without hand contact or with contact. In the others two conditions ("guidance"), the first partner was a leader (with eyes open) and the second partner (blindfolded) needed to follow the leader through the hand contact and vice versa. No instructions were given about the walking speed. The command to start walking was provided by an acoustic signal in the headphones. We examined the kinematics of both subjects, the interaction forces and the EMG activity of ten muscles of the upper limbs (7 on the side of contact and 3 on the contralateral side).

All subjects completed the tasks successfully. The contact forces were generally small (<10 N). Interestingly, in the "no role" conditions, proximal arm muscle activity could be conserved despite reduction in arm swing. In the "guidance" conditions, we found that the upper limb of adults was significantly less compliant when guiding a child partner, while children were more compliant in all roles when their partner was an adult. Augmented arm stiffness in adults guiding children was associated with increased activity of the posterior deltoid muscle.

Here we described a novel approach to evaluate human-human interaction forces when walking side-by-side with hand contact. The conservation of the proximal muscle activity of the contact arm is consistent with neural coupling between cervical and lumbosacral pattern generation circuitries ('quadrupedal' arm-leg coordination) during human gait. The findings suggest that individuals might integrate force interaction cues to communicate and synchronize steps during walking, modulating the mechanical properties of their arms to increase awareness and sensitivity to ongoing interaction. Applications of interactive locomotion related to walking assistance or rehabilitation should consider the effect of size of subjects and the compliant behavior of the upper limbs.

3-F-78 - Foot placement control strategies for human locomotion are context-dependent

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Details

Humans are capable of seamlessly modulating their locomotor control strategies across numerous sensorimotor contexts. Such adaptive control is crucial for meeting varying contextual demands while remaining stable. In this study, we seek to understand how stabilizing control strategies for locomotion are modulated as a function of two commonly used experimental contexts: treadmill and overground walking. We seek to answer this question both by analyzing the average steady-state control strategy as well as the variability-derived step-to-step control strategy. Similar to prior work in gait biomechanics which focuses on the average control strategy, but with larger sample size, we find a direction-dependent asymmetry in the average location of the foot across contexts: subjects demonstrated wider lateral foot placement and a greater base of support on the treadmill, but retained similar fore-aft foot placement and base of support across both contexts. However, this analysis of the average foot placement strategy alone does not provide insight into how the timescales and input space of locomotor control change across contexts. To understand this, we analyzed the autocorrelation in the time series of the foot placement, which revealed a context-dependent temporal pattern underlying the step-to-step variability in the lateral foot placement; subjects on a treadmill corrected lateral foot placement errors in the immediate subsequent step, whereas overground walking showed a slower timescale correction strategy. By further analyzing the step-to-step variability in the kinematics of the torso, we aimed to understand whether contextual variations in the body states affect foot placement control strategies. We discovered that integrating the history of body state kinematics from the start of gait enables the model to account for 30-40% higher variance of lateral foot placement deviations for overground walking, compared to only 10-20% for treadmill walking. We did not find a similar difference in the history-dependence of the forward foot placement control with context. These findings suggest that humans integrate state information over multiple steps to inform lateral foot placement control overground, but rely on a more bang-bang control strategy on the treadmill. Our study presents a data-driven framework to analyze time-varying inputs to locomotor control, and highlights the different control strategies for stable walking on the treadmill versus overground. Context-dependent control strategies for locomotion, as we identify here, may have implications for understanding the generalization and adaptation of locomotor control.

3-F-79 - Revealing forelimb pose representations in the cervical spinal cord of decerebrate cats through high-density linear electrode recordings

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Details

Voluntary movements can be viewed as a sequence of static postures. Under normal behaviors, however, it is difficult to address the neural mechanism for controlling posture and voluntary movement because it is functioning concurrently. Owing to these technical difficulties, the neural representation of limb postures, especially in the spinal cord, is largely unknown.

In this study, we addressed this issue with the immobilized and decerebrated animals, which enabled us to dissociate postural monitoring from the voluntary movement control because it could limit any voluntary and reflexive limb movement to occur. We hypothesized that spinal neural population, not only the specific neuronal category such as the spino-cerebellar tract neurons, may represent the limb postures. To test this hypothesis, we applied the high-density linear electrodes (Neuropixels 1.0), and recorded responses of the neural population in the cervical spinal cord of cats (n=2) with passive forelimb posture.

The electrodes were inserted perpendicularly approximately 1.5 mm laterally from the midline between the C5 and C6 segments, which covers almost the full range of the gray matter along the dorsoventral axis. Recordings were made for six static postures which were selected from the possible combinations of the shoulder (flexed/neutral/extended) and elbow (flexed/extended) joint positions. While recording the response of the spinal neurons, an experimenter held the cat's forelimb at a given static posture for 60 seconds. Among six postures, a posture with the neutral shoulder joint and the extended elbow-joint position was used as the standard posture for comparison with the other static postures.

The neural activity was recorded by the OpenEphys system, and the spike sorting was performed using Kilosort 3.0 and Phy software. Forty-one single-unit activities have been recorded in one animal. Each neuronal activities under the static postures were classified into excitatory and inhibitory response. First, with multiple standard postures, the mean and standard deviation of the firing rates were calculated. Then, unit responses above +1.5 SD were classified as excitatory ones, and those below -1.5 SD were classified as inhibitory ones.

Among 41 units, 12 neurons responded only one posture, 9 for two, two for three, 3 for four, and 0 for all postures. More importantly, almost every neuron represented a unique set of different postures. The inhibitory responses were located exclusively in the ventral horn of the spinal cord, and a majority of excitatory responses were found in the neurons located between the intermediate layer and the ventral horn. The excitatory activity was specifically found near the Rexed lamina …¦ of the cervical spinal cord.

Overall, the results of this study suggest that a group of neurons in the spinal cord could represents static postures.

3-F-80 - The cortical N1 response to balance disturbance is larger in anxious children and associated with the error-related negativity

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Details

A sudden balance disturbance evokes a cortical response (balance N1, ~150ms) in the EEG over the supplementary motor area that is presumed to have some role in balance recovery behavior. The balance N1 is associated with balance ability in young adults (Payne 2020) and with different aspects of balance and cognitive abilities in older adults with and without Parkinson's disease (Payne 2022), raising the question of whether it could be targeted therapeutically for balance disorders. However, the balance N1 also depends on cognitive factors including attention (Quant 2004, Little 2015) and perceived threat (Adkin 2008), suggesting any role in balance recovery behavior may be mediated through cognitive processes. The balance N1 appears to resemble the more widely investigated error-related negativity (ERN, Payne 2019b), which is evoked by mistakes in cognitive tasks and enhanced with anxiety. We hypothesized that the balance N1 shares neural mechanisms with the ERN and would therefore share its relationship with anxiety. We assessed N=28 anxious children (age 9-12, with Generalized Anxiety, Social Anxiety, and/or Obsessive-Compulsive Disorder) and N=50 nonanxious children. The ERN was measured at frontocentral electrodes (referenced to mastoids) as the mean voltage 0-100ms after errors in a cartoon Go/NoGo task, in which children occasionally pressed a button in response to a rare visual stimulus they were told to ignore. The balance N1 was measured as the mean voltage 50-150ms after sudden release of a cable supporting 5% of their body weight in a forward leaning posture. One-tailed t-tests assess group differences in the balance N1. Pearson's product-moment correlations measure associations between the balance N1 and the ERN or SCARED-parent report of child anxiety severity (Birmaher 1999), combining children across groups. All tests are repeated across Fz, FCz, and Cz electrodes. The balance N1 was larger in children with anxiety disorders (Fz $p=0.097$, FCz $p=0.013$, Cz $p=0.001$). Further, the balance N1 was associated in amplitude with the ERN (Fz $r=0.331$ $p=0.003$, FCz $r=0.371$ $p<0.001$, Cz $r=0.390$ $p<0.001$) and with parent-reported severity of child anxiety symptoms (Fz $r=-0.275$ $p=0.015$, FCz $r=-0.317$ $p=0.005$, Cz $r=-0.332$ $p=0.003$). These results are consistent with the hypothesis that the balance N1 shares neural mechanisms with the ERN and raises the question of whether anxiety (e.g., perceived threat or fear of falling) may confound, or be central to, relationships between the balance N1 and balance recovery behavior. More broadly, cognitive and emotional influences on information processing may span a wide range of behaviors, and individual differences in evoked brain activity may not be unique to the experimental task.

3-F-81 - Precise cortical contributions to sensorimotor feedback control during reactive balance in aging and Parkinson's disease

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Details

The role of the human cerebral cortex in shaping automatic whole-body motor behaviors such as walking and balance is poorly understood. Gait and balance are largely mediated through subcortical circuits, with the cortex becoming engaged as needed on an individual basis by task difficulty and complexity. However, we lack a mechanistic understanding of how increased cortical contribution to whole-body movements shapes motor output. Here we use reactive balance recovery as a paradigm to identify relationships between hierarchical control mechanisms and their engagement across balance tasks of increasing difficulty in young adults (YA), older adults (OA), and individuals with Parkinson's disease (PD). This work aims to provide a mechanistic understanding of how shifts in hierarchical control shape motor output in aging and impairment. We hypothesize that parallel sensorimotor feedback loops engaging subcortical and cortical circuits contribute to balance-correcting muscle activity, and that the involvement of cortical circuits increases with balance challenge, aging, and PD. To test this hypothesis, we use delayed feedback control models to identify relationships between sensory information, muscle activity, and cortical activity across balance tasks of increasing difficulty in YA, OA, and people with PD. We decomposed balance-correcting muscle activity based on hypothesized subcortically- and cortically-mediated feedback components driven by similar sensory information, but with different loop delays. The initial balance-correcting muscle activity was engaged at all levels of balance difficulty. Its onset latency was consistent with subcortical sensorimotor loops observed in the lower limb. An even later, presumably cortically-mediated, burst of muscle activity became additionally engaged as balance task difficulty increased, at latencies consistent with longer transcortical sensorimotor loops. We further demonstrate that evoked cortical activity in central midline electroencephalography (EEG) can be explained by a similar sensory transformation as muscle activity but at a delay consistent with a possible role in a transcortical loop driving later cortical contributions to balance-correcting muscle activity. We

then applied this model to OA and people with PD as both cohorts exhibit an increased reliance on cortically-mediated control of posture. We found OA to have a larger contribution of cortically-mediated muscle activity than people with PD, suggesting that the impairment found in PD may hinder the efficacy of cortically-mediated muscle activity.
These results demonstrate that a neuromechanical model of muscle activity can be used to infer cortical contributions to muscle activity without requiring direct recordings of brain activity. Our model may provide a useful framework for evaluating changes in cortical contributions to balance that are associated with falls in older adults and those with neurological disorders.

3-F-82 - The role of expectation in the neural processing of vestibular stimuli in humans

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Details

It is important that humans are able to discriminate between unpredictable vestibular stimuli and that which is self-triggered and thus expected. Such discrimination is crucial for ensuring that appropriate vestibular reflexes are triggered to maintain postural stability (e.g., triggering a reflexive action when head movement occurs during slipping/tripping but not when looking up at the sky). Disruptions in such ability to discriminate have been hypothesised to underpin higher-level disorders of 'functional dizziness', whereby dizziness occurs without any apparent peripheral vestibular dysfunction. Despite this, little is known about how expectation affects the cortical processing of vestibular input in humans, and if such discrimination (and thus disruption to) occurs at the level of the cortex. Here, we recorded EEG from 22 healthy young adults undergoing discrete whole body yaw rotations. During one condition ('Unexpected'), rotations were unexpected with respect to timing, direction and magnitude. During another condition ('Expected'), rotations were predictable in terms of direction and magnitude, and were self-triggered by the participants themselves. Alpha desynchronisation, a previously identified hallmark of vestibular processing, tended to be reduced during ‘Expected’ rotations. Expectation also significantly reduced the initial post-rotation theta activation (a marker of self-motion monitoring/vigilance). There was also a significant reduction in the vestibular-evoked cortical potential during the Expected condition. Overall, these findings reveal that humans can cortically down-weight the processing of expected (and self-triggered) vestibular stimuli. Ongoing work is exploring if these results can be used to assess higher-level cortical abnormalities in 'functional dizziness'.

G – Theoretical & Computational Motor Control

3-G-83 - Preparatory weight shifts when transitioning from two- to one-legged stance might reduce effort in the presence of physiological noise: a simulation study

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Details

Weight shifts are crucial for controlling posture and transitioning between movements. Though the movements are small, the consequences of inappropriately planning and executing these weight shifts can be serious; incorrect weight shifts cause most falls. In contrast to commonly studied external disturbances like trips, incorrect weight shifts result from physiological noise and planning errors. Characterizing the implications of noise on the control of weight shifts is therefore essential for elucidating underlying mechanisms of balance control and fall risk.

The well characterized preparatory weight shifts made before stepping serve as an exemplar task for studying weight shifts. In the frontal plane, the center of mass (COM) is shifted towards the stance leg, to be over the new, smaller, base of support created in single leg stance. Here, we developed a conceptual model of the transition from two- to one-legged stance, and simulated this movement twice, as a (1) deterministic and (2) stochastic optimal control problem.

This 2D model consists of 3 rigid links (2 legs, 1 torso), plus two massless feet, which offset the ankles from the ground and constrain the ground reaction force (GRF) points of application. The model was driven by torques at each of the 4 joints.

For both simulations, the model started in a default static (zero velocity) standing position and ended in a static position with only one foot on the ground over a span of 1 second. For the deterministic version, we minimized feedforward joint torques. For the stochastic version, we used a recently developed framework to solve for the feedforward torques and linear, time varying, full-state feedback gains that minimized expected effort in the presence of Gaussian motor noise [1]. We then qualitatively compared the resulting movements.

The presence of feedback and physiological noise shaped the control strategy. In the absence of noise, the model lifted the foot and shifted the COM simultaneously, using larger torques and joint accelerations. When noise was accounted for, the model first shifted the COM over the stance foot, then lifted the foot. This preparatory shift mimics the anticipatory postural adjustments seen experimentally before taking a step.

Our results suggest that the presence of noise can change the identified control strategy; with noise, the minimal effort strategy became more similar to experimental observations, shifting the COM before lifting the foot, without any constraints upon the model to move this way. Given that real world movements naturally include internal and external noise, it is important to incorporate noise in simulations designed to investigate neural control strategies. With this model we can test the effects of sensorimotor noise and weakness on frontal plane weight shifts and begin to understand the effects of aging which might lead to higher fall risk.

[1] T Van Wouwe et al. (2022). PLoS Comput Biol. 18(6): e1009338

3-G-84 - Linking neural population dynamics in the motor cortex to optimal feedback control of motor behavior

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Details

Understanding how neural activity in the motor cortex relates to behavior across tasks is a fundamental question in sensorimotor neuroscience. However, the complexity of biological neural networks poses challenges in deciphering the function of the observed neural activity. On the one hand, human movements have often been modeled in the framework of optimal feedback control (OFC), wherein real-time processing of sensory inputs orchestrates motor output for movement execution. OFC suggests that understanding goal-directed motor responses across tasks requires knowledge of the control policy and the state estimator. Here, control policy refers to the mapping between estimated body state and task goals to motor output. On the other hand, neural recordings show that the activity in motor cortex evolves in a low-dimensional space, with a few independent components (called neural factors) explaining a significant variance in activity (*Churchland et al. Annual rev of neuroscience. 2013; 36:337-59*). These neural factors occupy distinct, and orthogonal subspaces of preparation and movement (*Elsayed et al. Nat communications. 2016; 7(1):13239*). Additionally, neural factors within the same subspaces can be flexibly combined to produce multiple movement repertoires (*Gallego et al. Nat communications. 2018; 9(1):4233*). Despite describing population activity compactly, the dynamical system generating such neural factors remains elusive (*Kuzmina et al., Sci Rep. 2024; 14(1):3566.*).

To fill the gap between the theory of motor control and low-dimensional neural factors, we present a novel framework neural optimal feedback control model (N-OFC) integrating OFC principles with population dynamics of arbitrary neural circuits. By representing brain as a network, and body states as a joint dynamical system, and computing the optimal patterns of change in the neural circuit, N-OFC reproduced stereotypical patterns previously observed in both behavioral and neural activity in a center-out reaching task. It replicated human-like variability and corrective responses in another benchmark task where the reach targets offered redundancy along one task dimension (dot-bar task, *Nashed et al. JNP. 2012; 108(4):999-1009.*). N-OFC predicts distinct neural population activity patterns corresponding to different control policies in this task, offering novel insights into how the control policy shapes the associated population activity. Unlike the recurrent neural network models, where network weights are fit using black-box optimization, N-OFC is interpretable using optimal control theory, and the emergence of low dimensional factors is independent of the network or of a fitted set of connection weights. Overall, this framework not only elucidates existing neural phenomena but also has the potential to generate novel predictions when control policies changes due to differing task-demands arising from differences in movement costs and perturbations of body dynamics.

3-G-85 - Hierarchical goal-driven model of the cortico-basal ganglia loop during a time delay task

John Lazzari [1], **Zidan Yang** [2], **Hidehiko Inagaki** [2], **Shreya Saxena** [1]

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Details

The basal ganglia are a group of midbrain structures intimately tied to the control of movement. Through their connections to and from the thalamus and cortex, the basal ganglia are implicated in a wide array of functions such as action selection and initiation, control of movement invigoration, and encoding of time information on the order of seconds to tens of seconds. However, a computational understanding of how striatal population dynamics guide and control cortical activity to properly time and execute movement is lacking. Past computational models of the basal ganglia either focus on the relationship between the temporal difference error and dopaminergic firing patterns, or model striatal activity and connectivity in a non goal-driven manner while leaving upstream projections and feedback unaccounted for. Here, we develop a hierarchical, goal-driven model of the striatum using recurrent neural networks (RNNs) in the actor-critic reinforcement learning framework. Our task is inspired from a delay licking task in which mice received a reward after licking a fixed number of seconds following an auditory cue, where striatal and anterior lateral motor cortex (ALM) recordings are provided. We model the basal ganglia learning a signal that guides ramping activity in the ALM, where a lick occurs after a threshold is reached. We additionally incorporate the true ALM activity in the reward to properly guide the actor towards optimal solutions. Contextual feedback from the ALM is provided during training, and the actor learns to properly time the ramping for different lick times. After training, we use statistical analyses and dimensionality reduction to compare the resulting RNN population activity with that of the real striatal population and find similarities in their dynamical features. This demonstrates how a goal-driven, hierarchical population dynamics model of the striatum may provide insight regarding the underlying computations performed by the cortico-basal ganglia loop during the timing and initiation of movement.

3-G-86 - Bifurcation analysis on a two-neuron model of central pattern generators for both rhythmic and discrete movements

Kotaro Muramatsu [1], **Hiroshi Kori** [1]

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Details

The Matsuoka oscillator model is a neuronal network model which exhibits oscillatory activities due to adaptation property of each neuron and mutual inhibitions between neurons (Matsuoka, 1985; 1987; 2011). This is often used to model oscillatory neuronal circuits in the spinal cord called central pattern generators (CPGs) and to simulate biological locomotion such as human bipedal walking (Taga et al., 1991; Ogihara & Yamazaki, 2001). However, most previous studies have overlooked its convergent dynamics toward stationary states, corresponding to transient neuronal activities and non-oscillatory movements. In the present study, we conducted fixed point analysis on a two-neuron case of the Matsuoka oscillator model. Through this investigation, we (I) formulized the existence and stability of all possible fixed points, (II) depicted emergence of oscillatory solutions and bifurcation mechanisms between oscillatory and convergent dynamics, and (III) made predictions of a logarithmic scaling law of oscillation period and noise-induced oscillation. Our results possibly suggest that central nervous systems might take advantage of CPGs not only for rhythmic locomotion but also for non-oscillatory or discrete movements. The discussion of limitations revealed in this report will likely be followed by future extension of the Matsuoka oscillator model to understand an integrative mechanism for neural control of both rhythmic and discrete movements.

3-G-87 - Optimization of peripheral electrical stimulation to improve muscle contraction patterns

Laura Toni [1], **Simone Romeni** [2], **Claudio Verardo** [1], **Luca Pierantoni** [1], **Silvestro Micera** [3]

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Details

It has been shown that electrical stimulation of peripheral nerves via implanted interfaces enables coordinated muscle contractions, thereby restoring various grasping patterns in non-human primates. Computational modeling of peripheral nerve stimulation holds promise for accelerating the translation from animal studies to human trials and refining stimulation protocols for animals and patients already implanted. Utilizing the finite element method and biophysically accurate models of neuronal activation, we can predict activity patterns within the targeted nerves. However, existing computational models typically focus solely on estimating activation whether a neuron will fire without considering its firing rate. This assumption influences substantially what can be predicted through computational modelling, as both recruitment and firing rate influence muscle contraction. In our research, we have crafted a model that simulates neural activity by considering both the recruitment of nerve cells and their firing rates to estimate muscle force. This innovative model facilitates the in silico refinement of electrical stimulation protocols. By analyzing a particular nerve layout and implant design, we were able to predict the response of stimulated nerve fibers through a series of finite element analyses that quantify the extracellular electric potential. These responses were then transformed into firing rates applying a sigmoidal activation curve, the standard choice for the fit of the experimental relationship between the current applied to a neuron/nerve fiber and the resulting firing rate. Our approach further incorporates data from experimental measurements of muscle contraction speeds to establish a link between the firing rates of motor neurons and the force generated by muscle units, referencing a range of experimentally derived curves. Initially, our efforts centered on creating patterns of muscle force by applying random electrical stimulation sequences, verifying that our optimization process could faithfully recreate muscle contractions within the accessible scope of our in silico experimental framework. Following this, we detailed methods to fine-tune stimulation protocols that could elicit specific muscle contraction patterns. In both scenarios, we examined stimulation protocols that employed both monopolar and multipolar configurations, thus manipulating the electric potential landscape to orchestrate intricate muscle contraction patterns.

3-G-88 - Reduced complexity and altered spatiotemporal coordination in finger control after stroke

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Details

The human hand movement is complex, dynamic and variable. A recent investigation into hand activities has revealed that the complexity of hand postures resides on much higher dimension than previously thought (Yan et al., 2020). Much of this complexity is lost after stroke (Xu et al., 2023). However, these studies did not characterize the spatiotemporal coordination in isometric fingertip forces using Non-Negative Matrix Factorization (NNMF), which has been shown to identify interpretable coordination patterns in movement (Torres-Oviedo et al., 2006). We hypothesize that the stroke hand will have

reduced complexity in finger force coordination and altered coordination patterns. We predicted that (1) the number of modules needed to describe stroke hand force trajectories would be reduced compared to healthy hands and (2) modules identified in stroke hands would poorly reconstruct healthy force trajectories.
Isometric 3D forces were recorded from all five fingertips simultaneously from the right hand of 20 healthy controls, and both paretic (P) and non-paretic (NP) hands of stroke survivors. Participants were instructed to generate forces with one instructed finger to move a dot in virtual space towards a target in one of 6 directions (+/- XYZ of Cartesian space) at one of 4 force levels (0.2,0.4,0.6,0.8 % of maximum voluntary force), while keeping the uninstructed fingers inactive. Subject-specific force modules and their time-varying activations were identified from force trajectories across all tasks (Instructed finger and Target Direction). The complexity of finger control was quantified as the number of modules needed to explain 95% of the variance (Clarke et al., 2010). We also extracted modules from all three groups to examine if they could reproduce force patterns from other groups.
Both paretic (Mean = 19.67; SD = 2.50) and non-paretic hands (Mean = 20.5; SD = 1.22) required fewer modules than healthy hands (Mean = 22.5; SD = 1.93) (P vs healthy: $p = 0.007$; NP vs healthy: $p = 0.026$) to explain 95% of the variance in the force trajectories across trials, suggesting that finger force coordination in stroke hands has reduced complexity than healthy hands. Paretic (Mean = 0.73; SD = 0.09) hand force modules were less able to reconstruct healthy hand force trajectories compared to healthy hand modules (Mean = 0.822; SD = 0.06) ($p < 0.001$), as were non-paretic modules (Mean = 0.73; SD = 0.06, $p < 0.001$), suggesting that paretic and non-paretic modules have lost a certain level of capacity to reproduce healthy force trajectories. These findings indicate that stroke impairments reduced the complexity and altered the structure of finger force coordination. Our analysis allows further investigation into how neuromechanical constraints post stroke impact the ability to produce precise fingertip forces.

3-G-89 - Clinical sensory organization task effects on prefrontal cortical activation patterns in older adults with and without hypertension

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Details

Background: Hypertension (HTN) can lead to non-amnestic cognitive impairment over time (Reitz et al., 2007), however, it is unclear if this cognitive impairment affects the control of balance in older adults with HTN. The objective of this study was to evaluate the differences in prefrontal cortex (PFC) oxygenated hemoglobin (HbO_2) levels during a clinical sensory organization test (SOT) in older adults with and without HTN. We hypothesized that adults with HTN would show increased activation i.e., higher PFC HbO_2 during SOT tasks, and that this activation would increase as the task difficulty increased in comparison to older adults without HTN, due to compensation-related utilization of neural circuits hypothesis (CRUNCH) model. Methods: There were 15 adults in the healthy older adult (HOA) group (11 females; 65 ±9 years old; ‰¤120/80 mmHg), and 9 adults in the HTN group (3 females; 68 ±8 years old). The experimental paradigm consisted of 3 trials each of 6 conditions: Eyes open (EO), Eyes closed (EYC), Eyes open sway reference moving (EYO-SR), Eyes open plate reference moving (EYO-PR), Eyes closed plate reference moving (EYC-PR), Eyes open sway and plate reference moving (EYO-SPR). They were instructed to stand upright on the force plate while experiencing different perturbations throughout the test. Functional

Near-Infrared Spectroscopy was used to quantify PFC HbO_2 levels. A linear mixed effect model was conducted to investigate the effects of cohort, condition, and interaction between them on relative HbO_2 levels, using quiet standing while silently counting numbers as a baseline. To control for multiple comparisons, post hoc t-tests were carried out using Tukey's method. Results: We found that adults with HTN showed increased waist circumference, body mass index, and increased risk of cardiovascular disease compared to HOA. The linear mixed effects results showed that HbO_2 levels increased as the difficulty of conditions increased for both groups ($p<0.01$), with the HTN group showing increased activation than the HOA group. We also found a significant 2-way interaction in HbO_2 levels: cohort and task ($p<0.001$), where HTN exhibited lower HbO_2 levels during the most difficult condition (EYO-SPR) compared to HOA. Post-hoc t-tests suggested that there were task differences among both groups ($p<0.01$). Conclusion: Overall, HTN adults showed increased activation compared to HOA, which shows that their ability to focus on task execution is compensated. This study confirms the use of increased attentional resources in the PFC as sensory disturbances increase and suggests hypertensive adults had to recruit more attentional resources in comparison to healthy older adults for the same task, up until the most challenging task, which may be partly explained by CRUNCH model and "supply and demand" theory. **References:** Reitz et al. (2007). Hypertension and the risk of mild cognitive impairment. *Archives of Neurology*, *64*(12), 1734""1740.

3-G-90 - EMUsort and LITMUS: the enhanced motor unit sorter and robust benchmarking of motor unit sorters

Sean O'connell [1], **Jonathan Michaels** [2], **Runming Wang** [3], **Manikandan Venkatesh** [1], **Nevin Aresh** [1], **Samuel Sober** [4], **Chethan Pandarinath** [1]

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Details

Despite many recent advances in the study of motor control, understanding the activity of populations of motor units (MUs) is critically limited by an inability to robustly sort intramuscular recordings to reveal MU action potentials (MUAPs). MUAP waveforms are substantially more challenging to sort than cortical waveforms, due to their 1) larger variety of waveform shapes, 2) time delays across channels, and 3) high firing rates during critical behavioral periods, resulting in higher numbers of MUAP overlaps. Beyond sorting challenges, there is scarce literature or infrastructure available for evaluation of MUAP spike sorters, which is of critical importance to the field to demonstrate which sorters perform the best with MU data. To improve MUAP sorting performance, we developed EMUsort, a Kilosort-based spike sorter tailored to the unique properties of MUs. EMUsort accounts for muscle fiber conduction delays by optimally shifting channels in time and ensures that the learned templates incorporate enough information to fully reconstruct the more complex MUAP waveforms compared to existing methods targeted to cortical neurons. EMUsort also provides several convenience features for data management, manipulating OpenEphys recordings, and running parameter grid searches in parallel on multiple GPUs. To solve the need for robust and standardized performance evaluation of spike sorters, we are developing the Leaderboard Interface for Testing Motor Unit Sorters (LITMUS), a public MUAP sorting benchmark. LITMUS uses a variety of synthetic MU datasets to assess a range of standard metrics, such as accuracy, precision, recall, and fraction of units found. The website will include an interface for uploading sorting results (spike IDs and times), with metrics published to the leaderboard. This type of community validation will greatly benefit motor control research by making public which MUAP sorters perform best. Using our benchmarking methods and a parameter grid search on a 10 minute synthetic dataset of 10 MUs across 8 channels, EMUsort provided 0.908 +/- 0.043 accuracy on average, compared to unmodified Kilosort 3.0, which achieved 0.830 +/- 0.116 accuracy on average. In these tests, EMUsort consistently provided better sorting stability, reliably tracking all 10 MUs, whereas Kilosort 3.0 always failed to identify at least one MU. Because both sorter performances were compared using a dataset which had conduction delays removed, the true performance gap may be larger. As a part of LITMUS, we will produce additional synthetic datasets with 30-50 MUs on 16 channels, based on data recorded in humans, non-human primates, rats, and mice. These datasets will significantly raise the ceiling for sorter performance. We have also begun testing with Kilosort4, which may be incorporated into EMUsort in the future. Together, EMUsort and LITMUS will provide lasting value to the research community by providing open source tools for MUAP sorting and validation.

3-G-91 - Full-body modeling of human musculoskeletal system and neural control of locomotion with hierarchical reinforcement learning

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Details

The construction of a controllable human musculoskeletal system is important for the study of motor function. However, current dynamic models are often restricted to a limited range of body parts and with a reduced number of muscles. There is also a lack of algorithms capable of controlling over 600 muscles to generate reasonable human movements. To fill this gap, we build a comprehensive musculoskeletal model with 90 body segments, 206 joints, and 700 muscle-tendon units, allowing simulation of full-body neural excitation driven dynamics and interaction with various devices. We develop a novel algorithm that uses low-dimensional representation and hierarchical deep reinforcement learning to achieve neural-driven full-body motion control. We validate the effectiveness of our model and algorithm in simulations and on real human motion data. The musculoskeletal model and its control algorithm will promote a deeper understanding of human motor control.

Poster Session 4

Friday April 19, 2024

A – Adaptation & Plasticity in Motor Control

4-A-1 - Action effects of sequential actions are pre-planned in parallel similar to their coupled actions

Alexandros Karagiorgis [1], **Anwesha Das** [1], **Katja Kornysheva** [2], **Elena Azañon** [3], **Max-Philipp Stenner** [1]

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Details

According to ideomotor theory, actions and their sensory outcomes, also known as action effects, become coupled after exposure to fixed response-effect mappings, providing a bidirectional interface, such that activating one can co-activate the other. It is suggested that anticipating action effects can facilitate the planning of actions. Sequential actions are planned in parallel, evident in a Competitive Queuing gradient before execution of the first movement, according to which the first element of the sequence is represented the strongest, the second element the second strongest, and so on. We hypothesized that anticipated action effects that have been coupled with motoric sequences would be represented during the planning stage of the sequence and governed by the Competitive Queueing gradient. Here, we employed a discrete sequence production task where participants (currently N=17) learned to produce from memory two 5-element sequences on a keyboard that produced tones with a fixed response-effect mapping, just like a piano, resulting in a coupling of motor actions to auditory action effects. We recorded magnetoencephalography (MEG) data in a separate session with three blocked conditions. In one condition, the response-effect mapping experienced during learning was preserved. In the second condition, keypresses produced no auditory feedback. In a third condition, participants passively listened to the melodies of the respective learned motor sequences. In all conditions, each trial started with a visual cue, indicating which motor sequence subjects would have to produce, or which tone sequence they would hear, followed by a preparation time window. We trained a classifier to discriminate individual elements of the sequence (either individual finger presses during sequence production or individual tones during passive listening) and tested for a parallel representation of those elements during the preparation time window. Preliminary results of this ongoing study reveal a partial, parallel gradient during preparation, indicating that participants were pre-planning sequential movements, and anticipating the sequence of tones, up to the second sequence element. The gradient seems similar across the three conditions, indicating that people may pre-plan sequential action effects similarly to their coupled action. We are currently investigating (a) whether the presence of tones during production (vs. production without tones) has benefits both for motor performance and the Competitive Queueing gradient, and (b) whether parallel planning of either the action or the action effects involves a cross-modal planning of the coupled counterpart, following a cross-decoding approach across conditions.

4-A-2 - What makes some chords hard to play? Exploring the role of muscle synergies, biomechanical and cognitive factors of difficulty

Ali Ghavampour [1], **Shuja Sayyid** [1], **Jonathan Michaels** [1], **Jean-Jacques Orban De Xivry** [2], **J. Andrew Pruszynski** [1], **Joern Diedrichsen** [1]

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Details

Humans possess the ability to learn complex finger configurations (piano chords). Some finger configurations are harder to learn than others, but the underlying reasons remain unclear. We tested different models to explain what makes some configurations more difficult than others. Over 4 days subjects practiced all 242 combinations of finger flexions and extensions around the metacarpal joints (chords), guided by spatial visual cues. They were instructed to produce force patterns simultaneously with all cued fingers and as quickly as possible. We measured performance using reaction time(RT) and mean deviation from a straight force trajectory (MD), which quantifies simultaneity of force production and involuntary finger enslavement. Both measures improved with training. On day 4, all subjects successfully executed all 242 chords, implying there are no hard biomechanical constraints limiting chord execution. We found that RT and MD differed systematically between chords allowing us to estimate the explainable variability in chord difficulty (noise ceiling). To understand the factors underlying these difficulty differences, we built 4 models. In general, chords involving more fingers were harder. So, finger count was included as a baseline term in all models. First model captured the difficulty arising from interpreting the visual cue. This model quantified the number of changes in the spatial visual cue and treated different fingers or directions uniformly: all finger flexion would be 0 change while alternating flexion/extension, 4 changes. The model fully explained RT but did not reach the noise ceiling for MD, indicating that execution quality cannot be fully explained by the cognitive complexity. To capture the difficulty arising from biomechanical factors, the second model had separate terms for each anatomical finger's force directions (flexion/extension) and a term characterizing the interaction of adjacent fingers. This model outperformed the first model for MD (but not for RT), reaching the noise ceiling, showing that execution quality can only be explained by a model incorporating more detailed anatomical information. To test the hypothesis that easy chords use muscle synergies that are in the natural movement repertoire, we collected EMG from hand muscles while subjects performed chords and during a set of daily actions. We asked if chord difficulty related to 1) the magnitude of muscle activity required for chord execution, capturing biomechanical factors, and 2) the probability that this muscle activity pattern (independent of magnitude) occurs during daily actions. Preliminary results suggested that the muscle magnitude model, although very simple surpassed the anatomical-interaction model in predicting MD. Moreover, adding the probability of the pattern on top of the magnitude model explained MD slightly better, indicating that chords maybe easier if they can rely on learned muscle synergies.

4-A-3 - Study of key handwriting characteristics in healthy children and children with neuro-oncological diseases

Alisa Shalamkova [1], **Vsevolod Chernyshev** [2], **Vera Tolchennikova** [3]

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Details

Problem: In Russia in 2021, 619 cases of primary CNS tumors were reported in children aged 0 to 19. Evaluating the success of a child's rehabilitation program is essential, with handwriting dictation being one such exercise. A tool capable of distinguishing between texts written by healthy children and those undergoing treatment will aid doctors in impartially assessing treatment effectiveness and determining a child's ability to return to school. Studies on children with CNS tumors have revealed various challenges, including decreased intelligence, social and communication difficulties, emotional instability, fatigue, and problems with daily tasks, such as writing. Given the critical role of handwriting in learning, objectively assessing handwriting automation is crucial.

Objective: To identify handwriting traits indicating automation level, assess their significance via statistics, and develop a program gauging automation based on key descriptors.

Research methods: Assessment of key characteristics of the data sample, analysis of collected data, construction of graphs, and development of an original software product using machine learning methods; Jupyter Notebook development environment in Python was used.

Sample characteristics: The study involved 23 healthy children (mean age: 11.52, SD: 2.95) and 18 children who had undergone treatment for CNS tumors (mean age: 14.83, SD: 2.09). The child's gender was not considered in this study.

Stimulus material: scans of texts written with a ballpoint pen on an unlined A4 sheet of paper with the text "In the thickets of the South, citrus would live" in vertical orientation.

Results: 3 handwriting characteristics were identified:

1. Width dispersion of letters - coefficient of variation of letter width in the text.

2. Evenness of the 1st line of text, i.e., the ratio of the height of the 1st line to the height of its capital letter.

3. Evenness of the 2nd line of text, i.e., the ratio of the height of the 2nd line to the height of its capital letter.

It was found that the median value of the coefficient of variation (letter dispersion) is higher in diagnosed children (0.21 vs. 0.17) - they have greater variation in the data (0.07 vs 0.05 in healthy children), but on average their letters differ more from each other than those of healthy children.

When assessing the evenness of the 1st and 2nd lines, it was found that the range of data and the interquartile range for diagnosed children in these parameters is higher. Meanwhile, data for healthy children change insignificantly from line to line, whereas children with a diagnosis reduce the interquartile range by the 2nd line of text.

Surprisingly, in children who had CNS tumors, the evenness of the 2nd line was significantly higher than that of the 1st line.

Using classification models, a program was created that determines the degree of handwriting automation based on these features. The accuracy of such a program was 0.92, and the f1-score was 0.91.

4-A-4 - Anticipatory adjustments in reach and grasp: the influence of expected mechanical perturbations

Anna Akbas [1], **Mariusz Furmanek** [2], **Grzegorz Juras** [1], **Mathew Yarossi** [3], **Eugene Tunik** [3]

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Details

The purpose of this study was to investigate whether the anticipation of a mechanical perturbation applied to the arm during a reach-to-grasp movement elicits anticipatory adjustments in the reach and grasp components. Additionally, we aimed to evaluate whether anticipatory adjustments in the upper limb might be global or specific to the direction of the perturbation. Twelve healthy participants performed reach-to-grasp with perturbations randomly applied to their dominant limb. Participants were presented with three types of trials: unperturbed (control), trials perturbed in a predictable manner (either Up or Down), or perturbed in a partially predictable manner (knowledge about the perturbation but not its specific direction). EMG activity of 16 muscles, as well as the kinematics of wrist, thumb, and index finger, were acquired and analyzed. When the perturbation was expected, EMG activity of the *triceps* and *pectoralis major* muscles significantly increased about 50 - 200 ms before the perturbation onset. Peak acceleration of the reach was significantly higher and occurred earlier relative to control trials. Similar adjustments were observed in the grasp kinematics, reflected as significantly shorter time to peak aperture velocity and acceleration, as well as in increased activity of *flexor* and *extensor digitorum* 100 - 200 ms before perturbation onset. In summary, our data demonstrate that knowledge of an upcoming perturbation of reach during reach-to-grasp action triggers anticipatory adjustments not only in the muscles controlling the reach component, but also in those controlling grasp. Furthermore, our data revealed that the preparatory activations were generalized, rather than direction specific.

4-A-5 - Repeated exposure to visuo-motor delays in an interception task: No evidence for dual-adaptation in the temporal domain

Celine Honekamp [1], **Loes Van Dam** [1]

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Details

In interactions with our environment, we constantly adapt our behavior in both spatial and temporal terms. For the spatial domain, existing research has shown that we are efficient in using cues, helping with the adaptation process over repeated exposures to spatial offsets (dual adaptation). However, with modern technology, such as Virtual-Reality (VR), temporal offsets due to system delays become more prevalent and are experienced as visuomotor delays between an action and its visible consequence. Yet, few studies investigated repeated exposure to such delays and a potential occurrence of dual adaptation in the temporal domain. Here we started filling this gap using a VR bubble punching task.

In a VR setup, 14 participants were presented with linearly approaching soap bubbles (30 bubbles, one at a time) which they should intercept by punching them. The participant’s hand was tracked with a controller and shown as a blue sphere in the virtual environment either with or without a 335 ms delay. We analyzed changes in kinematic parameters of the hand movements, such as maximum velocity and its time point relative to bubble start. The resulting perceptual temporal offset between vision and movements was measured with a separate synchronization task. Here, participants tracked a target moving horizontally on a sinusoidal trajectory (5 cycles) without visual feedback of the hand. The temporal offset between hand and target movement in this task is indicative of the current temporal adaption state. Next, participants provided ratings for their senses of ownership and agency over the blue cursor sphere. Together, the three tasks formed one block. Overall, 10 blocks alternated between no delay and delay. All blocks were conducted within one session.

As expected from previous work, the delay overall led to a bigger lead of the hand in the synchronization task and a reduced feelings of ownership and agency. During the bubble punch task, the delay condition initially showed higher maximum velocity and a later timepoint of maximum velocity compared to no delay.

With repeated exposure to delay over blocks, the maximum velocity of the hand decreased and occurred earlier. Furthermore, the feelings of ownership and agency in delay blocks increased over repeated blocks. Interestingly, when looking at the results of the synchronization task, we found an increase of temporal offset for the no delay condition over blocks, converging towards the lead observed in delay blocks. The temporal offset for the delay blocks did not change.

Our results indicate a complex temporal adaptation process in which both the delay and no delay condition may be affected. More importantly, we found no evidence of dual adaptation in the temporal domain in the current paradigm, but a convergence of the temporal adaptation state between the two conditions. This suggests that participants converged on a solution that worked in both conditions without needing to switch behavior.

4-A-6 - Effect of central sensitization and neck pain on acquisition and retention of a forearm force matching tracking task

Hailey Tabbert [1], **Nicholas Antony** [1], **John Srbely** [2], **Paul Yielder** [1], **Bernadette Murphy** [1]

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Details

Neck pain is one of the most common musculoskeletal (MSK) disorders affecting 60% to 80% of adults globally. Chronic MSK pain is defined as persistent pain that lasts beyond the normal tissue healing time, which implies that it is mediated through the spinal cord and supraspinal centers. Central sensitization (CS) is increased responsiveness of nociceptors to normal or subthreshold input, leading to maladaptive plasticity within the spinal cord and higher levels. CS can be induced using a topical capsaicin cream, making it a valuable tool for investigating the underlying mechanisms of chronic MSK pain. Previous research suggests that CS may directly impact the ventral root of the spinal cord or motor unit excitability. Given this, it is likely that CS will impact neural processes involved in motor control and motor acquisition. However, it is unclear how CS influences the ability to learn novel motor skills and how this compares to those with neck pain.

13 right-handed participants aged 22.5 ± 1.73 performed a novel force matching tracking task (FMTT). Following pre-acquisition, controls (n=5, 2F) and NP (n=4, 3F) groups received Lubriderm, and a CS group (n=4, 2F) received 0.075% capsaicin over the C5-C7 dermatome region on the right neck, shoulder, and upper back. After ten minutes, participants completed acquisition and post-acquisition FMTT. Task performance was measured 24 hours later to assess retention. Performance accuracy was measured as absolute error normalized to baseline.

Relative to baseline, there was a significant effect of time, where controls improved by 16.4%, CS by 33% and NP by 29.5% ($p<0.001$) at post-acquisition. At retention, controls improved by 11.8% ($p=0.003$) compared to post-acquisition, while CS ($p=0.72$) and NP ($p=0.15$) showed no significant improvement. Both CS ($p=0.008$) and NP ($p=0.02$), performed significantly better than controls, with no differences shown between the CS and NP group ($p=0.93$).

These preliminary results show that all groups were able to acquire the task, however only controls were able to retain the task as demonstrated by continued improvements in performance from post-acquisition to retention. The NP and CS group outperformed the controls from pre- to post-acquisition, possibly due to the challenge point framework, which delineates an inverted-U relationship between task difficulty and resulting performance. Given the nature of the gripping action required in the FMTT, it is possible that the pain experienced may not directly impact motor acquisition, however it did appear to impact retention. It is of interest that CS and NP participants performed similarly, suggesting that altered performance in NP may be due to CS. This research offers insights into the effects of chronic pain and CS and its influence on skill retention.

4-A-7 - The effect of ethanol on movement and dynamic

Ian Howard [1], **Sylvia Terbeck** [2]

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Details

Ethanol has significant effects on human behaviour and performance, being readily absorbed by the digestive system and distributed throughout the body, affecting the central nervous system by penetrating the blood-brain barrier [1]. The extent of alcohol's impact varies with the consumed quantity and the task requirements [2]. Alcohol affects different brain areas, influencing various aspects of movement control, but the precise quantitative effects on motor tasks, especially on motor learning influenced by alcohol-induced performance decline, are not fully understood. This study investigates how different ethanol levels affect participants' ability to perform a simple dynamic motor learning task.

We recruited participants, randomly assigning them to one of three conditions: a no-alcohol condition, a medium-alcohol level where participants consumed vodka equivalent to 1.2 g/kg body weight (slightly above England's legal driving limit), and a high-alcohol level at 2.4 g/kg. In the no-alcohol condition, participants were given pure lemonade. The alcohol conditions involved mixing beverages with lemonade in a 2:1 ratio. The experiment began 20 minutes post-consumption to allow the alcohol to take effect.

The experiment involved a viscous curl field task using a vBOT manipulandum [3], to assess the impact of alcohol on point-to-point movements and adaptation to new dynamics. Participants made 16 cm centre-out movements towards targets at 0 °, 90 °, 180 °, and 270 °. They also made channel trials to the 0 ° target. The experiment comprised 162 null trials, 466 exposure trials, and 27 washout trials, with the direction of the curl field counterbalanced among participants. To quantify movement performance, we examined movement duration and length and absolute maximum deviation from straight movement. We also estimated predictive compensation in response to the curl field across trials for each condition. Increased movement variability, time, and maximum speed were observed with higher alcohol dosages, yet alcohol intake did not significantly affect dynamic motor learning, as seen in a steady decline in MPE (Maximum Perpendicular Error from a straight trajectory) and curl field compensation over time. These findings suggest further research on more complex tasks is necessary, which could have practical implications for activities like driving a car.

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4-A-8 - Neuroplasticity of finger representations induced by a TMS-based BCI-neurofeedback approach

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Details

Brain computer interfaces (BCIs) based on neurofeedback (NF) and motor imagery (MI) can be used in neurorehabilitation to train motor functions without having to perform overt movements. This is of relevance if motor execution is not possible, e.g. in the early phase after a stroke. However, little is known which neuroplastic changes are induced by such BCI-NF training. Here we used ”finger individuation”, i.e. the selective facilitation of single finger muscles without producing overt movements, as a model to study neuroplasticity induced by BCI-NF training.

We divided 32 healthy volunteers into a NF group and a control group (N=16 per group). The NF group performed four sessions of transcranial magnetic stimulation (TMS)-based NF training. During NF training we instructed participants to imagine moving a cued target finger (thumb, index, or little) to selectively upregulate corticospinal excitability, while downregulating excitability of the other, non-target, fingers. During MI we applied a single TMS pulse over the primary motor cortex using a round coil. This allowed stimulation of the whole hand area of the primary motor cortex, so we could measure motor evoked potentials (MEPs) of the thumb, index, and little finger muscle simultaneously. These MEPs were then used to provide participants finger-specific visual feedback about their corticospinal excitability. We measured MI performance pre and post training using the same task but without providing feedback. To assess whether neural representations elicited by finger-specific MI changed after training, we used 3T fMRI and representational similarity analysis pre and post training. Moreover, to investigate intracortical circuits contributing to MEP modulation, we used TMS paired pulse protocols to measure short intracortical inhibition (SICI) in the index finger muscle while the index finger was either the target or a non-target finger of motor imagery. The control group underwent identical pre and post assessments but did not undergo any TMS-NF training.

Our results confirm that the NF group improved finger-selective modulation of corticospinal excitability following the TMS-NF training sessions. Moreover, TMS-NF training changed neural finger representations such that they became more dissimilar from each other after training compared to the control group. Further, we observed a release of inhibition for the target vs non-target condition. This suggests that a reduction in SICI might contribute to the finger-selective upregulation of corticospinal excitability of the target finger.

These findings show that TMS-NF learning induces neural changes that might be driven by neuroplasticity. This is further supported by the finding that improved performance through TMS-NF training translated to settings without feedback indicating learning effects beyond BCI-NF control. Our results pave the way to apply TMS-NF in neurorehabilitation to aid recovery of fine motor functions.

4-A-9 - Role of DLPFC and SMG in Proprioception and Motor Skill learning: a cTBS study

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Details

Our ability to perceive our limbs in space, or proprioception, is essential for accurate movements. Proprioceptive deficits impair motor capabilities by increasing variability and decreasing accuracy of movement. Although the exact neurological underpinnings of these connections are unknown, several different brain regions are probably involved. The dorsolateral Prefrontal cortex (DLPFC) is one potential option. Improved proprioception and motor performance were associated with increased functional connectivity between the somatosensory cortex and DLPFC when anodal tDCS was used to modulate DLPFC (Stagg et al., 2013). Higher-order proprioceptive information is processed by the posterior parietal cortex (PPC), which serves as an interface between the motor and sensory cortices. Reduced position sense may be linked to diminished PPC function, particularly in the supramarginal gyrus (SMG) (Shabat et al., 2015; Findlater et al., 2016). In this study, we compare how activity in the DLPFC and SMG influences proprioception in relation to the acquisition of motor skills. Participants completed an upper limb motor skill learning task using the Kinarm Endpoint robotic manipulandum before and after the continuous theta burst transcranial magnetic stimulation (cTBS) was applied to inhibit the activity in DLPFC, SMG, or sham. Following a familiarization session, participants are allocated into three experimental groups at random: DLPFC, SMG, and Sham. There will be 24 participants enrolled in each group. For the participants in the DLPFC and SMG groups, subject-specific target locations were identified using anatomical brain scans. In the main session, proprioception, and motor skill (speed-accuracy tradeoff) assessments are performed first to acquire baseline measures (Pre). After that, cTBS over the target region was given and a second round of behavioral assessments was performed (Post 1). Following this another motor skill assessment (Post 2) is flanked between a maze-tracing task for training on motor skills for 40 and 80 trials respectively. An additional set of behavioral measures (Post 2 for proprioception and Post 3 for motor competence) are used to conclude the experiment. Preliminary data (8-10 subjects per group) suggests some worsening of skill immediately after cTBS for the DLPFC and SMG groups. Proprioceptive measures do not show any clear improvement. The sham group shows a steady improvement in movement accuracy across training. The DLPFC group improved more later in training, while the SMG group may learn more slowly as training progresses.

4-A-10 - Examining the impact of acute cardiovascular exercise, declarative practice, and focused-attention meditation on memory consolidation of motor learning

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Details

This study investigates the impact of acute cardiovascular exercise, declarative practice, and focused-attention meditation on the consolidation process of motor learning. Specifically, it examines how these interventions, when applied immediately after the acquisition of motor skills, influence the retention of implicit and explicit components of motor adaptation. Initially, participants completed a practice session to familiarize themselves with the task. This was followed by a baseline block and a 45-degree visuomotor adaptation training block. Following the training, participants were allocated into distinct groups, each undergoing a unique 20-minute intervention. These interventions included acute cardiovascular exercise, declarative practice, focused-attention meditation, a period of rest, or a visuomotor interference training session. To assess the effectiveness of these interventions, memory consolidation was evaluated 4 hours post-training. The results show that compared to those who experienced visuomotor interference, participants in the control and acute cardiovascular exercise groups exhibited enhanced memory retention. Notably, engaging in acute cardiovascular exercise immediately after training significantly boosted the preservation of implicit motor learning. Additional research is scheduled to explore the effects of focused-attention meditation and high-cognitive declarative tasks on this phenomenon.

4-A-11 - The importance of how tools are held when performing motor tasks

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Details

Introduction: When performing some professional know-how, segmental body organisation and, therefore, the resulting posture, can be constrained by contextual elements. In the case of hairdressing, the way scissors are held constrains the hairdresser's posture. The movement variability observed when a task is being performed depends on the interaction of different parameters. These can be intrinsic parameters of the person, such as age or expertise, or extrinsic parameters, i.e. contextual and environmental factors (Gilles and Wild, 2018; Gilles et al., 2022). Modifying how tools are held modifies the contextual parameters and, therefore, the movement itself. When using hairdressing traditional scissors (TS) the thumb and ring finger are each placed in a ring. Their placement imposes an orientation on the hand during the task of hair-cutting. This constraint of the distal segment is transferred to the adjoining upper limb, or even to the entire body. Analyses of hairdressing activity have shown the importance of the upper limb joints solicitations when using TS (Kitzig et al., 2015; Kozak et al., 2019). Ringless scissors ® (RLS) have been proposed as a mean for reducing these solicitations. The objective of the present study was to measure the postural adaptations induced by holding scissors with and without rings, and their effects on movement control when learning to use RLS. Methods: 9 experienced, right-handed hairdressers (30 ± 7 years old) participated. Over 4 successive days, they performed 3 basic haircuts on training heads: massive (MASS), progressive (PROG) and graduated (GRAD) cuts. Each cut was performed with TS then RLS for 6 minutes. Kinematics were recorded using an optoelectronic system (Motion Analysis 200hz). Kruskal Wallis ANOVA and Bonferroni post hoc tests were used to analyse the right wrist, elbow, and shoulder angles. The participants' feedback was recorded by video and their feelings assessed using VAS scales. Results and discussion: The preliminary results (not finalised to date) presented here only concern the 4th day of the study. It was observed that the use of TS places the wrist in extension while RLS align the hand on the forearm longitudinal axis with a decreased shoulder abduction, mainly in PROG. Most participants reported a decrease in pain felt in both their shoulders and the right wrist. Some reported that they experienced difficulties regaining the ability to cut hair with RLS. Conclusions and perspectives: After 4 days of using RLS, holding different scissors modified the postural organization of the upper limb. A new movement needs to be learnt to make the know-how effective again. This new movement seems to have been established over the 4 days of the experiment. Additional analyses are underway to investigate the existing postural variability during the 4 days of learning RLS use and its impact on movement control.

4-A-12 - Top-down processing activates deprived sensory brainstem nuclei following tetraplegia

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Details

Following a spinal cord injury (SCI), individuals experience a partial or complete loss of sensorimotor function below the level of injury. Such sensory deprivation has long been considered a major driving force for plasticity within the brain. However, in apparent contrast to deprivation-driven plasticity, we previously found that tetraplegic patients who lack sensorimotor hand function could activate somatotopic hand representations in the primary somatosensory cortex (S1) through attempted hand movements. This finding suggests that intracortical, i.e., top-down, processes may drive somatotopic activity within S1. While the major relay nuclei of the somatosensory stream classically rely on bottom-up input, research in animals has indicated that they are subject to descending cortical modulation through corticothalamic and corticocuneate projections. To what extent similar top-down processing may activate thalamic and brainstem somatosensory nuclei in humans remains unknown. However, tetraplegic spinal cord injury patients with a partial or complete interruption of ascending sensory input provide a model to study such top-down contributions. Here, we tested 1) whether attempted movements in complete tetraplegic patients, engaging the somatosensory processing stream via a top-down pathway, leads to preserved activation within the ventroposterior lateral (VPL) nuclei of the thalamus and the cuneate nuclei of the brainstem, and 2) whether the amount of preserved activity in tetraplegic patients is correlated with clinical measures of retained sensorimotor function and time since injury. We collected 3T fMRI data from sixteen chronic tetraplegic patients and twenty age-, sex-, and handedness-matched able-bodied control participants. Incomplete tetraplegic and control participants were visually cued to make overt right- and left-hand movements, whereas complete tetraplegic participants performed attempted movements. We found a clear laterality of hand activity in controls, with the highest activation located within the ipsilateral cuneate nucleus, contralateral VPL nucleus, and the contralateral S1 hand cortex. Importantly, this canonical pattern of hand activation was preserved in both complete and incomplete tetraplegic patients, suggesting that top-down processing may drive activation across the somatosensory processing stream. Notably, the amount of preserved activity in patients did not correlate with retained sensorimotor hand function, time since injury, and the amount of preserved spinal cord fibres. Together, our results reveal preserved activation of the hand somatosensory relay nuclei of tetraplegic patients despite absent or only partially intact transmission of bottom-up sensory input. This suggests, for the first time, that mere cortical processing can selectively activate the VPL and cuneate nuclei in humans.

4-A-13 - Subjective processes underlie risk-seeking bias in action timing selection under risk

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Details

Previous studies have reported a preference for risk-seeking motor planning when success and failure are juxtaposed. Here, we investigated the causes of this bias by examining the relationship between subjective risk attitudes (i.e., risk attitudes as perceived by individuals) and objective risk attitudes (i.e., risk sensitivity as assessed by the computational model). A temporal response task under risk was conducted with and without instruction on risk attitudes (Experiments 1-2) and strategies (Experiments 3). In this task, participants were required to respond in their own timing under the gain function in Experiments 1 and 3: gain = 0 if RT < 500 ms or 1500 ms < RT, and gain = 100 - (1500 - RT) / 10 if 500 ‰¤ RT ‰¤ 1500. In Experiment 2, we set three difference gain functions with the same characteristics as Experiments 1 and 3. The task required participants to determine how closely they would try to respond to 1500 ms while considering that although the gain was maximized at exactly 1500 ms, exceeding this time would result in failure (i.e., 0 points). Experiment 1 tested the association between this objective and subjective risk attitudes. For this purpose, participants were required to perform the task with the instruction on the subjective risk-attitudes. We set five levels of risk attitudes from very risk-seeking to very risk-averse in each experimental block, which included 25 trials. Also, we set the free condition to confirm the risk attitudes under free-choice situations. We also collected subjective risk attitudes using visual analog scales before and after each block. Based on Bayesian decision theory, we estimated the optimal aiming RT based on the variability of RT in each participant. Then, we assessed the distortion of the actual RT from the optimal RT as the objective risk attitudes. The association between objective and subjective risk attitudes showed that, in the with-instruction condition, participants performed actions in accordance with the instructed risk attitudes and strategies, indicating their near-optimal computational capacity with respect to risk attitudes. However, in the no-instruction condition, participants exhibited both subjective and objective risk-seeking behaviors. In Experiment 2, to validate these findings, we set three different gain functions, and similar procedures were conducted. We, again, found a well-matched association between subjective and objective risk attitudes, regardless of the differences in gain functions. Also, we consistently found the existence of the risk-seeking bias. In Experiment 3, we investigated the strategic preference underlying the risk-seeking bias. We found that the intention to seek the best performance contributed to the risk-seeking bias in free-choice situations. Overall, our data suggest that the risk-seeking bias is not due to a lack of computational ability related to risk attitudes but to individual strategy and attitude preferences.

4-A-14 - Human somatosensory cortex contributes to the encoding of newly learned movements

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Details

Abstract

Recent studies have indicated somatosensory cortex involvement in motor learning and retention. However, the nature of its contribution is unknown. One possibility is that somatosensory cortex is transiently engaged during movement. Alternatively, there may be durable learning-related changes which would indicate sensory participation in the encoding of learned movements. These possibilities are dissociated by disrupting somatosensory cortex following learning, thus targeting learning-related changes which may have occurred. If changes to somatosensory cortex contribute to retention, which, in effect, means aspects of newly learned movements are encoded there, disruption of this area once learning is complete should lead to an impairment. Participants were trained to make movements while receiving rotated visual feedback. Primary motor cortex (M1) and primary somatosensory cortex (S1) were targeted for continuous theta-burst stimulation (cTBS), while stimulation over occipital cortex served as a control. Retention was assessed using active movement reproduction, or recognition testing, which involved passive movements produced by a robot. Disruption of somatosensory cortex resulted in impaired motor memory in both tests. Suppression of motor cortex had no impact on retention as indicated by comparable retention levels in control and motor cortex conditions. The effects were learning specific. When stimulation was applied to S1 following training with unrotated feedback, movement direction, the main dependent variable, was unaltered. Thus, somatosensory cortex is part of a circuit that contributes to retention, consistent with the idea that aspects of newly learned movements, possibly learning-updated sensory states (new sensory targets) which serve to guide movement, may be encoded there.

4-A-15 - Adaptation in whole body movements

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Details

Humans rapidly adjust their movements to changes in dynamics that occur through either sudden or incremental changes in their surroundings. When faced with changes in dynamics during reaching, large kinematic errors occur. To counteract these unexpected perturbations and stabilize the movement, individuals increase their limb stiffness through co-contraction and tune their feedback responses to the environmental dynamics. Feedback responses are then gradually reduced as feedforward adaptation is tuned to the predictable components of the perturbations. Most studies on human adaptation examine simple planar reaching experiments where only movement of one part of the body is observed. In contrast, the adaptation and corrective mechanisms during whole-body movements, which are more complex due to the risk of falling and the need to maintain postural stability, remain less understood. These tasks require coordinating hundreds of degrees of freedom to keep balance, presenting a significant challenge compared to simpler reaching tasks. It has recently been shown that adaptation to perturbations during a whole-body squat-to-stand movement was similar to the learning of novel dynamics in reaching movements; however, we still do not fully know the extent to which our understanding of motor adaptation based on arm-reaching studies can be applied to whole-body motor control. Here, we examined how humans adapt their movements to changes in the environment in whole-body movement control that reflects a more natural daily setting. Specifically, we focused on how individuals adapt to unfamiliar dynamics while performing movements in an upright stance. Unlike in reaching, adaptation and corrective responses during whole-body motion have hard limits on the corrections that can be performed without losing balance and falling. In the experiment, healthy human participants stood on a force plate, while they controlled a real-time cursor on the screen representing the position of their center of mass. The participants' goal was to navigate the cursor between two targets. During the task, participants experienced systematic forward perturbations delivered by a force-controlled mechanism with a magnitude proportional to the horizontal side-to-side velocity of their movements. Initially, these disturbances led to significant challenges in executing whole-body movements, as evidenced by notable deviations in their COM trajectories. Over time, however, participants demonstrated notable improvements in their movements and a reduction in errors, paralleling observations from arm-reaching studies. Our experimental design, where individuals were perturbed during whole-body motions, allowed us a direct comparison with the arm-reaching paradigm.

4-A-16 - Enhancing co-adaptive myoelectric interfaces with eye tracking

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Details

Neural interfaces have advanced significantly in restoring motor function, yet they face challenges adapting to diverse users and contexts. Co-adaptive interfaces address this via on-line device adaptation to individuals through closed-loop interactions, potentially guiding user adaptation (Orsborn, 2014). However, current adaptive algorithms still rely on explicit knowledge of task structure for supervised training, limiting their generalizability. Prior work shows that eye movements evolve as people learn novel sensory-motor mappings and contain information about movement goals (Sailer, 2005). We therefore hypothesize that eye movements will provide an easily measured readout of user strategy and task goals during adaptive neural interface learning. Achieving this will require deeper insights into how eye movements relate to sensorimotor strategies in neural interfaces. In this study, we investigate eye movements during high-dimensional myoelectric interface control and then leverage this knowledge to enhance personalization and generalizability of interfaces.

We started by investigating how eye movements reflect the change in user internal controllers. Naive subjects controlled an adaptive cursor to follow a target with 64-channel sEMG. Adaptation was achieved through a supervised learning algorithm, incorporating a cost function considering both task error and mapping (decoder) effort (Madduri, 2022). We set out to explore the relationship between eye movements and users' proficiency in managing both the feedforward (intent) and feedback (error correction) aspects of this task during co-adaptation (Yamagami, 2021). Users' feedforward and feedback controllers were disentangled from the adaptive decoder in frequency domain using a control-theoretic estimation method. Findings (N = 7) suggest that eye gaze increasingly aligned with the target compared to the cursor position as users learned the interface and that eye movement patterns were correlated with user intent (feedforward).

We then employed eye movements to train the adaptive interface on-line in a less supervised manner, treating eye gaze as a proxy for the task goal. Results (N = 7) reveal the promise of gaze-based decoder training, with no observable difference in user learning or system performance compared to traditional supervised training based on task information. Preliminary results also suggest the potential for translating this adaptive decoder to other tasks, such as center-out reaching or less structured self-paced tasks like drawing.

Our results show the promise of using eye behavior to update and train adaptive decoder for myoelectric interface learning. Understanding how eye movements evolve as users adapt to novel sensorimotor mapping has the potential to modulate adaptive algorithms to shape user learning. Additionally, using gaze for training the adaptive algorithm holds promise for generalizing future co-adaptive neural interfaces across diverse tasks.

4-A-17 - Mindful movement: the neuromechanical abstraction of gravity is shared between motor and cognitive systems

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Details

Motor control strategies are optimized toward the satisfaction of abstract goals. Movements can be coordinated to control limb length, reach a specific end point target, minimize energy cost, or maximize utility, all of which require some degree of abstraction. To facilitate movement control, a combination of intended action, expected feedback, and actual sensation are used to build an internal representation of the movement and its abstract goals. However, different tasks often solve similar problems to achieve their goals and therefore build internal representations that contain redundant information. For example, most motor tasks must account for gravity, even though it is nearly constant between tasks. While these task representations may remain fully separate from each other, it would be advantageous for them to share gravity information. Therefore, *our Central Aim was to determine if gravity information is shared between different, gravity-dependent tasks.* We hypothesized that information-sharing does occur and tested this by exposing three groups of participants to a physical simulation of hypogravity jumping and then testing different behaviors for aftereffects. **Group 1** performed vertically targeted jumps before, during, and after exposure to simulated hypogravity and we analyzed their jumping performance for aftereffects. We found that after jumping in simulated hypogravity, preactivation (muscle activity just prior to landing) of the plantarflexor muscles was reduced and delayed, indicating an expectation of hypogravity despite a return to normal gravity. **Group 2** followed the same jumping protocol with the addition of vertically targeted arm movements before and after jumping in simulated hypogravity. After jumping in simulated hypogravity, the symmetry of their arm movement was altered, with the peak velocity occurring earlier in the movement. **Group 3** followed the same jumping protocol with the addition of a cognitive task that measured their perception of 'normal' gravity. They were shown a virtual reality space where a ball was dropped with different accelerations and indicated if it fell faster or slower than 'normal', allowing us to generate a psychometric curve to determine the gravity level that they perceived as 'normal'. Preliminary results indicate that faster gravity levels were perceived as more normal after jumping in simulated hypogravity. This result, along with the altered arm movement in Group 2, can be explained by an adaptation to hypogravity occurring during jumping that is used to inform subsequent, unrelated behaviors. Therefore, we conclude that gravity information is shared between different motor and cognitive tasks, despite the tasks using totally different muscle groups (Group 1 vs. Group 2) or no muscle groups at all (Group 3). As such, it appears that abstract aspects of behavior are not represented separately for each task that interacts with them, but instead can be adapted in one task and used in another.

4-A-18 - Impact of a new tool on movement smoothness: application to the hairdressing sector

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Details

French hairdressing sector is associated with a high prevalence of upper limb musculoskeletal disorders (MSDs). These MSDs could be linked to cutting gestures performed with Traditional Scissors (TS). Indeed, their use involves constrained postures that, combined with the repetitiveness of the activity, may contribute to the occurrence of MSDs. One prevention strategy could involve introducing a new working tool, such as RingLess Scissors (RLS), designed to minimize constrained postures. However, their introduction may be hindered by a temporary loss of expertise affecting the quality of gesture execution. Smoothness can be an indicator of the quality of gesture execution and expertise level. Various algorithms exist to measure smoothness, Spectral Arc Length (SPARC). The latter is based on the hypothesis that less smooth movements are more complex in terms of frequency composition. The objective of this study was to assess the effect of introducing a new tool (RLS) and a practice session on movement smoothness. Smoothness was assessed using SPARC, an algorithm based on the frequency content analysis of the velocity profile. The SPARC was calculated on a specific sequence within each cutting cycle, corresponding to the placement of the comb in the left hand until the first scissor cut. Six right-handed hairdressers participated in the experiment (practice level: TS > 3 years; RLS < 2 hours). Three conditions were imposed: use of TS (TS), use of RLS pre-practice (RLS1), and post-practice RLS (RLS2). For each condition, hairdressers performed three cutting gestures (MASS, PROG, GRAD) for 6 minutes on a mannequin head. A 20-minute open practice session was interspersed between RLS1 and RLS2. The kinematics of the hand holding the scissors was recorded using an optoelectronic system. Kruskal-Wallis ANOVA and Bonferroni post hoc tests were used to analyze the effect of the tool and practice on the SPARC. The effect size was determined using Cohen's d. The SPARC yields a negative score, approaching 0, indicating better smoothness. It was significantly lower in RLS1 compared to TS for all three cutting gestures (MASS: -11%, PROG: -5%, GRAD: -4%; $p < 0.05$). Effect sizes (d) were small for PROG and GRAD (0.5 ‰¥ d > 0.2) and moderate for MASS ($d > 0.5$). Regarding the practice effect, an increase in smoothness was observed in RLS2 only for the GRAD cutting gesture (+6%; $p < 0.05$, $d < 0.2$), with smoothness levels similar to TS. RLS introduction appears to result in a decrease in smoothness suggesting a decline in the quality of gesture execution. Since hairdressers had only two hours of RLS usage, the results provided by the SPARC as an indicator of gesture quality seem coherent. Furthermore, for one of the gestures, a 20-minute practice session allowed achieving a level of smoothness similar to that of TS with RLS. It is planned to replicate these analyses when the hairdressers have more experience with RLS.

4-A-19 - Can myoelectric prosthetic hand control and learning be explained by isometric force control and corticomuscular coherence?

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Details

Background: Myoelectric prosthetic hands are notoriously difficult to control, resulting in high rates of device abandonment and dissatisfaction. Difficulties controlling these devices is possibly driven by an impaired ability to generate and control isometric forces, and dysfunctions to the pathways between the cortex and muscle that are known to govern force control. In able-bodied individuals, the precision of isometric force control is positively associated with the strength of beta range (15 - 30 Hz) corticomuscular coherence (CMC) between the sensorimotor cortex (as measured via electroencephalography; EEG) and contracting muscle (as measured via electromyography; EMG). Beta CMC is proposed to reflect the cortical control of motor unit firing via the direct corticospinal pathway (Mima & Hallett, 1999), supporting the upregulation of afferent and efferent signals to promote a stable sensorimotor state (Baker, 2007). Impaired CMC has been observed in stroke patients and other movement disorders, yet it is unclear whether difficulties with force regulation and prosthesis control can also be explained by dysfunctions to CMC. The aim of this study is to establish whether CMC and upper-limb isometric force control can explain how well able-bodied participants can use a myoelectric prosthetic hand simulator.

Methods: Twenty participants will perform a sub-maximal (15% MVC) isometric hand grip task by squeezing a dynamometer with their anatomic hand whilst EEG and EMG (of the forearm) is recorded. This task will be completed both with and without the prosthesis fitted to the arm, to further investigate how the weight of the prosthesis might independently influence measures of force control and CMC, and whether the ability to regulate force under additional load might underpin successful prosthesis control. Participants will then complete a prosthetic hand training protocol, where proficiency will be tested across a range of object transportation tasks.

Expected outcomes: Preliminary findings are anticipated to reveal that individuals with superior isometric force control will exhibit greater beta CMC and demonstrate more proficient prosthesis control. Identifying these behavioural and neural mechanisms of prosthesis control in able-bodied participants may inform strategies to enhance prosthetic control in individuals with upper-limb difference, potentially reducing abandonment rates and improving user satisfaction.

4-A-20 - Athletic training characterizes the activation in human spinal locomotor circuitry

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Details

Bipedal human walking is mediated by spinal locomotor circuitry in the lumbar cord. As transvertebral magnetic stimulation to human lumbar cord is capable of inducing a cyclic alternative leg movement as in walking, it is presumed that spinal magnetic stimulation could activate a neural module involved in the spinal locomotor circuitry to induce walking-like movement. Using the spinal magnetic stimulation technique, here, we demonstrated that rhythmic burst of spinal stimulation can induce the cyclic leg movements with different patterns of left-right leg coordination depending on the stimulus locations and the persons who were conducting daily leg motor training for specific types of motor behavior. In a cross-sectional study, we recruited 37 college sports athletes; long-distance runners (n=10), road cyclists (n=11), weightlifters (n=8), and gymnasts (n=8). The participants were in semi-prone posture on a bed with both legs suspended from the ceiling and received the burst of spinal magnetic stimulation via a closed-loop paradigm while legs were fully relaxed. A 6 by 3 stimulation target grid was arranged over the back that covered 6 intervertebral spaces from Th11 to L5 and ~3 cm left to right from the midline. We classified stimulus-induced cyclic leg movements into 3 types; alternative movement where the left and right legs moved back and forth alternatively. Simultaneous-back movement where bilateral leg moved backward by the stimulation. Simultaneous-fore movement where bilateral leg moved forward by the stimulation. In the runners and cyclists who generally use alternative leg movement in their sports training, the spinal magnetic stimulation induced alternative movements at broader locations than other participant groups. The alternative movements were rarely induced in the weightlifters who frequently perform symmetric bilateral leg muscular contraction in their training. Inversely, in weightlifters, spinal stimulation dominantly induced simultaneous-back movements at broader locations than other groups. Gymnasts, in whom varieties of leg movement repertories are trained, showed to induce the simultaneous-fore movements that were rarely induced in other groups. These finding suggest that neural modules in the human spinal motor circuits involving locomotor behaviours may plastically change their activities by the daily motor training depend on the leg coordination pattern.

4-A-21 - Implicit adaptation determines proprioceptive bias measured by active hand localization

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Details

Motor adaptation refers to how the motor system adjusts its outputs to accommodate environmental or bodily perturbations, but it is often accompanied by perceptual changes. So-called active localization task requires people to reach and report their perceived hand location; motor adaptation biases the perceived location towards the visual perturbation, i.e., creates a proprioceptive bias. Previous studies argue that this proprioceptive bias is jointly determined by a motor mechanism (adapted internal model) and a sensory mechanism (recalibrated proprioception), with the latter playing a predominant role. Using motor adaptation tasks, the present study shows that the proprioceptive bias measured by active localization is nearly completely determined by implicit adaptation, a measure of the adapted internal model.

Experiment 1 measured proprioceptive bias and implicit adaptation in a visuomotor rotation task. The proprioceptive bias was quantified as the difference between the report and actual movement direction in self-generated movement. Implicit adaptation was measured by exclusion trials, where participants moved their hands directly to the target without strategies. The results show that proprioceptive bias amounts to 77% of implicit adaptation. Importantly, a general linear model fitting reveals that implicit adaptation significantly predicts proprioceptive bias within participants, with a slope close to 1. This observation suggests that the proprioceptive bias and implicit adaptation evolve concurrently with a nearly identical speed and amplitude.

Experiment 2 further examined this close resemblance between implicit adaptation and proprioceptive bias by removing possible confounds of explicit learning. We used error-clamped feedback to elicit “pure” implicit adaptation: participants were instructed to reach to a target with a cursor moved concurrently to a “clamped” direction. Participants gradually deviated movements in the opposite direction of the clamped cursor without knowing it. Similar to Experiment 1, proprioceptive bias amounts to 74% of the implicit adaptation, and implicit adaptation significantly predicted proprioceptive bias both within and between participants, with a slope close to 1.

In conclusion, we show that the active proprioceptive bias, measured with self-generated movement, is predominantly determined by the adapted internal model. Sensory mechanism appears to have a minimum effect. While the proprioceptive bias measured by a passively moved limb might be a valid measure for the perceptual consequence of motor adaptation, our findings call for a renewed interpretation of active localization. Furthermore, our findings of active localization indicate that people tend to report their desired hand position, as opposed to their actual position, when they are required to report after the movement. It suggests that efference information dominates when unreliable afference (e.g., proprioception) decays fast.

B – Control of Eye & Head Movement

4-B-22 - Similar gaze-gait interactions during perturbed walking in younger and older adults

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Details

When we walk, we move our gaze to collect visual information - either focusing on aspects which are needed to support gait and gait stability or on aspects which are not gait-related, such as visually exploring the environment. We adaptively weigh and prioritize information according to the situational and individual needs, for instance by lowering our gaze when walking on more difficult terrain. Here we study whether and how the prioritization of information in order to maintain gait stability changes across the lifespan. In 24 younger (aged 20 to 40 years) and 24 older (aged 60 to 80 years) healthy adults, we compare the allocation of gaze during walking under normal and challenging conditions. Participants walked on a split-belt treadmill at 1 m/s through a simple virtual environment along a straight path that was projected on a 240-degree screen and on the floor. Experimental blocks could contain gait perturbations, that is, on average after about every 16th step, the left or the right belt of the treadmill rapidly accelerated upon foot placement, resulting in a backward slip of the foot - which was perceived as if slipping on ice. In one condition, these perturbation events were associated with a visual cue - an approaching patch of ice on the path, that triggered the perturbation when stepped upon. As control conditions, there were blocks with no perturbation, either with or without the ice patches occurring in the visual display.

We used a mobile eye tracker to measure gaze orientation und pupil diameter, and a 3D motion capture system to track participants' gait kinematics as well as their head orientation.

In both age groups, we observed a reduction in gait stability, a lowering of gaze and a pupil dilation when confronted with gait perturbations. Said effects occurred both in immediate response to the perturbation, and - to a smaller extent - also as a longer-term adjustment to the challenging walking condition in perturbation blocks. Visual cues that inform of the occurrence of a gait perturbations were accompanied by anticipatory effects, that is, already prior to the perturbation gaze was lowered, pupils dilated and step width was increased. Even though, we observed typical age-related changes in gait stability in our older participants (e.g., a decrease in step length, an increase in variability of step length and of lateral step position), the effects that perturbations exerted on gait and gaze parameters were largely similar in both age groups.

In sum, we conclude that gaze-gait interactions are tailored to situational demands and that such adaptive processes are - at least in our setting - robust during healthy ageing.

4-B-23 - Interperformer coordination in wind instrument ensembles: relationship between synchronicity of performers' head movements and musical phrase

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Details

Research in the area of non-verbal communication within musical ensembles highlights the importance of bodily movements as visual cues, particularly "ancillary movements'' not essential for playing instruments. These ancillary movements are key for performers to share musical interpretations among performers and provide visual expressions for the audience. Notably, the head movements of musicians during ensemble performances correlate with the musical structure of the pieces they play. However, previous research has primarily examined instruments where head movements are not integral to the performance, such as the piano, leaving a gap in studies on wind instrument ensembles where head motion is crucial.

In our study, we investigate the relationship between head movements of wind instrument ensemble performers and the musical phrase. We used a marker-based optical motion capture system to record performances by three amateur wind instrument ensembles. Each group performed under four different performance conditions: normal, deadpan, immobile, and exaggerated, in a random order. The "normal" condition had musicians playing as usual, the "deadpan" condition had them reduce unnecessary movements and expression, the "immobile" condition kept expression natural but reduced movement, and the "exaggerated" condition increased both movement and expression. We derived velocities by calculating the three-dimensional norms from the displacement data of the markers on the top of the head. In order to elucidate the degree of coordination in head movements among performers in the time-period domain, a cross-wavelet transformation (CWT) analysis was performed. The periods considered in the CWT were set in accordance with the musical phrase of the performed pieces, ranging from one beat to four bars (1 second to 12 seconds). Additionally, the CWT power was computed as a measure of the strength of coordination in head movements. Since a CWT can only be conducted between two time series, it was applied to all pairs of performers within the ensemble (resulting in 6 pairs for ensembles of 4 performers and 3 pairs for ensembles of 3 performers). We then averaged the CWT power values across all pairs at each frequency to obtain the ensemble-wide CWT power.

Our finding showed that mean CWT power peaked at one-bar cycles in four different performance conditions. It was also confirmed that the CWT power under the "normal" condition was greater than that under the “Immobile” and "exaggerated" condition. This finding suggests that coordination at the phrase level is evident among wind instrument players and that such coordination may only be present in a natural state of performance, as it disappeared with exaggerated or immobile performances. Our next step is to conduct similar measurements with professional wind instrument ensembles to verify whether the results observed in this study are replicable among professional performers.

C – Disorders of Motor Control

4-C-25 - Reduced reciprocal inhibition during clinical tests of spasticity is associated with impaired reactive standing balance control in children with cerebral palsy

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Details

Children with cerebral palsy (CP) have balance impairments, but little is known about the relation between joint hyper-resistance, the most common symptom in CP, and balance impairments. Joint hyper-resistance is assessed by rotating the joint of a relaxed patient. Joint rotations also occur when perturbing functional movements. Therefore, joint hyper-resistance might contribute to balance impairments in CP. During standing balance perturbations, increased muscle coactivation is often observed. Recently, we demonstrated that this increased muscle co-activation is not a useful compensation strategy and might therefore be a consequence of reduced reciprocal inhibition. The response to balance perturbations has striking similarities with the response to isolated joint rotations in a relaxed condition. Muscle excitation, attributed to the neural response to stretch, is higher in children with CP than in typically developing (TD) children. In addition, co-activation between the stretched muscle and its antagonist is often observed in children with CP, but not in TD children. Yet, to our knowledge, the relationship between reduced reciprocal inhibition in response to isolated joint rotations and increased muscle coactivation during functional movements has not been studied.
Here, we investigated relationships between altered muscle responses to isolated joint rotations and perturbations of standing balance in children with CP. Twenty children with CP participated in the study. We performed an instrumented spasticity assessment of the plantarflexors followed by a standing balance assessment. During the instrumented spasticity assessment, the ankle was rotated as fast as possible from maximal plantarflexion towards maximal dorsiflexion. Reactive standing balance was perturbed by support-surface backward translations and toe-up rotations. Participants were instructed to maintain balance without stepping. Gastrocnemius, soleus, and tibialis anterior electromyography was measured. We quantified reduced reciprocal inhibition by plantarflexor-dorsiflexor coactivation and the neural response to stretch by average muscle activity. We evaluated the relation between muscle responses to ankle rotation and balance perturbations using linear mixed models.
We found that coactivation during isolated joint rotations and perturbations of standing balance was correlated across participants. The neural response to stretch was not correlated during both measurements. Our results suggest that reduced reciprocal inhibition contributes to altered reactive balance control in children with CP. Muscle coactivation in response to isolated joint rotations in relaxed

patients is attributed to reduced reciprocal inhibition in the spinal cord given the absence of other control processes in this condition. The observed correlations thus suggest that the increased muscle co-activation during standing balance control might at least partially rely in spinal processes.

4-C-26 - EMG-EMG wavelet coherence during 1:1 in-phase coordination in Parkinson's patients

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Details

Parkinson's disease (PD) is a progressive neurodegenerative disorder that affects the quality of life of more than 1.5 million people in the US. Deficits in movement speed, force timing, and force modulation are common in PD. These problems are even more pronounced when producing coordinated actions with the upper limbs. The current experiment was designed to examine the influence of inherent and incidental constraints on the stability characteristics associated with 1:1 in-phase coordination in individuals with PD compared to healthy older adults. Twelve individuals with PD (mean age = 72.5; 6 males) and 12 age and gender matched older adults (mean age = 71.9; 6 males) were required to rhythmically produce a 1:1 in-phase (0 °) coordination pattern using their left and right index fingers. Each participant performed 21, 30 second trials. Muscle activity from the First Dorsal Interosseus (FDI) muscles were recorded using EMG. EMG-EMG coherence between the two EMG signals was calculated using wavelet coherence to examine the synchronization between muscles. Results revealed significant differences in the coherence of EMG signals between the two groups. Specifically, healthy older adults demonstrated higher alpha peak coherence compared to PD patients. Similarly, beta peak coherence was greater in healthy older adults than PD. These findings suggest that healthy older adults exhibit stronger neuromuscular synchronization during isometric finger flexion tasks than PD patients, as indicated by the higher alpha and beta peak coherences. This could reflect differences in motor control strategies or compensatory mechanisms in response to Parkinson's disease pathology. Further investigation is warranted to explore the underlying mechanisms and potential implications for rehabilitation strategies.

4-C-27 - Medication improves movement velocity, reaction time, and movement time but not amplitude or error during memory-guided reaching in Parkinson's disease

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Details

The motor impairments experienced by people with Parkinson's disease (PD) are exacerbated during memory-guided movements. Despite this, the effect of antiparkinson medication on memory-guided

movements has not been fully elucidated. We evaluated the effect of antiparkinson medication on motor control during a memory-guided reaching task with short and long retention delays in participants with PD and compared performance to age-matched healthy control (HC) participants. Thirty-two participants with PD completed the motor section of the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS III). A lower score on the MDS-UPDRS III indicates less severe Parkinson's motor signs and symptoms. These participants also performed a memory-guided reaching task with two retention delays (0.5 s and 5 s) while on and off medication. During the memory-guided reaching task, participants were required to store a target location in memory for either 0.5 or 5 s before being cued to move their finger as quickly as possible toward the remembered target. Thirteen HC participants also completed the MDS-UPDRS III and performed the memory-guided reaching task. As expected, medication significantly decreased the score on the MDS-UPDRS III in people with PD. In the memory-guided reaching task, medication significantly increased movement velocity, decreased movement time, and decreased reaction time toward what was seen in the HC. However, movement amplitude and reaching error were each unaffected by medication. Shorter retention delays increased movement velocity and amplitude, decreased movement time, and decreased error, but increased reaction times in the participants with PD and HC. The effect of retention delay on memory-guided reaching was similar in participants with PD and HC. Together, these results imply that antiparkinson medication may be more effective at altering the neurophysiological mechanisms controlling movement velocity and reaction time compared with other aspects of motor control.

4-C-28 - Deterioration of cognitive aspects of motor control following subthalamic nucleus deep brain stimulation surgery for Parkinson's disease

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Details

After undergoing subthalamic nucleus deep brain stimulation (STN-DBS) surgery, people with Parkinson's disease (PD) frequently experience a beneficial microlesion effect, characterized by an improvement in PD motor signs in the days following surgery. However, a previous study found that surgery had a detrimental effect on a cognitive aspect of motor control, saccade latency, the day following surgery. Although the beneficial effects of surgery on motor function diminish in the months following surgery, the effects on the cognitive aspects of motor control in the months following surgery are unknown. In this preliminary study, we evaluated 9 people with PD approximately 1 month pre-surgery while OFF medication and about 8 months post-surgery while OFF medication and OFF STN-DBS treatment. Participants were withdrawn from medication overnight for at least 12 hours and STN-DBS for at least 3 hours. We examined two cognitive aspects of motor control, saccade latency and reach reaction time (RT), during a visually-guided reaching task. This task involved participants focusing on a central fixation point until a target appeared, cueing the participant to look at and reach towards the peripheral rightward target. We examined pre- to post-surgical differences using linear mixed-effect regression models with time as the fixed effect and participant as the random effect. We found a significant detrimental effect on both saccade latency and reach RT post-surgery. Of particular interest is the notable magnitude of this detrimental effect, with saccade latency increasing by 38% and reach RT increasing by 20% post-surgery. Meanwhile, there were no significant differences in OFF treatment Movement Disorder Society-Unified Parkinson's Disease Rating Scale (MDS-UPDRS) Part III motor scores between pre- and post-surgery. We suggest that the detrimental effect on these cognitive aspects of movement may be attributed to long-term tissue changes after lead implantation and/or neural changes after the withdrawal of chronic STN-DBS.

4-C-29 - Tool-use planning deficits in limb apraxia are amplified when tool and hand movements are misaligned

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Details

Tool use is a complex motor control problem requiring the appropriate manipulation of an object to achieve a given outcome. While the exact processes involved in planning and controlling tool-use actions are unclear, much insight can be gained from studying individuals with limb apraxia. Limb apraxia is a neurological condition often observed following left-hemisphere stroke that specifically impairs the ability to use tools without concomitant lower-level (e.g., strength, dexterity) motor impairments. Such deficits arise from damage to a specific left hemisphere "tool-use" or "praxis" network, and can be observed even on the ipsilesional side. These individuals may exhibit impairments in demonstrating the use of both familiar and novel tools, but in contrast have little difficulty with tasks like using a computer mouse or pointing with a stick. We hypothesized that a critical factor that makes tool-use challenging for individuals with limb apraxia is the degree to which people must plan the movements of both their hand and the tool end-effector (i.e., in cases where motion of the hand and that of the tool are misaligned). To test this, we created a set of novel tools that varied along two parameters. First, we varied the correspondence between the motion of the hand and the motion of the tool end to be either congruent or anti-congruent. For congruent tools both the tool-tip and the hand move in the same direction, like for a pair of pliers that close when the hand closes. In contrast, for anti-congruent tools, the tool-tip and hand move in opposite directions, like when the hand pushes down on a carjack lever to raise the car. Second, we varied whether the tool-tip was in line with or laterally displaced from the hand holding the tool. We asked a group of patients with chronic left-hemisphere stroke and neurotypical controls to use these tools to push a puck into a goal while we recorded movement kinematics. Patients with left-hemisphere stroke also completed a series of background assessments, enabling quantification of apraxia severity. We found that across all tools, apraxia severity correlated with slower reaction times and reach-to-grasp times. In particular, individuals with apraxia were slower to reach for anti-congruent and laterally-displaced tools compared to their congruent or non-displaced counterparts, possibly reflecting interference from online planning about how to use the tool. We also observed that despite repeated exposure to the tools, individuals with apraxia were slower to exhibit improvements in tool use relative to non-apraxic individuals. Together, these findings suggest that apraxia impacts planning of tool use particularly when the motion of the hand and that of the tool-tip are misaligned. Thus, the left hemisphere tool-use (praxis) network may be particularly critical when the mapping between hand and tool movements is complex and novel.

4-C-30 - Neural decoding of locomotor states from deep brain electrodes to support closed-loop therapies for gait in Parkinson's patients

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Details

Every year, millions of patients with Parkinson's disease (PD) receive a deep brain stimulation (DBS) implant in the subthalamic nucleus (STN) to alleviate motor symptoms that become unmanageable with dopaminergic medication. Despite these advanced therapies, a big number of patients still endure disturbances of gait and balance, including postural instability, festination, or freezing of gait, that are refractory to all existing treatments. Many patients often suffer falls in daily life, require personal assistance, and in cases remain wheelchair-bound.

Here, we introduce our current developments using the last-generation DBS implantable neuro-stimulators to (i) study the principles through which the STN encodes locomotor function and dysfunction under different therapeutic conditions, and (ii) to prototype neural decoding algorithms that predict gait states and deficits in daily life conditions. These combined efforts are pivotal to ensure that algorithmic developments are robust to the fluctuations arising over the course of the day.

First, we thoroughly characterize the changes induced by LDopa and DBS on gait biomarkers, across a variety of locomotor tasks of daily life. Tasks are repeated at various time-intervals after medication intake and post DBS activation, making it possible to capture the dynamic behaviour of STN changes over time for each patient. Second, we leverage this understanding to design a modular decoding framework that can cope with time-related changes in the condition of patients over the course of the day.

Considering the large number of patients treated worldwide with DBS implants, as well as the capabilities of newest commercial stimulators, our work pave the way for the possibility of controlling the stimulation in closed-loop neuromodulation therapies that address gait deficits in everyday life conditions.

4-C-31 - Comparison of frequency content under different deep brain stimulation states and setting patterns during continuous motor task

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Details

Deep brain stimulation (DBS) is a surgical procedure for implanting stereoelectroencephalography (sEEG) leads into a target brain area to deliver electrical pulses with different patterns to treat movement disorders such as dystonia and Parkinson's disease. Even though the underlying mechanism

is still unknown, current clinical treatment results show intermittent DBS (iDBS) can generate similar results to continuous DBS (cDBS) on some pediatric patients with dystonia based on standard clinic movement tests. Previous studies show that for dystonic patients, surface electromyography (EMG) of upper limb muscles contains the frequencies of the cyclic motion during the performance of a continuous motor task with these muscles. These “task-related” frequencies are well-resolved in intracranial motor control structures such as the basal ganglia, thalamus, and pedunculopontine nucleus (PPN) during intracranial continuous stimulation, which changes with different DBS settings. A possible mechanism of dystonia is reduced inhibition of involuntary muscle activity, indicating that there may be an external motor component combined with the desired movement. We hypothesize that compared with off-stimulation, the features of these “task-related” frequencies will become more centered while intracranial stimulation is turned on as either iDBS or cDBS with the same pulse frequency; meanwhile, “task-unrelated” frequency content still shows a difference based on DBS pattern settings between cDBS and iDBS even though both show positive therapeutic effects.

As part of the previously described procedure for DBS implantation for children with dystonia, we temporarily implanted AdTech MM16C depth leads into multiple targets - such as basal ganglia, thalamus, and PPN - to enable stimulation and to record the local brain signals. The subject was asked to perform 20 trials of motor tasks with both hands under multiple stimulation states and settings while recording kinematic trajectories, intracranial data, and EMG signals. Results show that both iDBS and cDBS may enhance "task-related" frequency components and decreases wide-band "task-unrelated" content with different frequency characteristics compared with off-stimulation. Meanwhile, kinematic trajectories also show different performances with different DBS stimulation states and patterns. These results may help further understand the mechanisms of DBS and their treatment results for movement disorders like dystonia. In addition, these results may also help to explain the mechanisms of why iDBS can generate similar treatment results as cDBS for some pediatric patients.

4-C-32 - Neurophysiology vs neuroanatomy of deep brain stimulation in Parkinson’s disease

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Details

Parkinson’s Disease (PD) is a progressive movement disorder, where motor symptoms in the advanced stages of which are typically managed using deep brain stimulation (DBS). DBS parameters are determined by trained clinicians though extensive open-loop programming sessions. Those parameters change the neuroanatomical target of the stimulation by changing the overlap of the volume of tissue activated (VTA) by the stimulation with target nuclei. Neural recording during DBS (LFP recordings from the DBS electrode and EEG recordings) have shown the sensitivity of neural oscillations, in the cortex and in the Basal Ganglia, to the change in stimulation. Specifically, activity in the beta band (12-35Hz) was shown to be enhanced in PD patients and decreased by DBS. While both neuroanatomical and neurophysiological aspects of DBS were studied intensively, they were not being studied in conjunction hence there is a limited understanding of their relationships and interactions. Exploring these relationships can improve our understanding of the network effects of DBS and increase the accuracy of DBS optimization. The aim of this study was to determine the role of active electrode location, and corresponding overlap of the VTA with target nuclei, on cortical oscillatory activity during changes in DBS settings in Parkinson’s disease patients.

Cortical recordings were obtained with mobile EEG during routine DBS parameter adjustment visits in the clinic. Arm tasks were used by the clinician to determine the efficacy of the DBS settings. From these task periods, aperiodic and periodic spectral features, as well as band-related bursting features (amplitude, duration, and rate), were extrapolated for the beta band. To obtain the volume of overlap corresponding to the DBS settings, leads were localized by merging pre-operative MRI and post-operative CT scans in LEAD-DBS (Horn & Kuhn 2015 NeuroImage). The location of the active electrodes was identified and VTA overlap was calculated with the corresponding nucleus. Following the extraction of these physiomarkers, the delta between them for each pair of DBS settings was calculated.

Typically, active contacts were found either near the subthalamic nucleus (STN) or the globus pallidus interna (GPi). While stimulating the STN, increase in overlap correlated with a decrease in beta burst amplitude and duration which was in line with expectations. This was incongruent with GPi stimulation, where increase in overlap was associated with increase in beta burst amplitude. Moreover, relationships between periodic and aperiodic features were investigated and showed different trends depending on stimulation location. We further demonstrate how neurophysiological response to DBS changes when small changes in the location of the active electrode change the nucleus being primarily stimulated.

D – Fundamentals of Motor Control

4-D-33 - The impact of handedness on the Fitts' relationship during imagined and perceived movements

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Details

Humans have the capacity to engage in a diverse array of actions that can also be imagined or perceived. Typically, actions executed with the dominant hand are carried out with greater speed and precision compared to those performed with the non-dominant hand. This study investigates whether the Fitts relationship varies across the two hands when actions are executed, imagined, or perceived. Given the frequency of actions performed with the dominant hand, it is hypothesized that imagination and perception with the dominant hand may be more precise than those of the non-dominant hand. Right-handed participants were instructed to execute and imagine reciprocal aiming movements between two targets with varying widths and amplitudes that created 3 different movement index of difficulties. Additionally, they were presented with images depicting these movements at different apparent movement times and asked to subjectively state if the observed movements were possible to perform accurately at those intervals. Eye movements were also recorded to investigate how the expression of eye movements during imagination compares with execution of the task and if they are modulated by hand dominance. Results demonstrated that the Fitts relationship is present across all tasks, regardless of the hand used to perform each task suggesting the existence of a common coding network underlying action execution, imagination, and perception. Movement times were lower for the right-hand compared to the left-hand when movements were executed, as well as

perceived, where the shortest perceived and executed movement times were longer for the left-hand than the right. Interestingly, during imagination, movement times were not different across hands. Overall, dominant hand advantages were seen in execution and perception, but not in action imagination indicates that imagination involves higher-order cognition and that the mechanisms involved in action imagination may be effector independent. This conclusion is further supported when manual asymmetries with hand differences did emerge with execution and perception as dominant hand likely uses a more efficient force planning and feedback control. Moreover, perception emerged to be more consistent with execution despite judgment and decision-making being more demanding cognitive task, as online visual information about the movements from the execution task can be used to calibrate perceptual estimates. While the movement time results are insightful, additional data will be presented once the eye-movement analysis is completed which may reveal motor planning differences between imagination and execution across the hands.

Poster Cluster (4-D-34 and 4-E-35)

4-D-34 - Different motor unit control schemes between two lower limb muscles

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Details

During movement, the dimensionality of the control space is reduced by the projection of common excitatory inputs to groups of motor units. In this way, there is a long-held belief that all motor units from the same muscle compartment (i.e. motor pool) receive the same inputs. This organisation would impose a rigid control of motor units, constrained by the size principle. However, this view has been challenged by recent studies reporting deviations from rigid control in arm muscles (Marshall *et al.*, 2022). Applying a factor analysis to motor units innervating anatomically defined synergist muscles from the thigh, Del Vecchio *et al.* (2023) observed that the activity of motor units from the same muscle were not necessarily correlated with the same latent component.

In our study, we investigated the dimensionality of inputs to motor units from two muscles of the lower limb, the vastus lateralis (VL) and the gastrocnemius medialis (GM) muscle. Participants performed either isometric plantarflexion (n=6) or knee extension tasks (n=7) at 20% of their maximal voluntary contraction while electromyographic (EMG) signals were recorded using four grids of 64 surface electrodes (total of 256 electrodes). We used a source-separation algorithm to decompose the EMG signals into motor unit discharge times. Using our electrodes configuration, we were able to decode 41.6 ±19.5 (range: 15-66) unique motor units per participant for GM and 47.1 ±8.8 (range: 35-59) unique motor units per participant for VL.

We first performed a factor analysis on the motor unit discharge rates to estimate the number of the latent components explaining most of motor units' behaviour. Specifically, we identified the maximum number of components above which any additional component did not improve the explained variance more than what would be expected from fitting random noise (Cheung *et al.* 2009). Using this criterion, we identified three latent components for the VL muscle, and only one latent component for the GM muscle (in five out of six participants).

Then, we used variational autoencoders to probe if the VL's apparent multidimensional control space could be in fact unidimensional, with a single latent input and non-linear motoneurons input-output functions. We found that when the linearity constraint is removed, one latent component explains the VL's motor units' behaviour better than the linear combination of three latent components.

Solely considering the results from factor analysis would imply that the dimensionality of the control space varies across the two muscles of the lower limb. However, results from variational autoencoders rather suggest that heterogenous input modulation at the level of the spinal cord would impact the linearity of the transformation of synaptic inputs into motor unit discharge rates. Likely candidates for this phenomenon would be Renshaw cells and neuromodulatory inputs to motor neurons.

4-E-35 - The volitional control of individual motor units is constrained within low-dimensional manifolds by common inputs

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Details

The implementation of low-dimensional movement control by the central nervous system has been debated for decades. In this study, we investigated the dimensionality of control signals received by spinal motor neurons in controlling one degree of freedom of either the ankle or knee joint. We hypothesized that the central nervous system would mainly adopt a rigid control of motor units; specifically, that the motor units active during these tasks would belong to a small number of synergies, each receiving common descending inputs. This hypothesis was tested using torque-matched isometric contractions, as well as with an operant-conditioning paradigm, where the firing activities of pairs of motor units were provided as visual feedback to the participants. The motor units of the gastrocnemius lateralis could be controlled largely independently from those of the gastrocnemius medialis during ankle plantarflexion. This dissociation of motor unit activity imposed similar behavior to the motor units that were not displayed in the feedback, leading to a two-dimensional control manifold, where each dimension represented a “synergistic” muscle. It was not possible to independently control the motor units within the gastrocnemius medialis muscle. During knee extension tasks, it was not possible to dissociate the activity of the motor units between the vastus lateralis and medialis muscles, which thus belonged to a one-dimensional manifold. Overall, individual motor units were never controlled independently of all others but rather belonged to synergistic groups. These results provide evidence for a synergistic low-dimensional control of motor units constrained by common inputs spanning one or more muscles.

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Poster Cluster (4-D-36 to 4-D-38)

4-D-36 - Bayesian inference as a framework for the sense of agency

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Details

The sense of agency, which is the attribution of an action and its outcome to oneself versus outside causes like other agents, is crucial for interacting with the world.
It relies on predictions about the sensory consequences of our own actions based on motor representations, so-called reafference or forward-model mechanisms.
These mechanisms help the organism to distinguish self-generated sensory signals from those sensory signals that are triggered by external stimulation.
Changes to our bodies and within our environments require constant adaptation of behavior, even without awareness.
However, it is poorly understood how a stable sense of agency is generated and maintained within such an ever-changing environment.

In this study, we propose to utilize a Bayesian observer model that quantifies sensory observations of oneself and another agent as likelihoods, to explain the formation of sense of agency within the logic of Bayesian inference.
More specifically, we sought to relate sensorimotor performance in goal-directed reaching movements to the model's likelihood parameters for self versus other.

To this end, participants (n=25) performed goal-directed movements to hit a puck towards a target within a virtual air hockey game, in which their actions could be perturbed by another simulated agent.
In different phases of the experiment, participants were either asked to hit specific targets, predict the action outcomes of themselves or the other agent, or to provide agency judgments along with confidence ratings of their judgments.

Preliminary results show the sense of agency to depend on the observed action outcomes: In the absence of perturbations by the other agent, participants considered themselves to be the agent of the observed action with high confidence.
Both self-agency judgments and confidence ratings diminish with increasing perturbation magnitude.
The Bayesian observer model correctly predicts 82.5% (SD 4.8%) of the agency judgments of participants supporting Bayesian inference as a viable theoretical framework to explain the formation of a stable sense of agency in a highly dynamic and ever-changing world.

4-D-37 - Prior belief in another agent directly decreases our sense of agency

Raz Leib [1], **Niklas Heimburger** [1], **Sae Franklin** [1], **David Franklin** [1]

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Details

The sense of agency originates from the ability of the individual to discriminate between self-made and other-made actions based on the outflow of motor commands and the inflow of sensory feedback. Given a certain outcome, we need to combine multiple aspects of movements and consequences to understand whether we are responsible for the outcome. Specifically, self-agency is formed when the observed outcome matches our actions and the high belief that the agent responsible for the outcome is us. This formalization suggests a Bayesian-based inference that is the basis for self-agency.

Although the idea of Bayesian inference as the basis for the sense of agency was suggested in the past to account for mental illnesses such as schizophrenia, there is only limited and indirect evidence for the validity of this model in healthy individuals. Here, we aimed to change the sense of agency by directly changing the prior belief in the acting agent. That is, we caused participants to believe that they were performing actions in the presence of another acting agent to test how this belief changed the ability of participants to claim ownership of the action's outcome. To do so, participants played a virtual game similar to shooting an arrow using a bow. After the basic game in which participants familiarized themselves with the system's dynamics, they observed a second virtual player that was consistently biased to undershoot the target. This was followed by a joint game between the participant and the virtual player. The arrow hit position was calculated as an average between the two players' shots. In this case, the participants had to compensate for the virtual player undershoot. During the joint game, we displayed the presence of the virtual player on the screen so participants could adjust their motor plan. Following this conditioning of the prior belief in the presence of the virtual player, we changed the effect of the virtual player on the arrow trajectory. Instead of setting the hit position of the arrow as an average with equal weights between the two players' shots, we used a weighted average with different weights between the players. We found that when the indication of the virtual player was displayed on the screen, participants had a higher probability of reporting that the arrow motion was affected by the virtual player, even in cases where this contribution was zero or not detectable before the prior conditioning. These results show the direct effect of elevated prior belief in other-agent actions on the sense of agency. The prior conditioning effect provides more evidence against a comparator model (such as a forward model) for forming self-agency since such a model is based solely on comparing actions and outcomes without accounting for past experiences. Further testing this effect and how the prior belief is shaped can help to understand how the sense of agency is formed and whether Bayesian integration-based models can explain this process.

4-D-38 - A modified Bayesian integration framework for the sense of agency

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Details

Hearing a crash while parking a car often comes with the feeling of fear about the amount of damage caused. However, if no damage is observed, we often wonder whether we were responsible for the crashing sound. In this case, our sense of agency, that is, the belief that we are responsible for any movements and changes in our body and environment, can change to the belief that someone else is responsible for the crashing sounds.

Forming the sense of agency is believed to follow a Bayesian integration framework. During interaction with the environment, humans consider prior beliefs regarding the acting agent and integrate this information with the likelihood that they are responsible for the observed outcome. While this framework can explain some aspects of self-agency, it does not consider different factors that can affect agency judgment. For example, when humans collaborate with others on a task where a reward is given based on a team effort and not individual performance, they tend to attribute successful outcomes to their acts and contributions, while less successful outcomes are attributed to other acting agents. In such a case, the Bayesian integration framework needs to be modified.

To explore how success or failure affects the integration between prior belief and observations, we designed a collaborative reaching task between a human player and a virtual player. In this task, both players simultaneously performed a blind reaching movement to a target displayed on a screen and stopped as close as possible to the center of the target. After returning to their start positions, one of the landing positions was displayed, that is, either the landing position of the human player or the virtual player. We rewarded the players with points based on the distance between the displayed landing position and the target's center. Following this reward display, we asked the participants whether they believed the displayed position resulted from their own or their virtual partner's movement. We found that in cases of both human player movement and virtual player movement, high points rewards triggered participants to claim ownership of the displayed movement. When the movement was inaccurate and less rewarding, participants tended to attribute the movement to the virtual player. These results suggest that despite having similar prior beliefs and sensory observations when comparing movements, the reward factor can also affect the sense of agency. We propose that this factor should be integrated into the idea of Bayesian inference as the basis for the sense of agency.

4-D-39 - Optogenetic manipulation of peripheral sensory nerve activity: facilitation and suppression through ChR2 and eNpHR3.0

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Details

Peripheral sensory nerve activity is integral in conveying sensory experiences to the central nervous system. Dysregulation of these nerves is a hallmark of various sensory disorders. Traditional treatments for manipulating nerve activity, such as pharmacological and electrical interventions, often lack specificity and may introduce adverse effects. In contrast, the advent of optogenetics, a neuromodulation technology using light-sensitive proteins, could offer an alternative solution with unprecedented temporal and spatial precision. Here, we investigated the potential of optogenetic techniques to manipulate the activity of peripheral sensory nerves, specifically targeting large-diameter afferents associated with tactile and proprioceptive sensations, vital for movement control.
Using adeno-associated virus serotype 9 (AAV9) vectors, we selectively transduced the excitatory (Channelrhodopsin: ChR2) and inhibitory (Halorhodopsin: eNpHR3.0) opsins into large-diameter afferents of the sciatic nerve in rats. Diverging from traditional dorsal root ganglion (DRG) approaches, we applied optical stimulation at the distal part of the afferent nerve. The intensity of optical stimulation varied to modulate the extent of facilitation and suppression of the afferent activity, and the influence of optical stimulation was evaluated by the activities recorded from the dorsal root of the same

afferents. Our findings show successful facilitation and suppression of activities in large-diameter afferents via optical nerve stimulation. By increasing the intensity of optical stimulation, the activity of fast-conducting afferent fibers was preferentially elicited or inhibited in an intensity-dependent manner. This result indicates the feasibility of finely manipulating sensory signals in these fibers using optogenetic approaches.
Furthermore, we extended this approach to nonhuman primates whose cellular tropism for AAV differs from that of rodents (Kudo et al., 2021). We found that intravenous injection of the AAV9 capsid variant (AAV-PHP.B) selectively transduced ChR2 and eNpHR3.0 into large-diameter afferents of the forelimb nerves in common marmosets. Using the same method as in rats, we demonstrated that optical nerve stimulation successfully elicited and inhibited activity in large-diameter afferents in marmosets. This innovative method for manipulating specific sensory modalities at the nerve level offers a more targeted and accessible alternative to traditional DRG stimulation, expanding the therapeutic scope in treating sensory disorders.

4-D-40 - Sequential planning is not always associated with a reaction time cost

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Details

Introduction

In daily life, individuals perform various movements, many of which contain a sequence of actions that need to be done swiftly and accurately. One important behavioral finding in the context of sequential actions is that reaction time (RT) - the time from the go-cue to sequence initiation - increases when more sequence elements are cued. This RT increase is often taken as evidence that people plan multiple elements of the sequence before initiating the first movement. Here we show that this RT increase largely reflects the complexity of identifying sequence order and that planning multiple sequence elements can happen with no RT cost if sequence order is cued spatially.

Methods

We designed two continuous sequential reaching experiments that manipulated the complexity of identifying sequence order. In both experiments, participants (N=9, 3f) executed sequences of five fixed-length reaches to visual targets and the location of targets was selected from a multi-layer hexagonal grid of circular targets. We varied the number of targets (horizon = 1 to 3) displayed on the screen during each trial, allowing participants to potentially plan multiple elements before initiation. Sequence order was indicated via target brightness. In our first experiment, initial targets were arranged to be equally distant from the home target, meaning that participants had to use their brightness to resolve sequence order. In our second experiment, there was a spatial affordance such that target locations were informative about the sequence order.

Results

In our first experiment, RT increased as a function of the horizon, consistent with the idea that multiple sequence elements are planned prior to movement initiation. In our second experiment, RT did not increase as a function of the horizon, suggesting that only the first movement was planned prior to initiation. However, first-reach kinematics were predictive of the future target locations from movement onset, indicating that future targets were taken into account when preparing the first reach. Moreover, the inter-target intervals (ITIs) - the duration from capturing one target to the next - decreased with horizon in both experiments, indicating that people planned multiple sequence elements in both experiments.

Conclusion

Our study shows that multiple sequence elements can be planned before movement initiation with or without RT cost, suggesting that increasing RT is associated with determining sequence order rather than planning multiple movements. Further studies are needed to determine how the brain can resolve sequence order with no reaction time cost for spatially cued sequence elements.

4-D-41 - Partial interference between adaptive and flexible control policies indicates shared neural mechanisms

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Details

Current theories have shown that humans can rapidly respond to changes in task parameters, including changes in target structure and velocity-dependent force fields (FF). These mechanisms are at play on very rapid timescales, within an ongoing movement, but do they recruit similar neural structures? We conducted three experiments to investigate this question. These experiments involved in total 52 participants aged between 19 and 36 years. The first experiment applied only sudden changes in target shape, such as a switch from a rectangular shape to a square or vice versa, to elicit flexible changes in control policy. In the second experiment, participants were exposed to a velocity-dependent FF in addition to the target switch. In these two first experiments, step-load perturbations to the right or left (about 1/3 of trials each) were applied. The last experiment was a standard motor adaptation task in which participants adapted to the same velocity-dependent FF as in the second experiment but without target change. The two first experiments were compared to highlight the influence of the FF on participants' ability to flexibly react to a change in target. When participants were exposed to both FF and target switches, their movement endpoints were less eccentric on the rectangular target when their hand was perturbed. A reduction in variance at the end of movement was also observed in the same condition. This means that participants made an unnecessary correction towards the centre of the rectangle in the presence of the FF. The second and third experiments were used to see the influence of flexible control (mechanical perturbation and target change during movement) on participants' ability to adapt to the FF. By analysing the evolution of maximal deviation across trials, we showed that the extent of adaptation was affected when participants reacted to mechanical and visual perturbations during movement. Confidence intervals obtained on the parameters of fitted learning curves showed that the extent of adaptation was reduced when they faced both target switches and force field (final asymptotes of 1.76 (standard FF) and 2.51cm with no overlap of the 95% Highest Density Interval), while participants were able to adapt at comparable rates (overlap of the 95% Highest Density Interval). This last result indicated that when responding to changes in environmental dynamics, the recruitment of flexible feedback responses to external loads reduced the ability of participants to compensate for the force field dynamics. These results suggest that there is some interference between the neural mechanisms responsible for motor adaptation and those supporting rapid and flexible feedback control.

4-D-42 - Assessing inter-subject variability in repetitive motion: canonical and idiosyncratic components of gait in healthy and pathological subjects

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Details

Inter-individual variability, i.e., the idiosyncratic manner in which a person responds to a stimulus or performs an action, plays a pivotal role in fields such as medicine. Due to the inherent complexity of the human body, every one of us expresses a unique perceptual-motor style on top of some more globally shared features across even the most mundane tasks. Assessing these elusive discrepancies between individuals may help with the early diagnosis of pathologies that impair the motor system and tailor personalized medical approaches.
In this work, we propose a novel unsupervised mathematical framework for the study of inter-individual differences in repetitive movements. Our algorithm builds upon the traditional convolutional dictionary learning methodology and extends it to search for personalized patterns. In other words, our technique finds all occurrences of a motif of interest in a signal and decomposes it into a common motif, i.e., the most recurrent shape in a dataset, and a personalized motif, i.e., idiosyncratic variations around the common motif.
After validating our method on a synthetic dataset, we show how it can be applied to the study of gait. Sixty participants were asked to conduct a specific sequence of movements while wearing an inertial measurement unit on their foot: standing still, walking ten meters, turning around, and walking back. Twenty healthy controls were tested against twenty patients with neurological pathologies (hemispheric stroke, Parkinson’s disease, toxic peripheral neuropathy, and radiation-induced leukoencephalopathy), and twenty patients with orthopedic pathologies (lower limb osteoarthrosis and cruciate ligament injury). Our algorithm detects gait-related patterns in the signal and provides a visual representation that highlights the inter-group variability in the characteristics of foot movement.
Overall, our results suggest that the rich variety of possible fluctuations during the course of a movement can offer valuable insights into a person’s condition. We believe that embracing this diversity will enhance the robustness and generalizability of research findings, ultimately paving the way toward more effective and tailored solutions in medicine, behavioral sciences, ecology, and engineering.

4-D-43 - EMG-EMG coherence of muscle coupling during bimanual coordination: age-associated differences and the effect of visual feedback

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Details

Research suggests that older adults may have more difficulty inhibiting or compensating for neural crosstalk that is dispatched to homologous muscles in the contralateral limb during bimanual coordination tasks than young healthy adults. The current experiment was designed to determine age-associated differences in the level of interference observed from the forces generated in one limb on the forces exhibited by the contralateral limb during a bimanual force production task. Ten older adults (mean age = 70.8 yrs.) and 10 young adults (mean age = 21.3 yrs.) were required to produce a dynamic pattern of force with either the dominant or non-dominant index finger while the contralateral effector produced a constant isometric force. Each trial was 20 s and visual feedback was removed from the limb producing the constant force after 10 s. Muscle activity from the right and left first dorsal interosseous (FDI) muscles were recorded. Mean force and root mean square error (RMSE) of force were used to evaluate accuracy and stability of each limb independently. Time series cross correlations between each limb were calculated to determine the influences of the forces generated in one limb on the forces produced by the contralateral limb. In addition, EMG-EMG coherence between the two EMG signals was calculated using wavelet coherence to provide a more comprehensive understanding of bimanual control and to probe the underlying mechanisms that may account for performance differences between the two age groups. As expected, the mean force and RMSE was greater for older than younger adults. Results also indicated positive time series cross correlations for both groups when visual feedback was removed from the dominant limb. Positive time series cross correlations indicate that as forces increase and decrease in one limb similar increases and decreases occur in the contralateral limb. However, when visual feedback was removed from the non-dominant limb less interference was observed in the contralateral limb for young but not for the older group. In addition, results indicated age-associated differences in average EMG-EMG coherence in the alpha (5-13 Hz) and beta (13-30 Hz) bands. Findings suggest that both subcortical and cortical influences may account for age-associated decrements in the bimanual control of force.

4-D-44 - Towards the study of cortico-striatal interactions underlying sensorimotor integration

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Details

The collective activity of neural populations within a specific brain area can be well captured by a relatively limited set of co-variation patterns, termed 'neural modes'. The study of these neural modes and their activity the 'latent dynamics' is shedding light into the neural basis of behaviour and cognition. Here we seek to understand how interacting neural populations from multiple cortical and subcortical regions drive naturalistic behaviour by examining the geometrical properties of their underlying manifolds and the dynamics within them.

In a previous study (Fortunato et al *bioRxiv* 2022), we showed that neural manifolds are intrinsically nonlinear due to the nonlinear responses of single neurons and their complex interactions. Importantly, for a given brain region, this nonlinearity becomes more evident as task complexity increases: linear approximations such as those provided by Principal Component Analysis become progressively worse as one studies tasks that are less stereotypic than those used classic laboratory experiments, or when one records from many neurons. In addition, manifold nonlinearity depends on the brain-region under investigation. For example, mouse motor cortex and dorsolateral striatum have manifolds with different degrees of nonlinearity during the same behaviour.

We are now leveraging these findings to study sensorimotor interactions during a higher-dimensional ‘naturalistic’ behaviour in head-fixed mice. We extended a standard 3D treadmill setup by integrating linear actuators that apply quick, random perturbations on the floating ball, which makes running mice rapidly adjust their movements. This paradigm allows us to study how sensory responses drive motor adjustments across the sensorimotor system. We are particularly interested in the interaction between sensorimotor cortex and dorsolateral striatum, the mouse homolog of the putamen. To study the role of cortico-striatal pathways in sensorimotor integration, we are recording from various sensorimotor cortical and subcortical regions using Neuropixels probes, and tracking whole-body kinematics using a deep learning-based pipeline for marker-less pose estimation. Our analyses focus on two questions. First, characterising the relative timing and geometric structure of sensory responses across the sensorimotor cortico-striatal pathways. Second, understanding how sensory responses are transformed into signals driving rapid motor corrections. By combining rapid mechanical perturbations designed to disentangle motor commands, efference copy signals, and afferent feedback and leveraging recent developments in neural manifolds, we hope to gain insight into the role of cortico-basal ganglia pathways in adaptive motor control.

4-D-46 - Muscle synergies in force field adaptation

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Details

A fundamental idea in motor neuroscience is that the central nervous system internally models the physics of one’s body and environment and reacts to changes. For example, in force field adaptation[1], reaching movements are perturbed by a force acting orthogonally to the reaching direction, leading to deviated trajectories. However, within several hundred trials, people adapt their internal model and ultimately reach baseline performance again[2]. Internal models may be efficiently implemented by muscle synergies[3]. Accordingly, multiple muscles act in functional units (synergies) and serve as building blocks, generating a large movement repertoire. For example, the combination of a few synergies allows reaching in multiple directions[3]. This study investigates how force field adaptation affects muscle synergies for reaching. We hypothesize (H1) that after adaptation, reaching is implemented by an adjusted activation of the baseline reaching synergies. If not, we hypothesize (H2) that the synergies employed when participants have adapted share dimensions with the subspaces spanned with the baseline synergies.

Thirty-six participants reached 15 cm horizontally to targets at -90 °, -45 °, 0 °, 45 °, and 90 ° (23 trials each) without perturbations in baseline and then to the 0 ° target in a velocity-dependent counter-clockwise force field (250 trials). EMGs of the upper body and the right arm were recorded. Behavior was analyzed with a kinematic (maximum perpendicular displacement: PD_{max}) and a dynamic measure (force field compensation factor: FFCF) to address adaptation. To investigate if adapted reaching only required an adjustment of synergy activations, spatial muscle synergies were extracted (NMF[4]) from the baseline, and the number of synergies was selected at the kink of the R^2 curve[3]. Then (H1), they were tested for their ability to explain the muscle patterns (R^2) in the adapted state. Afterward (H2), a bootstrap approach[5] was used to test whether shared-and-specific muscle synergies extracted from baseline and after adaptation share subspace dimensions.

Participants adapted (PD_{max}, FFCF: t-tests: $p < .01$). The 3.7 ± 0.8 baseline synergies explained well the muscle patterns in baseline (R^2 (cross-validated) = 0.80 ± 0.04), but badly the muscle patterns after adaptation (R^2 = -0.31 ± 0.79; t-test: $p < .01$), rejecting H1. Of 36 participants, 13 had no shared synergy, 12 had one, and 11 had 2-3 shared synergies. However, every participant showed 2.2 ± 0.9 baseline-specific- and 2.2 ± 0.8 adapted-state-specific synergies.

These results suggest that reaching in an environment with altered dynamics requires structural changes to muscle synergies compared to unperturbed reaching.

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4-D-47 - A novel approach to rapid TMS mapping for multiple upper limb muscles

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Details

Different muscle contraction movements are elicited based on the stimulation site when transcranial magnetic stimulation (TMS) is applied to the primary motor cortex (M1). Consequently, the correspondence between the stimulation site and evoked muscle activity enables the visualization of each muscle's innervated area within the M1, termed the "motor map." This physiological assessment, known as TMS mapping, is widely used to understand the neurophysiological foundations of motor learning and recovery. Yet, traditional TMS mapping techniques are limited to visualizing the motor map of a single muscle per session. As a result, assessing changes in multiple muscle motor maps becomes time-consuming and impractical due to the cumulative mapping time required for each muscle. This study introduces a rapid TMS mapping approach capable of estimating the motor maps of multiple upper limb muscles with just two sessions. A key aspect of this method involved defining the equation for map area changes in response to TMS intensity. To achieve this, we conducted evaluations of the motor maps of four right forearm muscles in five healthy adults, using six different TMS intensities with a robotic TMS system. The data underwent regression analysis, with the motor map area as the dependent variable and TMS intensity, muscle, and participant as independent variables. This analysis explored linear and sigmoidal relationships between TMS intensity and map area, finding that a linear model with participant-specific slope variations and muscle-specific intercept variations best fit the data. Furthermore, we expanded on a TMS-induced motor-evoked potential generation model (Goetz et al., Brain Stimul 2014) to develop a computational model simulating neuronal firing in the M1 due to TMS. This model positioned neurons within a two-dimensional space representing the M1, using a Gaussian function and a random number generator that follows a Poisson distribution. The model defined neuron firing probability via a sigmoid function relative to stimulus intensity, with stimulus intensity decaying quadratically from the TMS coil's location. Simulations of TMS mapping corroborated the experimental findings that map area linearly increases with TMS intensities ranging from 1.1 to 1.5 times the resting motor threshold commonly used in TMS mapping. By adjusting the Gaussian function's Ïƒ value, which should vary between muscles, and the rate of stimulus intensity attenuation, which should vary among participants, our model successfully replicated the experimental results for all participants. Our findings demonstrate a linear relationship between TMS intensity and motor map area. This characteristic enables estimating multiple muscle motor maps from TMS mapping at two intensities through linear interpolation of the resulting map areas, offering a more efficient approach to understanding motor function.

4-D-48 - Muscle coactivation primes the nervous system to quickly initiate and correct voluntary movements

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Details

Muscle coactivation is ubiquitous in human movement and presents across a range of tasks like walking over uneven surfaces or reaching in environments where the arm can be physically disturbed. A longstanding, impactful idea is that coactivation increases the stiffness of the limb to resist against physical disturbances. Recent work has challenged this idea, however, and raised the question of whether stiffness is the sole purpose of muscle coactivation. For example, recent studies have shown that the instruction to coactivate allows participants to become more responsive to the same mechanical perturbations by enabling excitation of their agonist muscles, inhibition of antagonist muscles, or distributed responses that engage both muscles in online control. Here, we test the hypothesis that coactivation can also prime the nervous system to quickly initiate voluntary movements in response to a visual stimulus. Healthy participants (N=20) performed reaching movements with their dominant arm supported in a Kinarm exoskeleton robot. They began each trial by moving a hand-aligned cursor into a start position. Participants were cued to initiate their movement when the goal target changed its color from gray to white. In separate blocks of trials, participants performed movements where they were instructed to initiate and move the cursor into the goal target at a comfortable, self-selected pace or initiate and complete their movement as fast as possible. When instructed to initiate and complete their movements as fast as possible, surface electromyographic recordings revealed spontaneous increases in the coactivation of upper limb muscles. Increases in muscle coactivation were evident while participants held the start position prior to being cued to initiate movement. After the go cue, the instruction to produce fast movements led to distributed muscles responses with greater excitation of agonist and inhibition of antagonist muscles. Consistent with our hypothesis, increased coactivation was linked with faster initiation of voluntary movements. In a follow-up experiment, the same participants encountered cursor jump perturbations on random trials while reaching with the same task instructions. The cursor jumped lateral to the goal (±4cm) to assess whether participants produce faster responses to visual feedback when instructed to initiate and complete voluntary movements as fast as possible. In addition to replicating the results of the first experiment, we found that increased coactivation in the fast condition was linked with faster corrective responses. These responses were distributed across muscles, such that agonist muscles displayed greater excitation and antagonist muscles showed greater inhibition. Collectively, the results support our hypothesis that muscle coactivation can prime the nervous system to quickly initiate and correct voluntary movements.

4-D-49 - Comparing motor skill learning processes and their impact on the properties of complex motor tasks

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Details

Motor skill learning involves several processes such as use-dependent learning, reinforcement learning, and error-based learning, each of which depends on specific neural pathways and time scales. These processes work together to account for skill learning, but their relative contribution to skill acquisition, consolidation, transfer, hand-eye coordination, and proprioception can differ based on the task. We tested five groups of healthy young adults who learned a maze navigation skill using their right hand. Each group received different feedback during training. The use-dependent learning (UDL) group practiced without any feedback, while the error-based learning (EBL) group received a score for their accuracy and online feedback during movement. Three groups received reinforcement feedback, one with a consistent threshold (RL) and one with an adaptive threshold (RLA). RLB received feedback like the RLA except the cursor was visible for 1ms in this group. The study assessed skill, transfer, and proprioception of the subjects before and after training. The speed-accuracy function (SAF) was used to assess skill, and the left-hand SAF was used to assess transfer. Proprioception was assessed using a two-alternative forced-choice shape discrimination task. Movement kinematics and gaze information was collected throughout the experiment. All groups showed a clear speed-accuracy relationship. Preliminary results suggest that the UDL group did not show any improvement post-training, while the EBL, RLA, and RLB groups showed improvements in some speeds. The EBL, RLA, and RLB groups showed a reduction in variability for some speeds post-learning. The left-hand SAF showed improvement in all groups except UDL, and EBL, RLA, and RLB showed a reduction in variability for transfer, indicating some transfer of skill. The proprioceptive measures show high variability among subjects and the different groups. Preliminary gaze data suggests that subjects fixated at the beginning and the end of the maze and had varying saccade lengths and saccade numbers depending on the group. These early results support the idea that different types of learning affect skill parameters differently.

4-D-50 - Using Neuropixels to compare neuronal population activity across the macaque fronto-parietal grasping network

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Details

In everyday life, primates perform a wide variety of grasping movements. The kinematics of grasping in primates depend on object characteristics such as fragility, size of contact surfaces, texture, and weight. As a result, specific grip types are used for each object and intended action. The frontoparietal grasping network, in particular the anterior intraparietal area (AIP) and the ventral premotor cortex (F5) is involved in the planning and execution of grasping movements. Many studies have investigated various aspects of the visuo-motor transformation within and between these areas. However, our understanding of how population dynamics are distributed within these areas is limited due to methodological constraints. The recently developed Neuropixels probes allow to record simultaneously from 384 channels, and therefore from a large neuronal population, in a single electrode penetration. To explore intra-areal differences in neural population activity, we trained a female Macaca mulatta to perform a visually instructed delayed grasping task. Using Neuropixels probes, we simultaneously recorded from 384 channels per day at various locations in AIP and F5, and then investigated differences in the population dynamics at various locations within and across AIP and F5.

Peristimulus time histograms (PSTHs) highlight the presence of neurons that are differently modulated during the three epochs of the task, indicating the importance of analyzing neural population activity separately during the cue, the memory and the movement execution epochs. This is supported by the correlation matrix of the object tuning properties across all neurons and all the recordings, which demonstrates how the dynamic changes between epochs.

Furthermore, comparing responses under condition-dependent modulation across sites - using either the Euclidean distance measure or the population variance in the neuronal space - revealed the presence of a different gradient during cue, memory and movement execution epochs across the sulcal extension of AIP. A similar result is observed when looking at condition dependent modulation.
In parallel, there is an ongoing correspondent analysis on the data collected from F5. The analysis of Euclidean distance and variance values across sites, indicates similar differences in F5.
To summarize, the Neuropixels technology has proven to be successful in recording high density populations in individual recording site (50-200 neurons) also in non-human primates. The analysis of the variance across conditions shows a spatial gradient in AIP, and an overall time- dependent increase of variance occurred along the anterior-posterior axis and from cue to movement.

Support: CRC 1528

4-D-51 - Partial slips may inform fast grip force adaptation to heavier loads in the absence of visual cues.

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Details

During object manipulation, humans adjust their grip force based on the weight of the object. This allows them to hold it with the minimum of grip force required. In the absence of visual cues, tactile and proprioceptive feedback guides this grip force control. Partial slippage of the skin of the fingers against the object is believed to provide crucial feedback, with the associated mechanoreceptor firing being important in the modulation of grip force while avoiding fully losing control of the object.

To investigate the role of tactile feedback in grip force control, we recruited 31 participants to perform a grip-and-lift task using visually identical cubes with different weights. The cubes were attached to an instrumented object capable of imaging surface skin deformations at the object-finger contacts using frustrated total internal reflection (device's weight without attachment: 235 g; light cube: 58 g; heavy cube: 180 g). The weight of the object was changed every 3 to 5 trials, and participants had no visual clue to indicate this weight change. Two different conditions were tested, one in which participants' finger pad skin came directly into contact with the object, and a second in which participants wore thimble-like finger covers on their index finger and thumb. These finger covers included an outer silicone layer with a coefficient of friction similar to skin, and an inner layer made of 3D-printed PLA. The inner layer featured a plastic annulus preventing contact over the majority of the finger pad; this is intended to reduce tactile feedback from skin slip. This condition is contrasted with the standard condition where participants used an unaltered pinch grasp, with the finger pad making a natural contact with the object.

All participants were able to execute the grip-and-lift task, and no object drops occurred during the experiment. In both conditions, a larger grip force was used when the heavier object was being manipulated, with an increase of 15.35% of the peak grip force with bare skin versus 12.55% with thimbles. In transition trials, i.e. trials in which the weight was different from the previous trial, the grip force profile differed from the grip force profile in non-transition trials. With naked skin, the difference in grip force was observed 350 ms after contact in transition trials to the heavier object, and 450 ms in transition trials to a lighter object. In contrast, while wearing thimbles, the differences in grip force were observed later, with a time of 700 ms after contact in transition trials to the heavier object, and 800 ms when transitioning to the lighter object.

This result supports our hypothesis that during object manipulation, tactile feedback from the finger pad enables faster adaptation of grip force to changing object weight. Future work will analyse the video recordings of the naked skin condition to explore the relationship between partial skin slip events and the speed of grip force adjustments.

4-D-52 - Subcortical consolidation of a motor sequence depends on demands for flexibility

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Details

The brain's ability to sequence discrete movements enables rich and ubiquitous behavior. For example, a concert pianist can flexibly play never-before-seen sonatas by following sheet music. However, to achieve fluid and error-free performance for a concert, she extensively practices a single piece until it is automatic and its execution is no longer dependent on sheet music. The neural circuits underlying automatic and flexible motor sequences are thought to differ, but the distinction is poorly understood. In neurological disorders, like Parkinson's disease (PD), patients fail to perform automatic motor patterns (like walking), but can do so if guided by cues (such as if instructed on how to walk). Determining which connections in the brain control motor sequence execution in different modes can help in advancing our understanding about the circuit disruption underlying these disorders.

We specifically focus on the sensorimotor striatum (DLS), which is indispensable for execution of motor sequences and investigate how cortical (motor cortex, MC) and thalamic inputs into DLS guide its functional role of controlling motor sequence execution in different modes and how their role changes with varying task demands. One hypothesis is that after extensive practice, MC tutors the thalamostriatal pathway to inform moment by moment kinematics and control automatic sequence execution. However, if there is a need to flexibly re-use motor elements, it could interfere with thalamostriatal consolidation and automatic sequence execution can still remain dependent on Corticostriatal projections (Mizes et. al. 2023). Here, we probe this question by probing neural circuits in DLS as rodents learn to perform motor sequences of three lever presses. To test our hypothesis, we trained separate cohorts of rats - one, where animals perform a single sequence (automatic-only), and second, which required flexible reuse of motor elements in addition to reinforcing a single sequence (flexible+automatic). We used an intersectional viral approach to silence thalamostriatal projections in both cohorts and observed that performance and movement kinematics were disrupted only in the automatic-only cohort. Interestingly, automatic sequence execution in the flexible+automatic cohort was unaffected by thalamostriatal silencing. Congruently, silencing corticostriatal projections with optogenetics in rats performing the flexible+automatic task impaired automatic sequence execution and kinematics, while sparing flexible sequence execution

Together, this work provides insights into the hierarchical and distributed control of motor sequences by showing that thalamostriatal circuitry controls automatic sequence execution only when there are no demands for flexibility. However, as soon as there is a need to flexibly re-use motor elements, execution of automatic sequences is controlled by Corticostriatal projections.

4-D-53 - Motor imagery leads to predictive tactile suppression

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Details

Contemporary accounts of sensorimotor control propose that sensory predictions suppress self-generated sensory signals, as reflected in attenuated self-touch during actively performed or mentally imagined movements. However, the same accounts claim that sensory predictions are unrelated to the suppression of sensory signals on a moving limb that are not caused by the movement itself, such as of externally generated sensations. To test this, we asked healthy human participants to actively perform and to imagine performing a goal-directed reaching movement to a visual target. Shortly after movement onset, a probe vibrotactile stimulus was delivered to the index finger of either the right reaching hand or the left static hand. Participants were to detect the presence of such probing stimulus during these tasks as well as during a separate resting block (i.e. baseline). We expected movement-related suppression on the right reaching hand, but not on the left static hand. If suppression is caused by feedforward mechanisms that involve predicting the sensory states of the moving limb, then suppression should occur also during motor imagery but only on the right hand involved in motor imagery and not on the left hand. In line with previous findings, movement times of actively performed and imagined reaching were highly correlated. As expected, active reaching led to tactile suppression on the right reaching hand but tactile processing on the left static hand remained intact. Crucially, motor imagery also led to tactile suppression on the right hand that was involved in motor imagery, but tactile processing on the non-involved left hand was again intact. Thus, tactile suppression on the right hand during motor imagery was not simply caused by memory or dual-task factors. Instead, our results demonstrate that tactile suppression is driven by the common denominator underlying the computational equivalence of motor execution and motor imagery, namely the recruitment of a forward model that predicts the sensory states of the moving limb and thereby downregulates associated sensory processing. Our findings elucidate the central role of predictive mechanisms on sensory processing during human action.

4-D-54 - The impact of task on StartReact may be different from its influence on the startle reflex

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Details

StartReact is characterized by the rapid release of a planned movement upon a startling acoustic stimulation (SAS) [1,2]. This startReact phenomenon is likely facilitated via the startle reflex circuitry, triggered by an activation of the reticular formation [3,4] - the origin of the reticulospinal tract (RSTs) [5]. An observable indicator of the startle reflex is the early onset of sternocleidomastoid (SCM) activity [6] - a primary neck flexor necessary to maintain head/neck stability. While the SCM activity is not necessary for rapid execution of the planned movement upon a SAS [7], it is argued that early SCM onset following SAS (<120ms), is a robust indicator of an excitation of reticular structures [6,8,9]. Consequently, most studies use the presence of SCM to distinguish true startReact facilitated via RST engagement, from false startReact associated with stimulus intensity effects[1,10,11]. Yet, it is unclear whether the SCM onset latency following SAS is task-dependent in a similar fashion as startReact. This is crucial, as SCM onset latency directly impacts the determination of a true or false startReact, and thus may change the quantification of the startReact effect, defined as the latency difference between these 2 conditions. We therefore investigated the whether the possible task-dependence of SCM latency is similar to that of startReact.

Previous results have showed that startReact effect is stronger in proximal tasks than distal tasks [11,12], likely due to RSTs' preference for more proximal muscles than distal muscles[13]. We therefore compared the SCM latencies for shoulder abduction (i.e., LIFT, a proximal task) versus hand opening (i.e., OPEN, a distal task) tasks, together with their startReact effect. We recruited 11 participants, with no neuromuscular disorders, performing a LIFT task and an OPEN task in response to a SAS (120 dB), while recording electromyography from the intermediate deltoid, extensor digitorum communis as well as the bilateral SCMs. Consistent with literature[11,12], our results showed a larger startReact effect, in the LIFT task than the OPEN task. However, the larger startReact effect was accompanied by a delayed SCM onset latency in the LIFT task compared to OPEN task.

The delayed SCM onset latency in the LIFT task compared to the OPEN task could potentially be attributed to task-related differences in anticipatory postural head/neck adjustments. Previous studies have demonstrated the impact of anticipatory postural responses on reflex responses [14,15]. For tasks likely to perturb posture, such as LIFT, there may be a feedforward mode of neural control whereby the anticipatory postural head/neck adjustments inhibit SCM reflexive activation [15] thus delaying the SCM onset latency. Our results highlight the task-dependent nature of SCM onset latency, prompting further investigation on the interplay between startReact and startle reflex.

4-D-55 - Rotational population dynamics in lumbar spinal networks during locomotion of awake rats

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Details

Mammalian locomotion relies primarily on networks located in the spinal cord, which can autonomously generate rhythms and patterns. Recently, it was found that rotational neural dynamics is exhibited in ventral populations of the turtle spinal neurons controlling rhythmic leg movements (Linden et al, Nature 2022). However, few, if any, direct observations of large-scale spinal network dynamics in awake-behaving mammals exist. Here, we report on the dynamics of spinal networks in rats while they perform volitional locomotion.

We sampled the activity of the lumbar spinal cord in freely moving rats using multi-electrode arrays (Neuropixels and Neuronexus probes). It allowed us to record individual spikes in up to 500 neurons as observed in the turtle spinal cord. Strikingly, the spinal network consistently displays low-dimensional rotational dynamics, where the frequency and amplitude correlate with the locomotor output. Further, we reconstructed the probe location from FISP (Fast Imaging with Steady-state free Precession) Magnetic resonance imaging sequences (9.4T structural scan) and examined the spatial distribution of the population activity by delineating the local contributions of dorsal and ventral laminae of the spinal cord to the overall dynamics.

Our preliminary results suggest that the dorsal and ventral regions exhibit different forms of dynamics. Finally, we asked whether distinct clusters of cells contributed equally to the phases of rotation. Interestingly, local spatial clusters demonstrate a higher phase coherence compared to electrophysiologically uniform cell groups, which displayed wider spatial distributions.

In conclusion, we observed spinal rotational dynamics as a ubiquitous feature correlated with rhythmic limb movement and distinct spatial areas contribute differently to sensorimotor processing.

4-D-56 - Hierarchical division of labor during cognitive-motor sequences

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Details

Many activities of daily living require coordination among multiple brain areas to determine and drive action sequences. Primary motor cortex (M1) is critical for such behavior. Yet during preparation, M1 activity reflects only the first movement within a sequence. Information regarding each subsequent movement arrives 'just in time' as the previous movement ends. Thus, M1 must rely on upstream areas to 1) determine which actions should be performed in what order, and 2) perform these computations during preparation. To investigate, we developed a novel cognitive-motor sequencing task. Monkeys used abstract rules to decipher a three-reach sequence and hold it in working memory until a go-cue. A "size rule" required targets be touched in order of increasing size. A "color rule" required alternation between red and blue targets. Each trial presented a previously unseen arrangement of targets and cues, requiring a novel solution. During preparation, monkeys had to apply the correct rule based on the stimulus to decide which three targets (out of four) should be touched in what order. The necessary cognitive processing depends on the rule context, yet the task can create situations where the solution (and thus motor output) is matched across contexts. We recorded large populations of neurons (~500 simultaneously) using Neuropixels-NHP probes within M1, supplementary motor area (SMA), and lateral prefrontal cortex (LPFC: Areas 8, 9/46, and 47). We confirmed that M1 activity is insensitive to both rule and the full sequence. We hypothesized that SMA and LPFC participate in sequence determination. In SMA, we could decode the identity of all reaches during preparation, but found no rule information. This suggests that SMA is critical for sequence generation, but does not participate in computing the correct order. In LPFC, we could decode both the rule and the full sequence during preparation. Our population analysis revealed that three distinct reach locations become specified ~150ms after one another in independent ('ordinal rank') subspaces. This is consistent with a mechanism where decision computations to select each target occur sequentially, despite all stimuli being present at once. Our analyses found that the monkey predominantly used backwards induction: solving the problem by first deciding the final target in the sequence, then the second, then the first. On single trials, we also found other ordering strategies. Our analyses show that the strategy is influenced by errors and target geometry. This suggests considerable neural flexibility during reasoning, i.e., decision computations can occur in any order, based on practical considerations. Our findings indicate a hierarchical division of computational labor underlying determination and generation of sequences; LPFC participates in cognitive computations that establish the correct sequence, SMA reflects the full chosen sequence, and M1 guides preparation and execution of individual reaches.

E – Integrative Control of Movement

4-E-58 - Vestibular signals differentially influence reach trajectory selection during planning versus execution

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Details

Many daily activities involve coordinating voluntary limb movement with body motion. In line with this, vestibular signals have been shown to contribute to both spatial and dynamic aspects of reach planning and execution. However, less is known about how they contribute to action selection. Recent studies have shown vestibular influences on goal selection for eye movements (Rincon-Gonzalez et al., 2016) and effector choice for reaching (Bakker et al., 2017). Here we explored how vestibular signals influence the selection of reach trajectories as we move among objects in the environment. We tested the hypothesis that vestibular signals influence the choice of reach trajectory around an obstacle and that this influence is mediated by distinct mechanisms during reach planning vs. execution. Human subjects made reaching movements while seated with their right arm supported in the horizontal plane by a robotic exoskeleton. Forward reaches were made in darkness to a remembered target located 20 cm away while avoiding collision with a remembered obstacle placed midway between the start position and the target. Subjects were free to choose whether to avoid the obstacle by reaching around it to the left or to the right, and we quantified how their choices varied with the obstacle's horizontal position. To address the influence of vestibular signals on choice behavior, in 20% of pseudo-randomly chosen trials galvanic vestibular stimulation (GVS) of unpredictable polarity (3 mA pulse) was applied to simulate body motion. In separate experiments, GVS was applied either: 1) during the memory period prior to reach onset for 2.5s; 2) during the memory period for a shorter duration tailored for each subject to ensure there was no conscious percept of body motion; or 3) during reach execution (750 ms). We predicted that GVS applied before reach onset would increase the proportion of choices relative to no stimulation controls in the same direction as the simulated motion, consistent with vestibular influences on "spatial updating" mechanisms during planning. In contrast, we predicted that GVS applied during reaching would increase the proportion of choices in the opposite direction to the simulated motion, consistent with vestibular influences on online correction mechanisms that act to stabilize the hand's trajectory in space (e.g., Martin et al., 2021). In agreement with these predictions, choices were biased in the direction of simulated motion when GVS was applied before reach onset regardless of whether the motion was perceived. However, choices were biased in the opposite direction when GVS was applied during reach execution. These results suggest that vestibular signals indeed contribute to trajectory selection and that their influence is mediated via distinct mechanisms during reach planning vs. execution.

4-E-59 - Motor cortical dynamics during voluntary gait modification in the mouse

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Details

Locomotion in complex environments requires continual adjustment of muscle activity across steps. While the basic locomotor pattern is produced by spinal networks, this pattern must be altered in response to environmental challenges, like when stepping over an obstacle. In primates, cats, and rodents, motor cortex is necessary for precise changes of muscle activity to traverse obstacles, acting on top of the ongoing locomotor pattern. Single neuron recordings in cats have identified changes in motor cortical firing rates during obstacle traversal. What remains unclear is how the coordinated, population-level patterns in motor cortex are related to specific aspects of behavior, and how transient patterns related to gait modification interact with an ongoing locomotor rhythm. Here, we use three-dimensional motion tracking and cortical neural ensemble recordings during unrestrained locomotion in mice. Animals were trained to trot on a linear treadmill with two obstacles attached to the belt that were ~0.9 cm in height. Individual steps were segmented based on forelimb swing and stance kinematics, and sequences of steps relative to obstacle traversal were identified. In comparison to locomotion over a flat surface, obstacle traversal required the mouse to make a voluntary gait modification and increase paw height. Cortical activity was recorded using silicon probes chronically implanted in the forelimb motor area. On the step over the obstacle, mice alternated between two movement strategies, with the forelimb contralateral to the neural probe either traversing the obstacle before the ipsilateral limb (contralateral lead condition), or after the ipsilateral limb (contralateral trail condition). Neuron firing rates aligned to step sequences showed that some cells were responsive to both the stepping rhythm and obstacle, whereas other cells were only responsive to the stepping rhythm, obstacle traversal, or the step preceding the obstacle. Because individual neuron responses were complex and heterogeneous, we next leveraged population analyses. From step sequences, we identified neural dimensions in which activity is rhythmic and others with large transients just before the obstacle. Surprisingly, the transient dimensions exhibited limb-independent activity synchronized with the leading forelimb, regardless of whether the limb was ipsilateral or contralateral to the neurons. Subsequent experiments are aimed at identifying how inputs from other brain areas, like the cerebellum and posterior parietal cortex, drive activity in these dimensions.

4-E-60 - Supranormal proprioception in legally-blind individuals with residual vision

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Details

What are the functional consequences of a severe visual impairment? Some blind individuals such as Stevie Wonder have extraordinary motor skills, which could be due to intense practice of motor skills, but also to supranormal auditory or tactile perception. However, it remains unclear how blindness influences proprioception, the sense of position and movement of body segments, given that the visual sense has been suggested to calibrate proprioception. Here we directly tested the contrasting hypotheses of cross-modal compensation or alteration by assessing proprioceptive perception in blind and sighted individuals. Results from an ipsilateral passive matching task revealed that arm proprioception is most accurate in individuals who are considered blind but have some limited residual vision (visual acuity below 1/20 for the best eye). This was found for the preferred and non-preferred arm, at the elbow and at the wrist joints, compared to totally-blind and sighted individuals. We also found that proprioceptive precision was lateralized in sighted but not in blind individuals. Overall, our findings reveal that proprioceptive acuity is supranormal in blind individuals with residual vision, and thus that visual experience critically influences proprioception, providing new insights into the principles of cross-modal sensory recalibration.

4-E-61 - Vestibular and visual contributions to online steering control

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Details

Human drivers can precisely control vehicles and avoid obstacles in the environment despite noisy and delayed sensory (mostly visual and vestibular) information and an equally noisy neuromuscular motor system. Here we quantify to what extent each modality contributes to the perception and control of self-motion and what their noise levels and delays are. To this end, we combined a behavioral driving task with computational modeling of the sensorimotor control loop. In the vehicle-motion task, participants controlled the lateral position of a chair mounted on a linear motion platform within a visual environment, while the motion of the platform and visual stimuli were perturbed with band-limited white noise. In the vehicle-stationary task, the motion platform remained stationary, but the participant had to control the position of a visual stimulus that was perturbed. Based on the behavioral data, we constructed the transfer functions for the two different tasks and show the benefits of vestibular feedback in reducing the effects of the perturbation in the higher frequency range. That is, gains and phase were more compensatory the higher frequency ranges in the vehicle-motion than the vehicle-stationary task. To understand the two steering scenarios, we build a control model, including the dynamics of the sensory and motor systems, and simulated the behaviour of this system when exposed to the same stimulus. We compare these model predictions to the experimental data and show a qualitative agreement. Currently we are fitting the model to the experimental data to estimate sensory noise levels and sensory latencies. In conclusion, using a neurocomputational framework in combination with a system identification approach, we dissociate vestibular and visual contributions to online steering control.

4-E-62 - Stimulation of the caudal origin of the frontal aslant tract (FAT) in the superior frontal gyrus impairs self-paced rhythmic movements independently from the effector

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Details

Background and objective: Human overt behavior in a changing world oscillates between two mutually incompatible timing strategies: either predicting the upcoming changes or reacting to them. Internally timed (predictive) actions are represented in the dorsal/medial frontal lobes, while externally triggered (reactive) actions are represented in the lateral frontal lobes. We have previoisly shown that the Frontal Aslant Tract (FAT), a white matter bundle connecting the medial and lateral systems, mediates competitive switching between predictive and reactive strategies. In the present work we aimed at investigating whether the cortex associated with the dorsal origin of the FAT is causally involved in the actual generation of internally-timed behavior.

Methods: We asked healthy human adult volunteers to perform repetitive speech (syllable) production or finger tapping, while applying individual tractography-guided TMS on 3 points in the left superior frontal gyrus (SFG), on the cortex associated with the origin of the FAT. Sham TMS served as control. The effects of TMS were analyzed by means of peri-stimulus time histograms.

Results: We observed that TMS over a specific caudal portion of the SFG convexity (immediately rostral to the precentral sulcus) produced an increase in probability of a motor event, compared to sham stimulation and to active TMS of the 2 more rostral portions of the SFG. The pattern of behavioral effects of TMS was observed for both tapping and speech tasks without significant differences between them.

Discussion: We show that the cortex at the dorsal origin of the FAT is associated with rhythmic, self-paced behavior. Such role is commonly attributed to the neighbouring supplementary motro area. The present works indicates that also the convexity of the SFG is necessary for internally generated actions. We also show that neural processes in the SFG controlling self-paced rhythms are domain-general, being effector-independent.

4-E-63 - Progressively shifting patterns of co-modulation among premotor cortex neurons carry dynamically similar signals during action execution and observation

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Details

Many neurons in the premotor cortex show firing rate modulation whether the subject performs an action or observes another individual performing a similar action. Although such “mirror neurons” have been thought to have highly congruent discharge during execution and observation, many if not most show non-congruent activity. Studies of such neuronal populations have shown that the most prevalent patterns of co-modulation captured as neural trajectories pass through subspaces which are shared in part, but in part are visited exclusively during either execution or observation. These studies focused on reaching movements for which the neural trajectories show comparatively simple dynamical motifs. But the neural dynamics of hand movements are more complex. We developed a novel approach to examine prevalent patterns of co-modulation during execution and observation of a task that involved reaching, grasping, and manipulation. Rather than following neural trajectories in subspaces that contain their entire time course, we identified time series of instantaneous subspaces, sampled trajectory segments at the times of selected behavioral events, and projected each segment into the series of instantaneous subspaces. We found that instantaneous neural subspaces were partially shared between execution and observation in only one of three monkeys and were otherwise exclusive to one context or the other. Nevertheless, the patterns during execution and observation could be aligned with canonical correlation, indicating that though distinct, neural representations during execution and observation show dynamical similarity that may enable the nervous system to recognize particular actions whether performed by the subject or by another individual.

4-E-64 - Intuitive grasping with tools. Awkward end postures are not automatically avoided when grasp orientation is rotated with respect to hand orientation

Molly Hewitt [1], **Ken Valyear** [1], **Simon Watt** [1]

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Details

Devices such as upper-limb prostheses, minimally invasive surgical tools, remote-manipulators etc. often feel unintuitive to use. A possible reason is that they alter the mapping between limb movements and movements of the acting end-effector in ways that are difficult for normal, largely automatic, sensorimotor control processes to account for. We examined one aspect of this: rotation of a device's grasp axis relative to hand-grasp orientation, which is analogous to rotating wrists on upper-limb prostheses.

When grasping objects at different orientations with our hands we automatically programme movements that avoid awkward end postures (e.g. switching from overhand to underhand grasp as needed). This ability relies on internal models of the hand/arm that allow the outcomes of different movements to be predicted and factored-in to movement planning. Here we ask whether this occurs when the grasp orientation of a tool is altered with respect to the hand/wrist, and so must be taken into account if end posture is to be anticipated appropriately.

Twenty participants reached for and grasped a bar, that could be grasped in only two hand orientations, 180 degrees apart. The bar was presented at all orientations in the fronto-parallel plane (5-degree increments), randomly ordered. It was grasped using 'rotating tongs', which varied the grasp orientation of the tool independently of hand-grasp orientation. Tool orientation was rotated 0, 45 and 90 degrees relative to the hand. Participants also completed a control condition using their hand. Movements were measured with motion capture. We reasoned that avoiding awkward hand postures, independent of tool-grasp orientation, would indicate the presence of internal models of the tools equivalent to those of the hand/arm, allowing automatic end posture to be automatically factored-in to movement planning.

For hand grasping, posture was highly reliable for most bar orientations, with a region of ~20 degrees around horizontal where movements transitioned monotonically from placing the thumb on one side of the bar to placing it on the other. In the 0 degree tool condition, results resembled the hand condition. For the 45 and 90 degree tool conditions, participants transitioned from one grasp posture to another at a similar hand orientation to the other conditions (i.e. independent of tool orientation), but performance was less reliable. Up to 25% of trials resulted in hand postures that were awkward, and not adopted with hand grasping.

Our results suggest that novel mapping between our hands and end effectors is readily considered when the mapping closely resembles the hand. Even mechanically straightforward changes here, rotation of the grasp axis can be difficult for automatic sensorimotor control processes to fully take into account. A better understanding of what classes of remapping are easily 'understood' by the sensorimotor system could enable devices that are more intuitive to use.

4-E-65 - Neural representations of goal-directed reaching cued with unimodal and multimodal sensory information

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Details

The human motor system relies heavily on the sensory systems in the planning and initiation of goal-directed movements. However, sensory information is not always useful for both movement planning and initiation. For instance, fielders in baseball use visual and auditory information to monitor if a ball has been hit to initiate movement, but only the visual information is used to plan how to catch the ball. Several studies have explored how humans integrate different sensory signals to plan goal-directed movement, but it remains less clear how sensorimotor neural representations of goal-directed movement change when some sensory stimuli are cue-related, but not goal-related. Here, we investigate neural representations of visually guided reaching when initiated with unimodal (i.e., visual only) and multimodal (i.e., audiovisual) sensory cues. Twenty-six right-handed healthy young adults completed two fMRI sessions during which they performed visually guided goal-directed reaches to targets with visual cues or audiovisual cues instructing movement initiation. Bayesian pattern component modeling of fMRI data in all sensorimotor ROIs showed strong evidence for representations of gaze location relative to targets (left vs. right), sensory modality (visual vs. audiovisual), and their interaction. This result suggests representational distinctiveness between left and right gaze relative to reaching targets depends on the sensory modality of the movement initiation cue. Strong evidence of target position and its interaction with modality was observed in primary visual and motor areas, and dorsal premotor cortex, suggesting that neural representations of the reaching target change between unimodal and multimodal movement initiation cues. The consistent evidence for the effect of modality and its interactions with gaze location and target indicates distinct neural representations for the planning of visually guided reaching when different sensory modalities are available to cue movement initiation. These results suggest that the central nervous system flexibly allocates tasks (goal-driven planning and initiation) depending on available sensory information. Notably, premotor and primary motor areas showed an effect of hand position without a hand X modality interaction, suggesting representational dissimilarity between left and right initial hand position is not modulated by the presence of an audio cue supplementing visual information to cue movement. Altogether, these results suggest that representations of gaze and target locations that are exclusively tied to the visual system are more susceptible to added load (when tasked to plan a visually guided reach and to initiate a reach with a visual cue) than representations of hand position with added proprioceptive inputs.

4-E-66 - Function and manipulation tool knowledge in anterior temporal and superior parietal regions: an fMRI study with representational similarity analysis

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Details

Fluent recognition and use of diverse tools are essential cognitive-motor acts in human life. The parietal lobe has traditionally been considered the neural substrate of this remarkable ability, with evidence suggesting its role in visuo-motor processing for manipulating objects. However, recent findings propose that the anterior temporal lobe (ATL) also plays a crucial role by encoding the “functional'' aspect of objects (i.e. their canonical uses). Despite these observations, a comprehensive model integrating these brain regions within a human tool-use network remains elusive. This study investigated the following hypotheses: (1) parietal and anterior temporal regions predominantly represent tool "action" and "function" information, respectively; and (2) the ventral ATL, the acknowledged "semantic hub” region, integrates various tool-relevant information including both function and action knowledge. We conducted a representational similarity analysis on functional MRI data from a tool-viewing experiment. The results revealed that tool-manipulative information significantly correlated with activation in bilateral superior parietal lobules, while tool function models aligned well with activity in bilateral anterior temporal lobes. Interestingly, the ventral portion of the left ATL showed significant representation of both function and action information. These findings highlight the critical roles of both superior parietal and anterior temporal regions in tool-use ability, suggesting potential integration within the ventral ATL. This necessitates a significant revision of the current, parietal-centric neuroanatomical framework of tool use.

4-E-67 - Multiplicative joint coding in preparatory activity for reaching sequence in macaque motor cortex

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Details

Whereas motor cortex has been found to encode the kinetics and kinematics of arm movements, its neuronal activity is also influenced by serial actions. Previous studies reported that neurons are tunned specifically to both sequence and serial order. However, the debate between parallel and joint coding is still controversial.

Here we trained macaque monkeys to perform a sequential reach task. There were three types of trials: single reach (SR), clockwise double reach (CW DR), and counterclockwise double reach (CCW DR). During the double reach trials, two targets of different shapes were presented simultaneously during a cue period, and after a 400-800 ms memory period, the monkey was required to reach to the memorized locations in a CW or CCW sequence without a compulsive delay between the two reaches.

In motor cortex, we collected 322 well-isolated, task-related neurons from single-electrode recordings (224 from monkey B, 98 from monkey C left hemisphere) and 162 units sorted from array recordings (44 from monkey G, 118 from monkey C right hemisphere). Although hand speed correlation between DR an SR was 0.99 0.006 (mean sd), neurons in motor cortex exhibited heterogeneous firing patterns related to reaching sequences. In detail, 52% of the 322 sequence recorded neurons and 76% of 162 array recorded neurons exhibited significantly different firing rates for SR and DR in the preparatory period (Wilcoxon rank sum test, $p<0.05$). To test whether such sequence-related response results from joint coding or parallel coding (i.e., Zimnik & Churchland, Nat Neurosci 2021) of movement elements, we fit neuronal activity into models following the two hypotheses. Results revealed that neuronal activities are better explained as a multiplication of directional tunings to reaching elements in the preparatory period (two-tailed Wilcoxon signed rank test, $p<0.0005$), and then converted to parallel coding after movement onset. The neural state analysis indicated that a gain-like interaction is embodied in the spatial structure of the initial states. Furthermore, simulation of RNN models performing this task also exhibited comparable temporal dynamics with real neurons recorded in the present study. The profile of regression coefficients of model nodes largely resembled that of real data (FrÉchet distance = 0.41 ±0.04), suggesting that the proposed gain modulation for sequential movements also emerges in a dynamical system. A simulation of such coding mechanism showed that gain modulation can contribute to robust linear readouts of movement elements, as previously mentioned (Ben-Shaul, Y., et al. J Neurophysiology 2004).

These results suggest that motor cortex is profoundly involved in concatenating multiple movement elements into a sequence, and that gain-like multiplication is a key computational signature of complex serial behavior.

4-E-68 - Muscle feedback in humans, an anticipatory system to prepare the body for changes in the environement

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Details

To interact with the outside world, sensory information informs us of changes in our environment that are relevant to our behavior. We act on this information, either by movement or by an internal reaction. In our daily lives, we face a wide variety of situations and the way our bodies react to them determines how we deal with them. Humans are predisposed to react in certain ways and these reactions are enriched by individual experience. In order to react appropriately, a 'feedforward' system exists that allows for great efficiency, anticipating the most appropriate movement strategy for the situation. At the peripheral level, our muscles have complex mechanoreceptors, the muscle spindles send information to the central nervous system about the state of stretching of the muscle, but they also have the particularity of being innervated by a sophisticated descending efferent system, called the gamma-fusimotor system. The microneurography technique, which allows in vivo recording in peripheral nerves in humans, allows us to directly access the unique responses of muscle afferents. Our group has shown the direct effect of top-down cognitive and emotional influences, as well as inputs from other senses such as vision, on the sensitivity of muscle receptors. We postulate that this anticipatory system exists to help prepare the body to respond appropriately to changes in the environment.

F – Posture and Gait

4-F-70 - Locomotor variability reveals neuromechanical control modules for stability by foot placement in mice

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Details

Foot placement control is a crucial component of stable locomotion in humans and legged robots. However, we lack evidence for foot placement control in neuroscientifically accessible animal models, thereby hindering our ability to probe its underlying mechanisms. To bridge this gap, we investigated the existence of human-like signatures of foot placement control by mining the locomotor variability present in over 200,000 steps of mouse locomotion data. Eighty mice walked in an open field arena for 80 minutes each while a camera captured their behavior through a transparent floor from below. Markerless motion capture was used to extract the kinematics of the individual limbs, nose, and tail throughout the experiment. We then computed the straight-line bouts, foot contact events, and phase-locked kinematics states of the torso and limbs. To identify the structure present within the step-to-step locomotor variability, we used linear models as they were sufficient to predict the modulation of each foot's contact based on the errors in body states during the preceding gait cycle. Echoing findings in humans and robots, our analyses reveal that mice correct intrinsic variations in body states by "stepping in the direction of the error" i.e. by proportionally modulating their foot placement in response to deviations in the body states. The errors in the positions and velocities of the body during a given foot's stance phase predict the modulations of that same foot's placement at its next contact, well before the launch of the foot's swing phase. With a delay of about 100 milliseconds between the error and subsequent modulation of foot placement, the observed timescale is greater than the short- and long-latency response loops and allows sufficient time for descending modulation. The step-to-step locomotor variability also reveals distinct neuromechanical functions for the control of fore- and hindlimbs, which are coherent with the spatial organization of the spinal cord. The errors in the sagittal body states modulate the foot placement for all limbs, while the frontal variability in the body states only modulates the forelimb foot placement. The neuromechanical module for frontal foot placement control also reveals direction-sensitivity to the input errors in body state; only abductive errors (i.e., errors directed outward from the sagittal plane) are corrected while adductive errors directed towards the sagittal plane are ignored by subsequent foot placement. Taken together, our results point to the existence of distinct neuromechanical modules for foot placement control in mouse locomotion. Our findings will help investigate the neural basis of locomotor stability, analyze foot placement control across neuromechanically diverse species, and discover neuro-inspired principles for legged robotics.

4-F-71 - Aging effects on modulation of spinal excitability with balance task difficulty and cognitive dual task performance

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Details

Greater cortical engagement during balance control frequently occurs with aging, and concurrent cognitive task demands can compete for cortical resources, compromising balance and increasing falls risk in older adults (OA). While spinal reflex modulation is essential for balance control, it is unclear how this modulation is influenced by descending signals when a cognitive task is performed concurrently with a balance task. Given the structural and functional changes in spinal and cortical circuits that accompany aging, it is essential to understand how these circuit changes translate to changes in neural control of balance. Here, we aim to determine if and to what extent aging affects the modulation of spinal excitability across varying levels of balance-task and dual-task difficulty.

We hypothesize that in OA, engaging in difficult balance tasks results in greater recruitment of cortical resources shared for cognitive tasks. Peripheral nerve stimulation (PNS) is used to elicit H-reflexes to quantify spinal excitability during balance tasks with different levels of difficulty. During each balance task, cognitive task difficulty is manipulated using the N-back verbal working memory task. We predict that 1) spinal excitability will decrease with increasing dual-task difficulty, but to a greater extent in OA; 2) balance performance will improve in young adults (YA) and worsen in OA with increasing dual-task difficulty.

YA (18-35 years) and OA (60-85 years) perform standing balance tasks with increasing levels of difficulty (quiet stance, QS; quiet stance on foam, QS on foam; narrow stance on foam, NS on foam) on a force plate. All standing conditions, in addition to a prone condition, are performed with visual fixation (control), 0-back, and 2-back tasks. Postural performance is assessed using center of pressure (COP) measures. Spinal excitability is quantified as the peak-to-peak amplitude of 20 PNS-evoked soleus H-reflexes normalized to the maximal muscle response in each balance condition.

From preliminary data collected in YA, H-reflex amplitude decreased from prone to QS (-46.02 ± 18.87%) but did not continue to decrease with increasing balance task difficulty (QS on foam: 35.70 ± 29.29%; NS on foam: -40.19 ± 15.89%). Across all standing conditions, we observed a trend in which the reduction in H-reflex amplitude from prone to standing was attenuated when a cognitive task was also performed. COP velocity and sway increased as balance task difficulty increased but were not different in single vs. dual-task conditions.

Our preliminary results in YA show that spinal excitability modulation from prone to standing was not affected by balance task difficulty but was attenuated with the addition of a cognitive task. Ongoing work comparing YA and OA will elucidate the effects of aging and dual-task difficulty on spinal circuits, laying the foundation for future studies to better understand and treat aging-related balance deficits.

4-F-72 - Dual task interference from auditory and visual secondary tasks do not interfere with walking in young adults with ADHD

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Details

Attention deficit hyperactivity disorder (ADHD) is a neurodevelopmental disorder defined by impaired levels of inattention, disorganization, and/or hyperactivity. ADHD is considered an executive function disorder - characterized by being unable to stay focused in the face of distraction, or flexibly allocate attention when presented more than one stimulus. This inability to remain focused may make it difficult to do two things at one time, or dual task. Dual task is a paradigm used to quantify allocation of attention by asking subjects to perform two tasks consecutively and measuring the difference in their performance when performing the tasks individually to their performance while completing them together. Typical paradigms use walking and a cognitive task. The type of cognitive task may be important in ADHD because people diagnosed with ADHD tend to exhibit poorer responses to auditory and visual stimuli compared to their typically developing peers, with a tendency to fare worse in response to visual stimuli rather than auditory. The purpose of this study was to examine the difference in dual task cost (DTC) between auditory and visual task stimuli in persons with ADHD tendencies. The hypothesis was people with ADHD tendencies would experience a higher cost of dual task under visual stimuli than with the auditory stimuli. To test this, 19 subjects (21.26 ±0.93 yrs) who scored **‰¥** 17 on the Adult ADHD Self-Report Scale completed 5 randomized 1-min collections of single task (ST) walking, ST Stroop Color test, ST Dichotic Listening, dual task (DT) Stroop (walking while performing the test), and DT Dichotic Listening. DTC was calculated as ((DT-ST)/ST). The cognitive DTC was calculated using the percent correct answer difference. The gait DTC was calculated for step width and gait speed. Step width and gait speed were examined as both step width and gait speed are thought to indicate stability while walking. Both the signed and absolute DTC values were analyzed to examine the direction and magnitude of the change, respectively. Wilcoxon-signed rank tests were used to compare DTC between visual and auditory tasks for percent correct, gait speed, and step width (Î±=0.05). The absolute value of the cognitive DTC was found to have significance (p=<0.001), with the auditory stimuli having a higher DTC than the visual. All other comparisons were not significant. Based on findings, little to no evidence was found to support the hypothesis. There was not a higher DTC seen under the visual stimuli. This might be due to attentional deficiency being modality specific within each subject, impaired left to right hemisphere transfer of information, and delayed maturation of the auditory system. It could also be due to the small sample size, the lack of a formal ADHD diagnosis, and not accounting for any ADHD medications taken. Future studies should examine those with a formal ADHD diagnosis, control for medications taken, and consider a larger sample size.

4-F-73 - The role of postural demands on tactile perception in young and older adults

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Details

Tactile signals provide key information about the state of one’s own body. However, human movement leads to the suppression of tactile feedback signals that arise on a moving limb. The strength of suppression can be reduced when feedback signals are important for the task at hand, but can increase when one’s own sensory receptors are degraded, such as in aging. The degradation of feedback signals might be compensated by relying more on predictive signals for motor control. In this study, we examined how different postural demands while retaining an upright stance influence the weighting of tactile feedback signals from the standing limb across different age groups.
We tested young (18 - 35 years) and older (56 - 72 years) adults in a stance retention task. To probe tactile suppression, we applied a brief vibrotactile stimulus (50 ms) of different intensities on the participant’s calf with a random delay of 2-3 s after trial onset. Participants had to indicate after each trial whether they had felt the vibration. The experiment consisted of three conditions presented in random order that varied in postural demands: (i) sitting, (ii) normal standing, and (iii) standing on foam. For the latter two conditions, participants stood on a force plate which was used to quantify whether their postural sway (center of pressure; CoP) was influenced by the standing demands. We quantified postural sway as the CoP distance traveled during a trial and the size of a 95% confidence interval ellipse of the CoP data. The

detection threshold was estimated with an adaptive QUEST algorithm to construct an individual stimulus range of 13 equally spaced stimulus intensities symmetrically distributed around the QUEST estimation. We then fitted the responses to these 13 stimulus levels to a psychometric function to estimate the detection threshold (50% correct) for each condition.
As expected, posture was less stable when standing on foam than on a rigid surface, independent of age; but standing on foam led to greater sway in older than young adults. Moreover, older adults had generally poorer tactile perception than young adults. While tactile perception was similar between sitting and standing, tactile feedback signals when standing were down-weighted when postural demands increased, and this suppression was more evident in older age. This suggests weaker reliance on the degraded tactile feedback, probably in addition to increased masking of the probing tactile stimulus by amplified afferent input due to larger sways.

4-F-74 - The Nodulus and Uvula in the primate cerebellum integrate vestibular and neck proprioceptive sensory information

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Details

The nodulus and uvula (NU) are known to integrate vestibular signals from the canals and otoliths to represent our orientation and self-motion. This orientation and self-motion information is essential for generating appropriate motor commands to maintain stable gaze and posture. However, since the vestibular organs are located in the head, the brain must use other sensory information to estimate motion of the body and generate appropriate reflexes to stabilize head and body posture. As a hub of receiving vestibular input, the NU is a likely candidate for integrating proprioceptive cues along with vestibular input to provide self-motion information to downstream targets in the vestibular and deep cerebellar nuclei. However, to date, it is unknown how or if the NU responds to neck proprioceptive signals alone and along with vestibular input.

We first characterized NU Purkinje cell responses to vestibular and neck proprioceptive stimulation independently in two rhesus monkeys. Of our 118 Purkinje cells that were sensitive to vestibular stimulation in the anteroposterior (AP) direction (whole-body translations), the majority (116) were also sensitive to neck proprioceptive stimulation (body-under-head translations). Results were similar during mediolateral (ML) translations. Based on each Purkinje cell's response in the AP and ML directions, we estimated preferred response directions and found that, as a group, preferred directions tended to cluster around 45 degrees (i.e., around the canal axis). Interestingly, we found a similar preferred direction for responses to proprioceptive stimulation. Thus, these preferred directions might facilitate the integration of proprioceptive and otolith along with canal signals of head motion. Next, we tested how NU Purkinje cells combine vestibular and neck proprioceptive signals when experienced concurrently (head-on-body translations). We found the linear addition of vestibular and neck proprioceptive responses independently predicted the phase of the response to combined stimulation reasonably well. Importantly, on average, responses to vestibular and proprioceptive stimulation tended to be additive, producing stronger modulation during head-on-body motion compared to vestibular stimulation alone. Finally, we tested how static head-on-body position altered Purkinje cell dynamic responses to vestibular stimulation in the naso-occipital direction. We found that Purkinje cell vestibular responses were modulated by static neck proprioceptive cues, with stronger responses during static ipsilateral head turns. This modulation by proprioceptive cues could facilitate the generation of appropriate reflexes based on the configuration of the body relative to the vestibular signals of head motion.

Our findings demonstrate that the NU integrates neck proprioceptive cues in such a way as to enhance the encoding of head motion and take into account the static configuration of the body to generate appropriate motor commands.

4-F-75 - Spinal networks act as a continuous attractor during pause of movement

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Details

How does a cat gracefully walk and suddenly freeze its ongoing movement when spotting a mouse? The common wisdom attributes this ability to neural circuits within the spinal cord that are well-known for their ability to generate rhythmic movements, doing so in symphony with the brain. However, the mechanisms behind this generation remain unclear. While the prevailing view suggests the existence of specialized modules for distinct functions, recent observations, including rotational neural activity during rhythmic limb movement (LindÉn 2022), challenge this perspective. Furthermore, the precise means by which the neural circuitry achieves a pause in ongoing movement across any posture remains elusive.

To investigate how spinal neural networks execute locomotion that can be paused at any point, we utilized high-density electrophysiology in rat spinal cords during voluntary locomotion, coupled with optogenetic perturbation of the pedunculo-pontine nucleus, a known regulator of movement arrest (Goni-Erro 2023). We present compelling evidence supporting the existence of continuous network attractor properties within the spinal network. We find that during volitional locomotion, the neuronal manifold activity exhibits robust rotational patterns, whose topology is invariant at various speeds and across animals. Furthermore, this trajectory converges to a stable point-attractor precisely at the moment of motor arrest, and it persists in this specific configuration until the movement is continued on the initial trajectory. Through computational modeling, we argue that the network is analogous to a Continuous Attractor Network (CAN), which has been demonstrated in grid cells of the entorhinal cortex associated with memory storage and retrieval (Gardner 2022). We finally suggest specific structural mechanisms by which the network is physically implemented and controlled to transition between locomotion and pause.

In light of these observations, we propose the presence of a CAN-analogous spinal network with rotational properties as the mechanism behind generation as well as the arrest of ongoing movement.

4-F-76 - The relationship between corticospinal tract connectivity and balance performance during non-steady state walking

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Details

The corticospinal tract (CST) is the major descending motor pathway involved in mediating motor coordination of skilled movements. Although, theoretically there can be limited involvement of CST during steady-state walking, our previous work demonstrated that damage to CST following stroke, is associated with worse lower extremity Fugl-Meyer scores, poor muscle coordination patterns (fewer modules), slower walking speeds, and poor propulsion symmetry (a quantitative measurement of the coordinated output of the paretic and non-paretic leg for creating a forward propulsive force during walking). However, the influence of decreased CST connectivity following stroke on volitional non-steady state walking mobility tasks (which are expected to depend on CST) is not known. In the current study our goal is to evaluate the relationship between CST connectivity and balance performance during non-steady state walking typically observed in community walking. Community dwelling stroke survivors often present with impaired balance that can result in falls, fear of falls and limited independence in walking. Therefore, better understanding of the underlying neural mechanisms is needed to improve treatment focused on improving balance and mobility in stroke population.
30 stroke survivors were included in the current analysis. Individuals walked on the treadmill at four different task conditions in a randomized order including self-selected speeds (SS), fast walking speeds (FS), speeding-up from SS to FS, and slowing down from FS to SS. Diffusion based imaging was used to compute the CST connectivity on the lesioned and non-lesioned hemispheres. Interhemispheric asymmetry computed as the ratio of CST fibers between the two hemispheres was used for further analysis (CST asymmetry). Fluctuation of whole-body angular momentum in frontal plane (a measure of global balance during walking) was used to quantify balance performance (H_R). To evaluate the effects of CST asymmetry on H_R during different mobility tasks, a linear mixed model was used with task, CST asymmetry, and task X CST asymmetry interaction as fixed effects, participants were included as random effects. Significance level was set at $p=0.05$. We found a significant main effect of task ($p<0.001$) and task X CST asymmetry interaction ($p=0.04$). We did not find any significant main effect of CST asymmetry. These results suggest that CST asymmetry influences balance performance during non-steady state walking mobility tasks consistent with the increased CST demands expected for the volitional tasks. Future studies are needed to evaluate the effect of additional underlying factors that are associated with impaired balance such as impaired cognitive function and impaired muscle coordination (fewer modules). This multimodal approach will provide a comprehensive understanding of underlying neural, motor, and cognitive mechanisms of impaired balance and help design patient specific treatment approaches.

4-F-77 - Conscious movement processing maladaptively reduces the cortical N1 response to discrete balance perturbations in healthy adults.

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Details

Background: Balance performance can suffer when individuals direct too much attention towards the conscious control of their movements (i.e., conscious motor processing; CMP). However, the underlying

neural mechanisms through which CMP exerts its influence upon balance remain poorly understood. The present study therefore explored the direct effects of CMP on electroencephalographic (EEG) perturbation-evoked cortical (i.e. N1) responses and subsequent postural control performance.
Methods: Twenty healthy young adults (mean age 25.1 ± 5 years) stood on a force plate-embedded moveable platform whilst mobile EEG was recorded. Participants completed two blocks of 50 discrete perturbations containing an even mix of slower (186 mm/s) and faster (225 mm/s) perturbations. One block was performed under conditions designed to induce CMP, whilst the other block was performed under 'Control' conditions (no additional instructions provided).
Results: Cortical N1 signals were larger for faster perturbations, and larger cortical N1 signals were generally associated with greater peak centre of pressure (COP) velocities (i.e., poorer postural control). However, for both slow and fast perturbations, CMP resulted in significantly smaller cortical N1 signals and significantly greater peak COP velocities compared to the Control condition.
Discussion: The present findings provide the first evidence that the maladaptive effects of CMP upon balance appear to be expressed by insufficient activation at the cortex (i.e., insufficient cortical N1 responses). We propose that conscious attempts to minimise postural instability through CMP acts as a cognitive dual-task that dampens the sensitivity of the sensorimotor system for future losses of balance.

4-F-78 - Motor unit coordination during locomotion in mice

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Details

Coordinated neural inputs within and across muscles drive complex behaviors. Motor units, each of which consists of a single motor neuron and all the muscle fibers it innervates, generate the forces behind movement through their recruitment and rate of firing. Neural control strategies behind dynamic movements, such as locomotion, rely on the appropriate activation of motor units, accounting for the biomechanical context of the muscle. Using novel electrodes we developed (Myomatrix arrays), we recorded directly from motor units across different heads of the triceps in freely walking mice. Combining these high-resolution recordings with quantitative behavioral analysis revealed how motor unit spike patterns are coordinated with the movement and each other. Motor units in the long head of the triceps were primarily active early in the stance phase of each stride. Firing rates of these units either remained constant or scaled with the walking speed (0.1 "" 0.3 m/s). Lateral head units came on partway through stance until terminating around swing onset. Firing rates of these units increased drastically for faster walking speeds. These different firing patterns across muscles reflect the types of units measured and their role within the motor pool towards driving coordinated limb movement. Ensemble analysis of simultaneously recorded units demonstrated complex patterns of co-timing across motor units, including epochs of highly ordered recruitment and variable de-recruitment. Lateral head units tended to have more random de-recruitment, likely because of the rapid unloading in the muscle right before the swing phase. Activation of additional units within a stride also tended to decrease the firing rates of those previously active, possibly reflecting the inhibitory interneuron circuitry in the spinal cord that functionally links motor neurons. Overall, we demonstrated different neural coordination patterns, even for closely associated muscles, that the central nervous system uses to regulate limb movement across locomotor speeds. Future work will build on these results to manipulate genetically defined spinal populations and dissect interneuron contributions to locomotor coordination.

4-F-79 - Neural correlates of complex arm reaches during different full-body contexts in freely moving rhesus macaques

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Details

Systems neuroscience of goal-directed behavior aims to understand processes involved in perceiving, planning, and executing actions towards specific objectives. Various regions of frontoparietal cortex are known to contribute to goal-directed reach behavior, for example. Yet, the natural repertoire of skeletomotor behaviors in primates goes far beyond single-limb reaching or periodic movements like walking. More complex behaviors, such as foraging in complex or social environments, remain hardly explored.

To overcome these limitations, we introduce a free-foraging paradigm called the Playground Experiment (PE), designed to induce a rich repertoire of full-body actions in rhesus macaques. We encouraged complex, ecologically relevant behaviors in our recently introduced highly modular Exploration Room (ExR) setup by simultaneously offering monkeys 12 stations: two wall-mounted touchscreen-based kiosk systems (XBIs) providing fluid rewards upon touch, four flexible strings (artificial branches) providing access to hanging grapes when pulling them down against varying physical resistances, and six strategically positioned litter piles through which the monkeys had to search to retrieve treats.

To track and classify the complex behavioral data, a novel approach combining image-based 2D action classification with 3D keypoint tracking is proposed. Leveraging our newly developed Primate-FairMOT model for action classification, transition behaviors during station switching and station interactions are successfully identified using a minimal camera setup of only four cameras covering the ExR with close to $30m^3$. The results demonstrate that different station types consistently evoke distinct full-body actions across sessions and animals in both solo and dyadic experiments.

Furthermore, the combination of PE and Primate-FairMOT facilitates the application of established epoch-averaging analysis methods. A comparison of goal-directed arm reaches during different station-specific postures reveals varying behavioral characteristics, e.g. wrist velocities, dependent on the behavioral context. Intriguingly, neural findings indicate that, when presented with multiple available full-body behavioral contexts simultaneously, single neurons in the dorsal premotor (PMd) and primary motor cortex (M1) are not modulated by wrist velocity alone but exhibit selectivity for specific full-body contexts. This is corroborated on the population level through a dynamical systems approach, revealing neural trajectories separating on a “behavioral-context” axis independent of differences in wrist velocities.

In conclusion, the integration of PE in the Exploration Room together with Primate-FairMOT offers a powerful framework for investigating neural dynamics associated with a diverse repertoire of full-body actions in complex and social environments. The findings contribute to a deeper understanding of the neural correlates of complex behaviors beyond traditional paradigms.

4-G-80 - Natural walking would require dynamic reflex gain modulation : computational study

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Details

Theoretical frameworks for neuromuscular control, including reflex [1] and synergy [2] models, have been explored through forward dynamics simulations. However, computational research examining the role of supraspinal signals and reflex gain modulation on walking dynamics remains scarce. The purpose of the study is to investigate the necessity of reflex and its neural modulation during walking, as shown in the experimental studies [3]. We hypothesize that the spinal reflex can respond to unexpected perturbation, while the supraspinal modulation is required to generate natural motion.

The musculoskeletal model in RaiSim has 14 degrees of freedom and 22 hill-type muscles on the lower body. We implemented three neural controller models for the walking motion. The first model is the reflex-based circuit model from Song & Geyer [1] (model A). Feedback gains in this model are different for stance and swing but are constant within each gait phase [1]. We modified model A to modulate the gains based on information on the body's state (model B). We modeled gain modulation by a multilayer perceptron (MLP) with an input delay of 100 ms that outputs gating variables of the gain. Lastly, we trained a model with only supraspinal control, as a MLP with an input delay of 100 ms whose output is muscle excitation (model C). Every learnable parameter, including reflex gains and weights in MLP, was jointly optimized using reinforcement learning with proximal policy optimization with Deepmimic [4] and activation minimization rewards. The reference motion of a subject from the CMU motion capture dataset was used.

Previous studies reported that soleus muscle reflexes had higher amplitude during the stance phase [3]. This could be reproduced in our simulation, as model B showed higher average gating variables of 0.41 during stance than 0.27 during swing. The root mean squared error (RMSE) between the simulation and the reference motion for five successive gait cycles was compared between model A and B. Model B showed lower RMSE (hip 3.9 °, knee 4.3 °, ankle 7.4 °) than model A (hip 5.7 °, knee 11.7 °, ankle 12.7 °). Models B and C were also tested for walking under anterior and posterior force perturbations on the pelvis for 200 ms at toe-off. Model B could maintain balance at higher perturbation forces (anterior 1.2 BW, posterior 1.8 BW) than model C (anterior 1.0 BW, posterior 1.2 BW).

Appropriate modulation of the feedback response was necessary to generate natural walking motion. Robustness to perturbation during walking could take advantage of the short feedback. The results supported the hypotheses about the role of reflex and its modulation. Further simulation studies with neuromuscular control models may provide more understanding of the nervous system.

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4-G-82 - Sequential learning in recurrent neural networks create memory traces of learned tasks

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Details

Animals can learn and perform many behaviors without interference. However, it is unclear how changes in neural activity during learning avoid interference with activity underlying similar behaviors. Recently, Losey et al. (bioRxiv, 2022) identified a possible neural substrate by examining monkey motor cortical population activity under a brain-computer interface (BCI) paradigm where linear mappings controlled a computer cursor. The activity produced for a known mapping was altered after learning a new mapping in a way that made the activity more beneficial for this new mapping. That is, the activity retained a “memory trace” of the new mapping without compromising the performance for the already known mapping. Since these memory traces suggest a potential substrate for continual learning, we sought to understand how and when they arise.

To probe the effects of different learning processes on the memory trace, we modeled motor cortical neural activity during the same BCI paradigm using a recurrent neural network. We replicated several experimental results by sequentially training the network on two mappings that required activity in the same low-dimensional subspace, or manifold, representing “within-manifold” perturbations. Intriguingly, we observed memory traces even when network activity was not specifically constrained to maintain both maps. Thus, memory traces may inherently arise from sequential learning. While the presence of these traces was consistent across different BCI maps, their magnitudes differed greatly. Initial changes in behavior imposed by a given mapping were a good predictor of the memory trace’s magnitude, but initial changes in network activity were not. This allowed us to characterize, for the first time, differences in learning between different BCI mappings that represent easily-learnable within-manifold perturbations. When we controlled for the initial changes in behavior, mappings representing “outside-manifold” (OM) perturbations led to larger memory traces than those representing “within-manifold” (WM) perturbations. Although OM mappings were learned more slowly, activity related to OM mappings were retained more following the perturbation, suggesting that OM mappings can coexist without interference more easily. When we included an upstream network and restricted learning to the upstream network, we saw smaller memory traces, suggesting that the locations of learning are also important for continual learning. Overall, we provide a taxonomy of the neural and behavioral factors shaping continual BCI learning, allowing us to examine potential underlying mechanisms and behavioral constraints in future work.

4-G-83 - Advancing prosthetic control: a dilated causal CNN-enhanced transformer framework for natural hand kinematics

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Details

Achieving parity with the dexterity and adaptability of the human hand remains a formidable challenge in bionics and neural engineering. A major challenge in hand prosthetic control lies in the intricate task of accurately interpreting user intent from muscle signals. Existing prosthetic hands decode a limited set of predefined motions, offering proportional control over overall hand movements. This work focuses on developing a framework to enable users to control individual joints of an artificial hand naturally, similar to human hand movement. We introduce a new method for interpreting neural data, allowing users to independently manipulate 11 hand joints continuously. We tested this framework with six able-bodied individuals, who performed everyday object manipulation tasks, including dynamic movements like grasping and static tasks like squeezing. We captured the electromyographic signals from five extrinsic hand muscles in the forearm, concurrently with monitoring the movements of 11 hand and finger joints using a sensor-equipped data glove. Rather than merely establishing a direct correspondence between current muscle activity and intended hand movements, we devised a novel time-series transformer mechanism that combines muscle activity with past joint movements to estimate future joint movements. Specifically, our multivariate time series prediction framework is grounded on a transformer model architecture comprising convolutional neural networks (CNNs). Specifically, the model architecture leverages dilated causal CNNs (DCC-T) when processing the multivariate time series input before the encoder and decoder blocks of the transformer model, effectively capturing temporal features from different possibilities and concurrently by condensing lengthy information inputs. This holistic approach addresses the challenge of analysing temporal features within the input data and reducing computational load, limitations prevalent in existing forecasting models. We evaluated the impact of different configurations of the CNN structure within the prediction model on forecasting accuracy for a horizon of 7s. At $p<0.05$, our approach featuring a dilation rate of 1 (DCC1-T) exhibited superior performance, with a mean RMSE of 1.2 °, outperforming the conventional transformer model (mean RMSE: 1.48 °) and LSTM model (mean RMSE: 7.52 °). Moreover, compared to DCC1-T (36.736k trainable parameters), the proposed approach with a dilation rate of 2 (DCC2-T) requires less computational cost (35.433k trainable parameters) with a mean RMSE of 1.37 °, still more effective than conventional transformer model in predicting joint movements. Our findings underscore the effectiveness of the DCC-T method, especially when combined with electromyography inputs. This approach shows potential for enhancing natural and intuitive control in neurotechnology applications, particularly in prosthetic limbs where intricate dexterity is crucial for complex movements.

4-G-84 - Action-based and sensory-based temporal predictions differentially dampen the perception of expected touch

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Details

Predictions based on our motor commands are known to attenuate the perception of self-generated touches compared to externally generated ones. Theoretically, this attenuation stems from a temporal prediction of the somatosensory consequences of one's action based on an 'efference copy'. For instance, we can't tickle ourselves because our brain predicts our self-generated touches in time (action-based prediction). External touches can also be predictable when cued in time, such as anticipating our dancing partner's movements on the music's rhythm and melody (sensory-based prediction). However, very little is known about how sensory-based temporal predictions affect somatosensory perception, particularly in relation to action-based temporal predictions, due to limited research and earlier conflicting findings. Here, we investigated how these two types of temporal predictions affect somatosensory perception. By including both in a single paradigm, we further tested their potential interactions. In a force discrimination task, participants judged the intensity of test forces applied to their left index finger relative to a reference force. Two sessions were held on different days: one where the test forces were generated by the subjects' right hand (i.e., action-based predictions), and another where the test forces were external (i.e., no action-based predictions). In both sessions, participants formed sensory-based predictions by experiencing pairs of auditory tones and test forces, where the tone frequency predicted the force onset. Then, in two intermixed conditions, they discriminated test forces delivered either at the time expected by their sensory-based prediction or at an unexpected time. Across both sessions and conditions, we quantified the participants' somatosensory perception (magnitude and precision), and decision-making (reaction time). Furthermore, we used a hierarchical drift diffusion model to model their performance in terms of drift rates of evidence accumulation and decision thresholds. In two experiments external touches were discriminated with lower somatosensory precision but were perceived as having similar magnitude when their onset aligned with sensory-based predictions compared to when it violated them. Conversely, sensory-based predictions did not affect the precision of self-generated touches, which had an attenuated magnitude only when fulfilling the action-based prediction. Reaction times were faster when touch onsets matched sensory-based predictions, for both self-generated and external touches, validating our experimental manipulation. Crucially, computational modelling revealed that sensory-based predictions selectively slowed the drift rate of evidence accumulation for expected external touches, with no analogous effects for self-generated touches. Our results support distinct dampening mechanisms depending on the source of prediction.

4-G-85 - Mind in motion: investigating the interplay of cognition and movement

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Details

Motion and cognition are processes that might share an evolutionary history, as evidenced by the neuronal responses that correspond to the same areas when movement and the thought of movement occur. Given the fact that cognition occurs not only in the head but is also embodied, studying movement might be a direct way of understanding cognitive processes in organisms. Movement has been studied not only as an output of cognitive processes but also as a mediator and predictor of cognition. It has also been used as a measure of executive functions and as a way of understanding spatial cognition. As suggested by other authors, studying behavior through movement might help describe the components of the cognitive algorithms that operate when movement is occurring.

We find it important to focus on studying movement not merely as a causal relationship between brain activity and behavior, but as an active component of a cognitive process, all of this working under an Active Inference framework. By using deep learning algorithms such as DeepLabCut and Keypoint-Moseq to analyze human interaction with objects and the environment, we can describe how movement provides a clue to how humans relate to and understand the materials they have built, shaping their understanding of the environment. As part of the XSCAPE ERC Synergy Grant Project (ERC-2020-SyG 951631), the Material Minds Lab we research the intricate relationship between human interaction with materials and the environment and its profound impact on our perception of the world. Through the study of movement combined with other methodologies, we explore how ancient societies organized themselves based on the materials they crafted, and how our cognition is intertwined with these artifacts.

4-G-86 - Optimal reaching subject to computational and physical constraints reveals structure of the sensorimotor control system

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Details

Optimal feedback control provides an abstract framework that describes the overall structure of the sensorimotor system without prescribing any implementation details at the level of a neural system, such as what coordinate representations to use, how feedback should be incorporated, or how to accommodate changing task complexity. The question therefore arises of how the primate sensorimotor system arrives at its particular form. We approach this question by starting with a computationally and physically constrained model of the sensorimotor system in which all connection weights between neurons, feedback, and muscle are unknown. By optimizing these parameters with respect to a simple objective function, the model develops neuron to muscle connectivity patterns similar to observed muscle fields, cosine tuning curves, and other characteristics of M1 motor neurons. We find that the optimization process results in a preference for an intrinsic (joint angle) coordinate representation of inputs and feedback, and that it produces a system that calculates a weighted feedforward and feedback error. Further, we show that in more complex reaches around an obstacle, the computational limitations of a linear system require additional inputs from a separate nonlinear path planning system akin to premotor cortex. We propose a form for this path planner based on the concept of via points and find that, in a neural network implementation, neurons segregate into groups of "avoidance" neurons that encode the rough direction for reaches to go around an obstacle and serve as a bias, and “placement” neurons that make more fine-tuned adjustments to the via point placement in specific regions of space and reach directions. Our results demonstrate both the surprising capability of computationally constrained systems and how their limitations inform coordinate choices and other observed characteristics of the sensorimotor system.

4-G-87 - Shannon entropy as a framework for redundancy problem

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Details

In our daily lives, the movements of our bodies often present a captivating puzzle: the degrees of freedom problem. Consider reaching for a cup of coffee, a seemingly simple task executed with perfection by the body. However, upon closer inspection, the analysis of this motion becomes an intricate challenge mainly due to the vast number of neurological, muscular, skeletal, and task-space variables at play. How does the nervous system handle this complexity? Constraints play a pivotal role in determining the available degrees of freedom for motion and coordination: anatomical, task-specific, and internal control constraints. However, our capabilities to extract information from these constraints are limited and require additional tools. For example, a solution might not represent the best, most optimal, or necessary one, yet the nervous system might employ it. Moreover, some elements within the solution set might be heavily utilized while others are sparingly used, and some may never be employed throughout our lives. Such information should be considered for redundancy problems and can be derived from human-generated data. We suggest utilizing statistical information that encapsulates data characteristics and properties for additional constraints. Therefore, we propose a framework for exploiting statistical constraints: Shannon entropy. Statistical moments such as expectation, variance, skewness, and kurtosis can be incorporated into the Shannon equation as constraints. Subsequently, employing the principle of maximum entropy, we can obtain the probability distribution that best represents the current information state. To demonstrate the potential applicability of this method in multi-joint movements, we selected the drawing task in a two-dimensional plane. The hand's endpoint was permitted to move in a vertical plane while the shoulder, elbow, and wrist joints were restricted to a single degree of rotational freedom. Mathematically, this system is redundant since we have three unknowns and two kinematic equations. We calculated all sets of joint configurations that leave the hand's endpoint unchanged and their respective potential energies within the hand's workspace. We assumed the nervous system would not employ configurations with equal likelihood, as they have varying potential energies within a set. Consequently, we generated data with diverse expectations and variances within a solution set. These statistical constraints are added to the Shannon equation, and probability distributions are approximated. The study showed joint configurations with potential energy near the expected value have a higher likelihood, whereas those further away have a lower likelihood. In addition, the spread of joint configurations was controlled by variance. Based on the available information, this methodology presents the optimal probability distribution of the elements in the solution set instead of decreasing the number of solutions.

4-G-88 - Modeling the contribution of sensory feedback and internal models on motor cortex activity dynamics and task execution

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Details

Little is known about how the sensory feedback and internal forward models shape motor cortex (MC) dynamics during movement generation. We take a modeling perspective to probe this question. Goal-driven models of MC based on recurrent neural networks (RNNs) when trained to transform high-level task-specific inputs into experimentally observed EMG exhibit rotational dynamics resembling the MC rotational activity patterns. Therefore, it is assumed that the intrinsic recurrent connections of MC give rise to its experimentally observed rotational dynamics with negligible contribution from sensory feedback. However, recent studies show that the models of MC based on feedforward networks without any recurrent connections also exhibit rotational activity patterns when trained to transform proprioceptive feedback into muscle activations, thus suggesting that sensory feedback contributes substantially to MC rotational dynamics. In order to evaluate these conflicting theories about the role of sensory feedback in MC dynamics, we develop a biophysically and anatomically accurate feedback-driven sensorimotor framework.

The developed goal-driven dynamical systems model of MC, termed Musculo-RNN, transforms sensory feedback along with a high-level task-specific scalar input into muscle excitations using an RNN. The Musculo-RNN controls an anatomically-accurate musculoskeletal model of a non-human primate to produce experimentally recorded kinematics from muscle excitations. While training, we also implement neural constraints, e.g., minimization of neural firing rates, that govern neural dynamics. We found that the Musculo-RNN, trained using deep reinforcement learning, successfully reproduces the experimental kinematics and exhibits the experimentally observed rotational MC activity patterns even on unseen testing conditions that are significantly different from training.

To dissect the role of sensory inputs, we perform ablation studies by eliminating specific inputs to the Musculo-RNN and observe its effect on resulting movement kinematics and network activity patterns. Surprisingly, we found that the ablation of sensory feedback still gives rise to rotational activity patterns. However, the network is not able to achieve desired movement kinematics. Moreover, the ablation of only the task-specific scalar input disrupts the separation of rotational dynamics trajectories across different conditions. The task-specific scalar input may thus reflect communication from the upstream brain regions representing the internal forward models that the network uses to separate the rotational trajectories across different conditions. Therefore, we conclude that while the intrinsic recurrent connections of MC can give rise to observed rotational dynamics, these rotational dynamics alone do not guarantee accurate task execution. These rotational dynamics are then harnessed by sensory brain regions and task-specific internal models to achieve the desired movement.

4-G-89 - The impact of haptic communication on coordination and role distribution in collaborative object manipulation

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Details

Motor control research predominantly explores tasks requiring humans to independently adapt to environmental dynamics or manipulate objects. These dynamics are often restricted to specific mappings, the object's properties, or physical laws. However, interactions in the real world require us to continually adjust to what other people are doing - for example, to our teammates and opponents in basketball. Introducing other autonomous agents into these motor control scenarios makes the interaction bidirectional and less predictable, thus elevating task complexity. The underlying mechanisms enabling humans to coordinate with and distribute tasks among collaborators remain to be fully understood. Previous studies on collaborative target tracking or object manipulation have shown that haptic feedback is a key communication channel. However, these tasks often tightly limit the range of possible behaviors for collaborators, leaving little room for autonomous action. How do collaborators utilize haptic feedback in complex tasks requiring close coordination, especially when they have wider ranges for individual strategies? Addressing this, we designed a series of studies where participants, either two humans or a human and an artificial agent, were tasked with jointly controlling a board to roll a ball on it into a target area in a virtual environment with different haptic conditions. As the ball can only be indirectly controlled, this task demands high coordination between partners for success. First, unlike most previous studies where haptic feedback often improved task performance, we found no significant difference in task completion time with or without haptic feedback. Notably, the absence of haptic feedback led to more pronounced leader-follower roles, i.e., the leader became more dominant while the follower became more passive. This could be the mechanism adopted by the participants to compensate for the missing haptic communication. Next, we observed that haptic communication improved the coordination between the collaborating agents. Interestingly, the coordination only improved when the follower, not the leader, received haptic feedback. To the best of our knowledge, this is the first time that a distinction in the utility of haptic communication between leaders and followers has been found. Finally, we investigated whether different sources of haptic information affect performance differently. We provided participants with haptic feedback from only the environment or the partner and compared it with full or no haptic feedback. Results showed that the coordination was only enhanced by the haptic feedback from the partner but not the environment. We show that humans can extract partner-specific signals from the combined feedback. Overall, we show how humans manage the unpredictability introduced by another agent's autonomy and how they employ haptic feedback to improve coordination.

Thank you

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