abstract
book

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Satellite Meeting

Session 1: Peripheral vestibular processing

Vestibular peripheral processing during natural self-motion: Implications for perception and action

Kathleen Cullen

Johns Hopkins University

A fundamental question in neuroscience is: How does the brain compute accurate estimates of our self-motion relative to the world in everyday life. In this talk, I will describe recent findings from my laboratory that have provided new insights into how the vestibular peripheral afferents encode self-motion.

We first examined the statistics of the natural self-motion signals and then explored the coding strategies used to encode these stimuli by semicircular canal and otolith afferents in primates.

Canal Afferents: We found 2 distinct information channels in the canal system: The firing rates of regular afferents transmitted more information, compared to irregular afferents. In contrast, irregular but not regular afferents reliably discriminate between different stimulus waveforms through differential patterns of precise (~6 ms) spike timing, Otolith Afferents: We also found 2 distinct information channels in otolith system: Irregular otolith afferents transmitted more information about dynamic stimuli via both rate coding and precise spike timing (including phase locking). In contrast, regular afferents better discriminated between different static head orientations relative to gravity.

We then explored whether canal and otolith afferents differentially encode active versus passive self-motion during natural behaviors including locomotion in primates. Recordings were made from individual semicircular canal and otolith afferents during walking and running in monkeys. Using a combination of mathematical modeling and nonlinear analysis, we establish that that afferent encoding is actually identical across passive and active conditions, irrespective of context. Thus, taken together our results are instead consistent with the view that the vestibular periphery relays robust information to the brain during primate locomotion, suggesting that context-dependent modulation instead occurs centrally to ensure that coding is consistent with behavioral goals during locomotion.

Taken together, these findings have important implications for our understanding of the brain mechanisms that ensure stable perception and accurate behaviour as we move through and explore our world.

Discharge properties of neurons in the 8th nerve, vestibular nucleus and abducens nucleus may explain suboptimal VOR characteristics in response to neuroprosthetic stimulation

James Phillips

University of Washington

Neural basis of VEMP Testing: Canal and Otolith afferent responses to clicks and tone bursts

Hong Zhu

University of Mississippi Medical Center

Sound-evoked vestibular myogenic potentials recorded from the sternocleidomastoid muscles (the cervical vestibular-evoked myogenic potential or cVEMP) and the extraocular muscles (the ocular VEMP or oVEMP) have been widely used in clinical assessment of vestibular function. To provide the neural basis for developing discriminative VEMP testing protocols, we employed single vestibular afferent recording technique to examine the extent to which air-conducted click or tone bursts differentially activate the five vestibular end organs. Our results demonstrated that both semicircular canals and otoliths can be activated by sound. However, specific combinations of sound parameters can be used to achieve selective assessment of otolith and canal functions.

Calcium transients in vestibular hair cells and supporting cells

Holly Holman
University of Utah

Calcium ions play numerous roles in vestibular physiology, particularly in hair cell mechanotransduction, mitochondrial bioenergetics, and synaptic transmission. Using a genetically encoded calcium indicator (GCaMP5G), we examined intra- and intercellular calcium transients in the sensory epithelium of the utricle and crista ampullaris in postnatal and adult mice. At birth, utricular hair cells have robust spontaneous calcium transients, which precede spontaneous calcium transients in supporting cells. On postnatal day 3, calcium transients can be evoked by acetylcholine (ACh). Evoked calcium transients in the urticle sensory epithelium exhibit irregular intervals in contrast to the intercellular calcium wave propagation in supporting cells and hair cells in the crista amullaris and organ of Corti of the same inner ear. In the first postnatal week, ATP and ACh evoked calcium transients in supporting cells of the eminentia cruciatum (EC) are significantly faster with more prominent changes in CGaMP (F/F) calcium transients than hair cells and supporting cells in the surrounding crista, utricle, and organ of Corti. Overall, our results provide direct evidence that vestibular supporting cells and hair cells have spontaneous and evoked calcium transients in early postnatal ages, likely affecting vestibular development and function.

Session 2: Central vestibular signals & integration I (eye-head coordination, VOR, reafference, compensation)

Organization of the gravity-sensing system in zebrafish

Martha Bagnall
Washington University

Motor circuits develop in sequence from those governing fast movements to those governing slow. Here we examine whether upstream sensory circuits are organized by similar principles. Using serial-section electron microscopy in larval zebrafish, we generated a complete map of the gravity-sensing (utricular) system spanning from the inner ear to the brainstem. We find that both sensory tuning and developmental sequence are organizing principles of vestibular topography. Patterned rostrocaudal innervation from hair cells to afferents creates an anatomically inferred directional tuning map in the utricular ganglion, forming segregated pathways for rostral and caudal tilt. Furthermore, the mediolateral axis of the ganglion is linked to both developmental sequence and neuronal temporal dynamics. Early-born pathways carrying phasic information preferentially excite fast escape circuits, whereas later-born pathways carrying tonic signals excite slower postural and oculomotor circuits. These results demonstrate that vestibular circuits are organized by tuning direction and dynamics, aligning them with downstream motor circuits and behaviors.

Are the eyes yoked or independent? Evidence from neuroanatomical studies

Paul May
University of Mississippi Medical Center

Mike King brought new life to the theories of Helmhölst by demonstrating that a number of cell populations within the horizontal gaze circuits of the pons show preference for the movement of one eye or the other, instead of binocular coding, as would be expected based on the theories of Hering. This work suggested that during disjunctive saccades, each eye is independently directed when the eyes look between targets located at different distances from the viewer, eliminating the need for a separate vergence signal. We have been examining the premotor populations that control lens accommodation, and believe our findings may shed some light on the long running dispute between the theories of Helmhölst and Hering. This is due to the fact that when looking between targets located at different distances from the viewer, it is also necessary to change the degree of lens accommodation in order to see the target clearly.

The experiments were carried out in Macaca fascicularis monkeys and employed the use of rabies virus as a trans-synaptic retrograde tracer. The n2C strain of rabies virus was injected into the ciliary muscle in order to retrogradely label the circuits controlling lens accommodation. At shorter survival times, we were able to demonstrate labeling of postganglionic motoneurons in the ciliary ganglion and preganglionic motoneurons in the Edinger-Westphal nucleus. At longer survival times, premotor populations became evident. These premotor neurons were located at three locations: the supraoculomotor area (SOA), particularly caudally, the central mesencephalic reticular formation (cMRF), lateral to the medial longitudinal fasciculus, and the tectal longitudinal column (TLC) found on the midline between the colliculi. They were not found in the pons, so the horizontal gaze circuitry can not directly control lens accommodation during disjunctive saccades. The other striking feature of these populations was that they were all distributed bilaterally, even though a single eye had been injected. In order to further examine these bilateral populations, we injected one eye's ciliary muscle with a recombinant rabies virus that fluoresces green and the other eye's ciliary muscle with a recombinant rabies virus that fluoresces red. On each side and in each nucleus, we observed singly labeled red, singly labeled green and doubly labeled neurons.

Since it is likely that many of cells in the SOA and cMRF code for both lens accommodation and vergence angle, we believe that our data suggests that the brain may take advantage of both yoked eye movements (á la Hering) and independent eye movements (á la Helmhölst). In essence, nature takes advantage of both possible mechanisms for controlling lens accommodation and vergence angle. In this regard, the SOA is likely to be particularly important in contributing a position signal to maintain the vergence angle, as well as allowing vergence pursuit, while the cMRF is likely to control disjunctive saccades. The function of the TLC is unknown at this point.

Oculomotor plant hypothesis (OPH) 2.0: Abducens neuron behaviors during combined eye-head gaze shifts, disjunctive smooth pursuit and sleep in monkeys

Wu Zhou
University of Mississippi Medical Center

The motoneurons of the oculomotor system receive inputs from the premotor structures and send motor commands to control the extraocular muscles to generate various types of smooth and ballistic eye movements that either maintain fixation on a target against self and/or target motion (gaze stabilization) or redirect fixation to a new target (gaze shift). The relationship between motoneuron firing rate and eye movement is central to all models of gaze control. Because eye movement is generated by the summed actions of agonist-antagonist extraocular muscles, the relationship between motoneuron firing rate and eye movement should depend on how the agonist-antagonist pairs of extraocular muscles behave during an eye movement. Assuming push-pull actions of agonist-antagonist extraocular muscles, Robinson (1971) proposed the oculomotor plant hypothesis (OPH), which supposes that motoneuron activity is directly related to eye movement, no matter how the eye movement is generated. The OPH greatly simplifies neural models of gaze control and is widely accepted as the common component of current models of gaze control. Using abducens neuron firing rate-horizontal eye movement as a model, here we report that the OPH was violated in three conditions. First, when monkeys made combined eye-head gaze shifts, we found that the abducens neurons exhibited little modulation in their firing rates during the ocular counter rotation (OCR) phase of combined eye-head gaze shifts. Second, when monkeys tracked a target moving along the visual axis of an eye, the monkeys made disjunctive smooth eye movement. We found that their firing rates were substantially modulated when there was no movement in the eye they innervated. Third, when monkeys were in sleep, they exhibited slow drifting eye movements that were often disjunctive. We found that the relationships between abducens firing rate and eye position/velocity were substantially different from that during awake. These results suggest that the OPH, which is valid during single type of eye movement, may not be appropriate during conditions that involve multiple eye movements. These results put important constraints on new models of gaze control in natural conditions.

Neural circuits suppressing brain omnipause-neuron activity and triggering saccadic eye movements

Mayu Takahashi
Tokyo Medical and Dental University

Omnipause neurons (OPNs) in the nucleus raphe interpositus have tonic activity while the eyes are stationary ('fixation'), but stop firing immediately before and during saccades. To determine a saccade triggering signal to suppress OPNs, we analyzed synaptic inputs from the superior colliculi (SCs) to OPNs by using intracellular recording and staining, and investigated pathways transmitting the input in anesthetized cats. Electrophysiologically- or morphologically-identified OPNs received monosynaptic excitation from the rostral SCs with contralateral dominance, and received disynaptic inhibition from the caudal SCs with ipsilateral dominance. Cutting the tectoreticular tract transversely between the contralateral OPN and inhibitory burst neuron (IBN) regions eliminated inhibition from the caudal SCs, but not excitation from the rostral SCs in OPNs. In contrast, a midline section between IBN regions eliminated disynaptic inhibition in OPNs from the caudal SCs, but did not affect the monosynaptic excitation from the rostral SCs. Stimulation of the contralateral IBN region evoked monosynaptic inhibition in OPNs, which was facilitated by preconditioning SC stimulation. Three-dimensional reconstruction of HRP-stained cells revealed that individual OPNs have axons that terminate contralaterally in the contralateral IBN area, and

that individual IBNs project to the contralateral OPN area. The present findings suggest that during fixation, OPNs are tonically excited by the rostral SCs. Prior to saccades, OPNs are disfacilitated by decreased excitatory input from the rostral SCs, and simultaneously inhibited by IBNs that are activated by increased caudal SC activity. Thus, IBNs shut down OPN firing and help trigger saccades and suppress ('latch') OPN activity during saccades.

Coding strategies for representing natural self-motion across ascending vestibular pathways

Jerome Carriot
McGill University

Understanding the neural mechanisms by which sensory input gives rise to perception and behavior requires knowledge of how the sensory representation changes across successive brain areas. Here we investigated how natural self-motion stimuli are represented at distinct stages of processing in ascending vestibular pathways from the level of the subcortical vestibular nuclei to central cortical areas that contribute to both vital reflexes as well as spatial perception. We recorded the activity of single neurons within the vestibular nuclei (VN), the ventral posterior lateral (VPL) Thalamus, and the parieto-insular vestibular cortex (PIVC), in response to both artificial (sinusoidal) and naturalistic self-motion. We first found that responses to artificial self-motion stimuli were similar across stages and consisted of changes in firing rate that followed the stimulus' detailed timecourse. In contrast, we found that neurons at each of these three distinct stages demonstrate increasingly optimized encoding for naturalistic self-motion stimuli.

Specifically, while VN neurons transmitted information about naturalistic self-motion through a combination of changes in firing rate and precise spike timing, VPL neurons efficiently and unambiguously represented self-motion exclusively through changes in firing rate. Surprisingly, we further found that PIVC neurons reliably signaled the occurrence of specific stimulus features via bursts of firing. In contrast, individual PIVC neurons do not provide reliable information as to the stimulus' detailed timecourse but instead fire bursts of action potentials that reliably detect rapid changes in head velocity during naturalistic. Further analysis at the population level revealed that the representation of naturalistic self-motion stimuli is distributed across PIVC neurons, as pooling their activities provided reliable information as to the stimulus' detailed timecourse.

Taken together, our results show an evolution in the coding strategy used by ascending vestibular pathways - from the vestibular nuclei to cortex to represent naturalistic self-motion. Notably, neurons at each level respond in a fundamentally different manner to naturalistic as opposed to artificial self-motion stimuli. Perhaps the most striking difference was found in PIVC neurons, which responded to artificial self-motion stimuli through changes in firing rates that followed the stimulus' detailed timecourse but instead reliably detected features of naturalistic self-motion stimuli through burst firing. This finding suggests that our perception of natural self-motion stimuli differs fundamentally from that of artificial self-motion stimuli that have been used to date and that a critical rethinking of self-motion perception may be necessary.

Session 3: Central vestibular signals & integration II (motor learning, eye-hand coordination, self-motion/navigation, central balance control, ascending vestibular signals for navigation and heading)

Eye movements for active sensing and memory during visually-guided navigation

Dora Angelaki
New York University

We will summarize recent findings on the role of active sensing (gaze) in planning and memory. By analyzing the spatial distribution of human gaze to transiently visible goals in simple and complex virtual mazes we found that environmental complexity mediated a striking tradeoff in the extent to which attention was directed towards two complimentary aspects of the world model: the reward location and task-relevant transitions. The temporal evolution of gaze revealed rapid, sequential prospection of the future path, evocative of hippocampal neural replay. These findings suggest that the spatiotemporal characteristics of gaze during navigation are significantly shaped by the unique cognitive computations underlying real-world, sequential decision making.

Reference frames for encoding spatial motion in the cerebellum

Andrea Green
University of Montreal

Whether running to catch a ball or turning to reach for a coffee cup, our ability to interact with the environment depends critically on knowing our motion and orientation in space. Importantly, different tasks require different types of motion representations (e.g., head vs. body motion) encoded in different reference frames. For example, when running to catch a ball, keeping our eyes on target requires head-centered estimates of head motion. In contrast, controlling our heading, maintaining balance, and reaching accurately to catch the ball require different types of body and/or world-centered estimates of body motion. While much is now known about the neural mechanisms underlying the computation and use of head-centered motion signals (e.g., for gaze stabilization) we have much more limited knowledge about the nature of the different body- and world-centered motion estimates required for many of our daily tasks and where they are computed. In this talk I will describe recent experiments aimed at shedding further light on this question by examining the three-dimensional spatial tuning properties of motion-sensitive neurons in several brainstem-cerebellar regions across changes in the head's orientation with respect to the body and the body's orientation with respect to gravity. I will summarize the reference frames in which vestibular signals are encoded across these different regions and discuss what the results might imply about their respective roles in constructing head- versus body-centered motion estimates for different behaviors.

Characterization of head orientation and heading during everyday activity in humans: implications for modeling perceptual biases

Paul MacNeilage
University of Nevada, Reno

Control of posture and locomotion, as well as perception of spatial orientation, is supported by estimation of head orientation relative to gravity and the direction of linear self-motion (i.e. heading). Estimation processes are likely constrained by natural stimulus distributions via both efficient encoding and probabilistic decoding, but empirical data describing natural distributions of human head orientation and heading is lacking. Using a head-mounted tracking camera (Intel T265) that integrates visual and inertial measurements, we measured head position and velocity over dozens of hours of unprescribed natural activity in natural environments outside the laboratory setting in ten human subjects. We have previously validated measurements obtained with this device (Hausamann et al 2021). Across-subject distributions of head orientation were centered close to upright, and heading distributions were centered close to straight ahead, as expected. The head roll distribution was symmetrical with relatively low variability and high kurtosis, while the head pitch distribution exhibited greater variability and was asymmetrical with an over-representation of forward head pitch. The heading azimuth distribution was highly variable and multimodal, with modes at 0° and ± 90° (forward and lateral headings, respectively), while the heading elevation distribution was unimodal with fat tails.

Using these distributions as empirical priors in a probabilistic framework, we proceeded to model reported biases in perception of orientation (roll: DeVrijer et al 2008; pitch: Cohen and Larson 1974) and heading (azimuth: Cuturi & MacNeilage 2013; elevation: Crane 2014). For all models, free parameters specify sensory and/or stimulus noise and how it varies with eccentricity. Reasonable qualitative fits were obtained in all cases. For roll perception, the model accurately predicts increasing bias with increasing roll angle. For pitch, it accurately predicts differences in bias for forward versus backward pitch. For heading azimuth and elevation, the model accurately captures points where biases transition from attractive (underestimation) to repulsive (overestimation). On balance, results support the hypothesis that natural stimulus distributions shape perceptual biases in spatial orientation.

Explaining inter-individual variations in central spatial-orientation processing

Faisal Karmali
Massachusetts Eye and Ear

The vestibular organs are imperfect, yet the brain is able to synthesizes a robust estimate of three-dimensional motion and orientation in most individuals. The mechanisms that perform this estimation process include velocity storage. It is well known that the dynamic behavior of velocity storage varies substantially across individuals. This includes variations with age and peripheral damage. However, a mechanistic explanation for these variations has been lacking. We have recently shown that these variations may be explained by a central optimization of velocity storage to variations in the statistics of vestibular neural noise (i.e., variability) and experienced motion. First, we found that age-dependent changes in the VOR are explained by a velocity storage model responding to death of motion-sensing hair cells [1]. Second, we found that these models predict reduced velocity storage time constants for unilateral damage [2]. Third, we predicted that the persistence of inappropriate three-dimensional estimates of motion depends on individual variations in noise. Together, these results explain individual variations in central spatial-orientation processing. These results provide a conceptual understanding for a common diagnostic criteria and could lead to a better understanding of vertigo.

[1] Karmali, F., Whitman, G. T. & Lewis, R. F. Bayesian optimal adaptation explains age-related human sensorimotor changes. J Neurophysiol 119, 509-520 (2018).

[2] Madhani, A., Lewis, R. F., & Karmali, F. (2022). How Peripheral Vestibular Damage Affects Velocity Storage: a Causative Explanation. Journal of the Association for Research in Otolaryngology, 1-16.

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Probing Some Links Among Aging, Vestibular Function, and Balance

Dan Merfeld
Ohio State University

Falls are the leading cause of accidental death in older adults. This talk reviews a series of published studies over the past 10+ years that link vestibular thresholds to balance to falls. Specifically, data show that increasing roll tilt thresholds – which are an assay of vestibular sensory noise – correlate with increased imbalance, and that increased imbalance is correlated with falls. Unpublished data also show that roll tilt thresholds can be reduced and that this threshold reduction is accompanied by reduced sway. These findings provide hope that we may be able to improve vestibular precision to improve balance and reduce falls.

Session 4: Dysfunctional vestibular signals

The effects of noise exposure of vestibular function

Natela Shanidze[1], Courtney Stewart[2]
[1]The Smith-Kettlewell Eye Research Institute, [2]LTC Charles S Kettles VA Medical Center, Ann Arbour

Integration of Magnetic and Gravity Cues for Avian Navigation

David Dickman
Baylor University

Birds, like many animals have the ability to use cues from the Earth magnetic field for spatial navigation. Recently, neural correlates for the magnetic sense signaling the direction, intensity and polarity of the Earth magnetic field have been discovered in brainstem neurons (MR cells) in pigeons (Wu and Dickman, 2012). However, how these magnetic cues are referenced to the external world and are integrated into spatial signals in the brain remain unknown. Here, we report findings that MR cells encode magnetic signals referenced to a world fixed gravity coordinate system. This is accomplished via integration from vestibular inertial and magnetic signals by brainstem neurons. We also report direction thresholds for magnetic cues by MR cells, determined using signal detection theory. These findings continue to expand the role of vestibular information into higher level cognitive functions and denote a possible complete reference frame transformation from egocentric to allocentric spatial cues at the brainstem level.

Imbalance and dizziness caused by vestibular schwannomas correlate with vestibulo-ocular reflex precision & bias

Susan King
Massachusetts Eye and Ear

Imbalance and dizziness are disabling symptoms for many patients with vestibular schwannomas (VS), but symptom severity typically does not correlate with the vestibulo-ocular reflex (VOR) amplitude-based metrics used to assess peripheral vestibular damage. In this study, we tested the hypothesis that imbalance and dizziness in patients with VS relate to VOR metrics that are not based on response amplitude. Twenty-four patients with unilateral, sporadic VS tumors were studied, and objective (balance) and subjective (dizziness) vestibular dysfunction was quantified. The VOR was tested using two yaw-axis motion stimuli, low-frequency en-bloc sinusoidal, and high-frequency head-on-body impulsive rotations. Imbalance correlated with the VOR precision (the inverse of the trial-to-trial variability) and with low-frequency VOR dynamics (quantified with the time constant), and these two metrics were also strongly correlated. Dizziness correlated with the VOR bias caused by an imbalance in static central vestibular tone, but not with dynamic VOR metrics. VOR accuracy (mean response amplitude relative to the ideal response) was not correlated with the severity of imbalance or dizziness or with measures of VOR precision or time constant. Imbalance in patients with VS, therefore, scales with the VOR precision and time constant, both of which appear to reflect the central vestibular signal-to-noise ratio, but not with VOR slow-phase accuracy, which is based on the magnitude of the central vestibular signals. Dizziness was related to the presence of a static central tone imbalance but not to any VOR metrics,

suggesting that abnormal perception in VS may be affected by factors that are not captured by yaw-axis VOR measurements.

Effect of head tilt and stimulus tilt on saccade direction biases

Jorge Otero-Millan
University of California Berkeley

When looking around a visual scene, humans make saccadic eye movements to fixate objects of interest. While the extraocular muscles can execute saccades in any direction, not all saccade directions are equally likely: saccades in horizontal and vertical directions are most prevalent. Here, we asked if head orientation and scene orientation affect the saccade direction biases. In Experiment 1 participants (n = 14) viewed natural scenes and abstract fractals (radially symmetric patterns) through a virtual reality headset equipped with eye tracking. Participants' heads were stabilized and tilted at -30°, 0°, or 30° while viewing the images, which10 could also be tilted by -30°, 0°, and 30° relative to the head. In Experiment 2 participants (n=9) viewed tilted scenes at -30, 0, and 30 degrees, and were asked to either fixate a central small target or free view the image while we recorded their eye movements. We found that during free viewing of fractals, saccades largely followed the orientation of the head, however when participants viewed an Earth upright natural scene during head tilt, we found that the orientation of the head influenced saccade directions with biases aligned with an orientation in between the head orientation and the scene orientation. During fixation we found that microsaccade distributions were not affected by the presence of a tilted scene in the background. However, during free viewing we found that saccades biases tilted towards the direction of the scene tilt with large amplitude saccades more closely oriented to the scene tilt than small saccades. These combined results appear to indicate a combined effect of two reference frames in saccade generation, one egocentric which appears to dominate for small saccades and in the absence of visual cues for orientation and another allocentric one that biases the saccades along the orientation of the image.

Team & Individual Oral Abstracts

Tuesday July 26, 2022

08:00 – 10:00 Session 1, Panel I

Beyond a visuo-centric view: The crucial role of proprioception in sensorimotor learning

Jonathan Tsay[1], Cristina Rossi[2], Hannah Block[3], Chris Miall[4]
[1]University of California Berkeley, [2]Johns Hopkins University, [3]Indiana University Bloomington, [4]University of Birmingham

A visuo-centric perspective on motor learning is appealing. Not only does it fit with a zeitgeist which holds vision as a "dominant" sense, but it also matches our intuition of how we view task success: In day-to-day life, we frequently interact with visual objects, whether it be picking up a glass of water or moving the computer mouse over a desired icon. When a perturbation is introduced, we try to re-establish conditions such that the visual feedback is once again reinforcing. However, this visuo-centric perspective neglects evidence regarding the role of proprioception in motor control and learning: For instance, deafferented individuals struggle to generate specific patterns of muscle contractions in a feedforward manner. Moreover, neurologically healthy and congenitally blind individuals can adapt to a force-field perturbation without the aid of vision, presumably relying solely on proprioceptive input. This panel will present an alternative to the visuo-centric framework, arguing that proprioception may play an indispensable role in motor learning. We will show behavioral, theoretical/computational, neurophysiological and case-study results addressing both basic and clinical questions related to proprioception: Jonathan Tsay will present a new mechanistic understanding of implicit adaptation, a process that is elicited to minimize a proprioceptive error, the distance between the perceived hand position and its intended goal. He will use this proprioceptive re-alignment model (PReMo) to re-examine many phenomena that have previously been interpreted in terms of learning from visual errors, as well as offer novel accounts for unexplained phenomena. Cristina Rossi will present new findings that characterize the multiple learning mechanisms involved in locomotor adaptation, and their relationship to perceptual changes. A common mechanism may result in motor aftereffects and perceptual aftereffects, whereas another mechanism allows the locomotor system to flexible scale its adaptive response to different task demands (i.e., speed ratios on a split belt treadmill). Hannah Block will present new results that strengthen the behavioral and neural link between visuo-proprioceptive recalibration and motor planning. She will also show how these perceptual changes are not only difficult for people to consciously detect but are also robustly retained even after participants are permitted to view their actual hand. Chris Miall will present data from deafferented participants, showing how intact proprioception is critical to allowing an implicit representation of actions, and how without it, actions are governed explicitly, with consequent loss of adaptive sensorimotor responses. We will conclude with a 20-min discussion about the role of proprioception in sensorimotor learning. Prof. Denise Henriques will join the panel to help catalyze a stimulating discussion.

10:30 – 11:15 Early Career Award Winner Talk

Insights into motor control from brain-computer interfaces

Emily Oby, *University of Pittsburgh*

We are capable of a nearly endless repertoire of movements: we can walk, run, skip, reach, grab, kick, throw, dance, and more. The ease with which most of us perform these movements conceals the fact that motor control is one of the most complex tasks the brain performs. How can we make sense of this vast complexity? To do so, scientists always seek simpler systems as a starting point toward full understanding. A brain-computer interface offers one such simplification. A brain-computer interface, or BCI, directly connects the brain to the external world, bypassing damaged biological pathways. It replaces the impaired parts of the nervous system with hardware and software that translates a user's internal motor commands into action. A BCI can provide new insights into the natural processes of motor planning, control, and learning. In turn, the better we understand natural motor control, the better BCI systems will be. My research addresses both sides of this relationship. First, I use BCIs to address basic science questions about how we execute movements and learn new motor skills. How does the brain learn to make skilled movements? How do neural dynamics drive skilled movements? Then, I apply what we have learned about the brain to develop BCI algorithms to improve clinical BCIs. How can BCIs generalize between diverse skilled movements?

11:15 – 12:30 Session 2, Perspective I

Cortical control of human balance and mobility

Jasmine Mirdamadi[1], Sue Peters[2], Sam Stuart[3]
[1]Emory University, [2]Western University, [3]Northumbria University

Postural control involves hierarchical coordination of sensorimotor circuits mediated through automatic, subcortical mechanisms and top-down cortical mechanisms. Cortical involvement in balance and gait has traditionally been inferred indirectly, through degradation in performance during a cognitive task. Direct measures of brain activity during balance and mobility using electroencephalography (EEG) and functional near infrared spectroscopy (fNIRS) offer mechanistic insight into declines in function that are needed to predict fall risk, detect declines in function before a fall, and develop targeted interventions. Greater cortical activity may compensate for declines in automatic postural control. However, whether greater brain activity is compensatory or dysfunctional remains unclear due to a large emphasis on a single brain region (e.g., prefrontal cortex), the same task difficulty, or same environmental context. We will discuss recent advancements in brain activity during balance and mobility, highlighting individual, group, and task-dependent changes and their associations with function in health, aging, and neurological impairment. Jasmine Mirdamadi will discuss EEG activity evoked by standing balance perturbations as a function of task difficulty and an individual's balance ability. She will then translate this work to whole-body motion perception to provide a mechanistic framework for how cortical sensory integration needed for perception may contribute to balance function. Sue Peters will discuss cortical activity involved in planning of limb coordination for step initiation and walking and how cortical activity changes with attention and rehabilitation interventions in people with and without stroke. Sam Stuart will discuss the use of mobile brain/body imaging, through separate and combined fNIRS and EEG devices, to monitor brain activity response to cueing interventions (i.e., visual, auditory, tactile cues) for walking impairment in Parkinson's disease (PD). He will also describe brain activity changes with pharmaceutical intervention and complex mobility tasks (i.e., turning). Lessons from the field will be provided on using combined mobile imaging and inertial sensor technology in clinical populations. Main discussion points include: which aspects of cortical activity distinguish individual differences in balance and mobility function? Is altered cortical activity compensatory or dysfunctional? How can cortical activity inform mechanisms of interventions or guide precision medicine? Are we ready for a multimodal neuroimaging approach?

15:00 – 17:00 Session 4, Individual I

Manual force encoding in the motor cortex of macaques and humans

Elizaveta Okorokova[1], Anton Sobinov[1], John Downey[1], Ashley van Driesche[1], Qinpu He[1], Charles Greenspon[1], Nicholas Hatsopoulos[1], Sliman Bensmaia[1]
[1]University of Chicago

From prehension to pianism, object interactions require precise control of both the movement of the hand and of the forces it exerts on objects. Recent work shows that time-varying posture of the hand is encoded in the activity of populations of neurons in primary motor cortex (M1). Less is known about how manual forces are encoded in M1 because simultaneously tracking hand postures and exerted forces has proven challenging. To fill this gap, we developed an experimental apparatus that allows us to monitor both hand movements and manual forces. We then recorded the neural activity in M1 as monkeys grasped sensorized objects, identified a population of neurons whose activity tracks manual forces, and characterized the force signal in this population. Next, we applied the insights gleaned from able-bodied macaques to develop manual force decoders in a person with tetraplegia. We instructed the participant to grasp a set of objects, in a virtual environment, with varying amounts of force while we monitored the M1 activity via chronically implanted electrode arrays. We then built decoders that harness force signals in M1 to allow the participant to exert forces with his virtual hand. The participant then performed a variety of tasks in VR that required the manual exertion of graded forces on objects. We show that non-linear decoders of force with temporal dependence (e.g. LSTM) significantly outperform standard linear methods. These results pave the way for brain-controlled bionic hands that allow the user not only to precisely shape the hand but also to apply well-controlled forces with it.

Motor cortex isolates skill-specific dynamics to implement context-specific feedback control

Eric Trautmann[1], Najja Marshall[1], Hannah Chen[1], Francisco Sacadura[1], Elom Amematsro[1], Elijah Aliyari[1], Daniel Wolpert[1], Michael Shadlen[1], Mark Churchland[1]
[1]Columbia University

Performing two skills, such as swinging a tennis racquet or ax, requires both differences in typical motor output and different feedback-driven adjustments. The motor cortex (M1) is involved in specifying motor output, but its role in performing computations underlying skill-specific feedback control is not well understood. Neural activity in M1 reflects the underlying dynamics necessary to create motor outputs (muscle activity) and reflects the output during context-dependent feedback-driven corrections. The major features of M1 activity don't reflect outputs per se, but instead may be structured to not only create the typical output, but to enable rapid sensory-guided adjustments. This extension makes a strong prediction: M1 activity should be very different when two skills require different feedback-driven responses, even if outputs are matched. We assume a central component of skilled performance is learning a feedback control policy; i.e., a mapping from errors conveyed by the sensory inputs to corrective motor outputs. It is typically challenging to discern which aspects of neural activity reflect motor outputs and which reflect skill-specific feedback control. Here, we employed a 1D force production task with two contexts that required the same typical motor output, but opposite responses to sensory feedback, comprising different skills. We trained a monkey to match the vertical position of a cursor to a variety of scrolling dot paths. Pushing forward on a handle determined cursor height. In the

positive-gain context force moved the cursor upwards, while in the negative-gain context, force moved the cursor downwards. Mirrored paths were presented across contexts so that forces were nearly identical. Using 45 mm primate Neuropixels, we recorded thousands of neurons in the M1 and basal ganglia (GPi). Most neurons in M1 had complex patterns of activity that were strongly context (gain) dependent and did not directly reflect force or muscle activity, and GPi activity was strongly context-specific. Unexpectedly, identical motor outputs under the two gain conditions were driven by very different internal patterns of neural activity in M1. We then introduced cursor jump perturbations on some trials, and using demixed PCA (dPCA), we found a high-variance dimension attributable to context, and lower-variance dimensions for visual perturbation and force output. This empirical data suggest that context-dependent neural trajectories may allow each context to leverage different dynamics to flexibly transform the same sensory feedback into opposing outputs. Collectively, these results suggest that skills are produced by skill-specific (not output-specific) neural trajectories that allow for flexible input-output relationships produced by dynamics close to that trajectory. A prediction of this hypothesis is that motor cortex activity may leverage the vast volume of a high-dimensional neural space to store the repertoire of distinct motor skills.

Nonlinear manifolds underlie neural population activity during behaviour

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The activity of neural populations during behaviour can be well-described by relatively few population-wide activity patterns spanning a "neural manifold". This observation, which holds true across many brain regions and species, is largely based on studies analysing linear flat neural manifolds spanning the neural population activity. We hypothesised that since neurons have nonlinear responses and make thousands of recurrent connections that may enhance this nonlinearity, nonlinear manifolds should capture the neural population activity better than flat manifolds. Analysis of a centre-out reaching task in monkeys confirmed that, even during a relatively simple behaviour, motor cortical population activity is best captured by a nonlinear manifold: nonlinear manifolds identified with Isomap needed fewer dimensions to explain the neural population variance than linear manifolds identified with PCA. Moreover, these nonlinear manifolds preserved the structure of the data better than their flat counterparts. To investigate if manifold nonlinearity arises due to the dense connectivity patterns of brain circuits, we trained RNNs with varying degrees of recurrent connectivity to perform a similar task. As predicted, neural manifolds only became nonlinear if networks had many connections. Intriguingly, for the same amount of connectivity, more heterogeneous connectivity patterns led to greater nonlinearities, suggesting that cytoarchitecturally distinct regions may present different degrees of manifold nonlinearity. To test in vivo this presumed influence of circuit connectivity, we compared neural manifolds from two anatomically distinct motor regions - motor cortex and striatum - using simultaneous recordings from mice performing a grasping and pulling task. Manifold nonlinearity was indeed strongly region-dependent: striatal manifolds were consistently more nonlinear than cortical manifolds. In addition to circuit connectivity, we also expected task complexity to shape manifold nonlinearity: if manifolds are nonlinear, more varied tasks requiring a richer set of neural activity patterns should reveal greater nonlinearities, as this activity would explore a larger portion of the manifold. We confirmed this using neural population recordings from human motor cortex during attempted handwriting. Drawing lines of varying length across 16 directions and writing all letters in the English alphabet had more nonlinear manifolds than the simpler tasks of drawing lines in a single direction or writing a handful of similar letters, respectively. Thus, linear dimensionality reduction methods that identify flat manifolds find linear approximations to an intrinsically nonlinear manifold. This nonlinearity is influenced by the underlying circuit architecture and becomes more evident during more complex behaviours. Accounting for these-region specific nonlinearities may be crucial as the field moves toward the study of more complex and naturalistic behaviours.

Effector-specific sensorimotor transformations in dorsolateral prefrontal cortex during a head-unrestrained reach task

Veronica Nacher[1], Parisa Abedi-Khoozani[1], Vishal Bharmauria[1], Harbandhan Arora[1], Xiaogang Yan[1], Saihong Sun[1], Hongying Wang[1], John Crawford[1]
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Dorsolateral prefrontal cortex (DLPFC) is associated with executive control and response selection, but the extent to which it is involved in effector-specific transformations is unclear. We addressed this question by recording 711 single neurons from DLPFC while two trained monkeys performed a head-unrestrained reaching paradigm. Animals touched one of three central LEDs at waist level while maintaining gaze on a central fixation dot and were rewarded if they touched a target appearing at one of 15 locations in a 40° x 20° (visual angle) array. Animals typically shifted gaze first, followed by sustained head movement and a reach (Arora et al. J. Neurophys. 2019). Analysis of 499 neurons in two monkeys showed an assortment of target/stimulus, gaze, pre-reach, and reach-timed responses in DLPFC. Most neurons could be described as falling into three main groups: 'Early" (increased firing rate during the target presentation / gaze onset), "Early-late" (sustained activity from target presentation through reach), and "Late" (peaking during reaches). Importantly, early gaze-related activity only occurred when followed by a reach (compared to 172 neurons also tested in no-reach controls). We then tested the spatially tuned neurons using a model-fitting procedure to determine their spatial codes (Keith et al. J. Neurosci. Meth. 2009). Early responses were often gain modulated by initial hand position (41%), gaze position (19 %), or initial head position (5 %), with some overlap between these modulations. Individual neurons showed a variety of preferred spatial codes (target, gaze, head, hand) but at the overall population level, early responses showed a preferential coding for head movement, whereas later responses showed a preference for coding hand movement. Overall, these data suggest a specific role for DLPFC in eye-head-hand coordination where gaze signals appear to trigger posture-dependent head and hand control signal, and a more general role for this structure in cognitive-motor integration.

Reformatting of the representation of action from neocortex to striatum

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The interplay between two major forebrain structures - motor cortex and dorsal striatum - is critical for voluntary, goal-directed movements. Canonical accounts have proposed a division of labor in which the motor cortex represents critical signals for the planning and online execution movement, with subcortical striatum playing a more circumscribed role in behavior control. For example, it has been proposed that striatum may be critical for representing action identity, selection and/or initiation, or effort cost and/or movement vigor. Alternatively, a few groups have focused more on the striatum as a critical component of the specification of movement execution. This latter alternative has led to proposals that striatum may be critical for specifying, via reinforcement learning, many continuous parameters for motor control. These alternative predictions - an abstracted representation of action versus a rich representation of movement parameters - can potentially be distinguished by comparison of representations observed in motor cortical and striatal activity across movements that vary in their kinematics and kinetics, putative parameters underlying descending forebrain control of movement. However, to date it has been difficult to distinguish amongst these models because many lab tasks have been designed to exhibit little variance in any movement parameter or to vary primarily along a single parameter or without large scale cortical and subcortical recordings. To address these questions we developed a novel task in which a variable-torque joystick could be robotically positioned in front of a head-fixed mouse. Mice reached to pull the joystick at two locations and with two independent force requirements to elicit a water reward. We combined this task with simultaneous, high density electrophysiological recordings from primary motor cortex, a premotor frontal cortical area, and dorsal striatum. Mice exhibited readily distinguishable, but variable, reaching trajectories and forces to each joystick position while successfully completing 80% of trials across locations and torque requirements. Multiple analyses led to the conclusion that activity in striatum does not represent an abstracted subset of action parameters, but rather encodes the full dimensionality of movement representations observed in primary and premotor cortical recordings. For example, the performance of a continuous decoder of movement and classifier of trial type using striatal activity was equivalent to or greater than the performance from premotor or motor cortical activity. However, there was a notable difference - examination of individual subcortical and cortical units contributions to decoding revealed a greater spatiotemporal separation in striatum. This suggests a 'reformatting' of cortical representations in the dorsal striatum to support action parameter-specific credit assignment; a key problem for reinforcement learning.

Somatosensory and motor cortex both causally contribute to speech motor learning

Matthias Franken[1], Timothy Manning[1], Alexandra Williams[1], David Ostry[1]
[1]*McGill University*

Speakers readily adapt their articulation to various sensory perturbations, such as formant alterations, pitch shifts, or loudness modulations. It is thought that this sensorimotor adaptation, much like in non-speech motor learning, relies on comparing predicted sensory feedback with observed sensory feedback. However, the neural mechanisms that support this learning are poorly understood. Interestingly, there is accumulating evidence that the somatosensory system plays an active role in motor learning. For example, somatosensory stimulation such as facial skin deformation may alter subsequent speech motor learning. In the present study, we investigated whether the primary somatosensory cortex and the primary motor cortex are causally involved in speech motor learning. The hypothesis is that if a brain area participates in speech motor learning, then disruption of its activity using magnetic brain stimulation prior to learning will either reduce learning or eliminate it altogether. Fifty participants performed a speech motor learning task, in which they produced the words 'shame' (/ ʃ eɪm/) and 'shake' (/ ʃ eɪk/) while receiving auditory feedback through headphones. After thirty baseline productions, the frequency spectrum of the initial fricative sound was shifted in real-time by 3 semitones, resulting in a shift from / ʃ / towards /s/, and held at this value for the remaining 150 speech productions. Such altered auditory feedback typically leads to adaptation, in which speakers compensate for the altered auditory feedback by shifting their vocal output in the opposite direction. Participants performed the speech adaptation task after continuous theta-burst stimulation, which was used to disrupt activity during learning in the lip area of either primary motor cortex or primary somatosensory cortex, in a between-participants design. The findings to date show that whereas participants show speech motor adaptation in a control condition, adaptation is blocked by disrupting either primary motor cortex or primary somatosensory cortex. Motor-evoked potentials measured at the lips before and after theta-burst stimulation in the somatosensory condition confirm that blocking adaptation in this condition was not caused by indirect effects of somatosensory stimulation on primary motor cortex. These results show that the primary somatosensory cortex is causally involved in speech motor learning, in line with recent studies suggesting that motor learning is driven, at least in part, by the somatosensory system. In addition, this is the first study showing that both primary motor and primary somatosensory cortex causally contribute to motor learning. The current results show that even in altered auditory feedback, the somatosensory system may be crucial for updating the memory of the adaptive motor commands and their associated somatosensory representations.

Wednesday July 27, 2022

08:00 – 10:00 Session 6, Panel II

Cancelation of self-generated sensations: neural mechanisms and functional advantages across species and sensory modalities

Konstantina Kilteni[1], David Schneider[2], Avner Wallach[3], Kathleen Cullen[4]
[1]Karolinska Institutet, [2]New York University, [3]Columbia University, [4]John Hopkins University

Distinguishing the sensations that are produced by our own movements (reafference) from those produced by external causes (exafference) is a fundamental problem for our nervous system and a prerequisite for our survival. Compare how dramatically different our responses are (a) to the footsteps we hear, when these are not due to our walking (auditory reafference) but due to a stranger following us (auditory exafference); (b) to our vestibular input, when this is not generated by our head motion (vestibular reafference) but because we accidentally fall on the floor (vestibular exafference); and (c) to the touch we feel on our cheek, when this is not due to our hand (somatosensory reafference) but due to an insect crawling on our face (somatosensory exafference). To solve this problem and guide our behavior appropriately, the nervous system uses information about the organisms' own movements to predict the reafferent sensory signals. The prediction can then be canceled from the incoming sensations, thus amplifying the difference between self-generated and external sensations. This panel will raise questions on the similarities and differences in this cancelation mechanism across four different species (mice, electric fish, monkeys, humans) and four different modalities (auditory, electrosensory, vestibular, somatosensory), as well as its functional advantages in motor control. In mice, David Schneider will show that auditory responses to self-generated sounds are suppressed relative to sounds that are unexpectedly shifted in frequency. He will argue that this frequency-specific suppression in the auditory cortex arises from a stable, learned, and specific movement-based prediction that is implemented over short time scales with within-movement temporal specificity. Avner Wallach will show that the responses of the electrosensory lobe output neurons in freely swimming electric fish selectively encode external stimuli. He will argue that the cerebellum-like circuitry of the electrosensory lobe learns and stores multiple motor-based predictions specific to different sensory contexts. Kathleen Cullen will show how vestibular reafference is canceled in primates by a cerebellum-based mechanism, when there is a precise match between the actual and expected proprioceptive feedback. She will argue that this cerebellum-based mechanism displays rapid updating whenever a new sensorimotor relationship is established. Konstantina Kilteni will show that the responses of the human somatosensory cortices to self-generated touch are attenuated compared to externally generated touch, or self-generated touch that is shifted in time, and that the functional corticocerebellar connectivity is related to this attenuated perceived intensity of the somatosensory reafference. She will argue that somatosensory attenuation depends on an internal model between the specific action and its temporally precise feedback.

10:30 – 12:30 Session 7, Individual II

Predictability as control priority in a functional task: computational research with clinical applications

Rashida Nayeem[1], Salah Bazzi[1], Mohsen Sadeghi[1], Reza Sharif Razavian[1], Dagmar Sternad[1]
[1]Northeastern University

Humans physically interact with complex objects every day. An example is picking up a cup of coffee: the hand applies forces not only to the cup, but also to the sloshing liquid, which creates complex forces back onto the hand. Challenges of complex interactions become evident in individuals with motor impairments, where small disturbances can lead to failure, e.g., spilling the coffee. Dynamic behavior can evolve rapidly, making it difficult to correct errors given the latencies in the neuromotor system. How do humans manage these complex dynamics? Our previous work showed humans seek to make interactions predictable, to avoid error corrections. In two follow-up studies we investigated how humans prepare a virtual 'cup of coffee' to make subsequent interactions more predictable. A third study used a real-life version of the task to assess how our theoretically derived metrics may quantify impairment severity after stroke. When transporting a complex object from rest, the transient dynamics can display unpredictable behavior, which depends on the initial conditions. A first study examined whether humans prepared a complex object and exploited initial conditions to increase predictability of the interaction. Participants transported a 'cup of coffee', a virtual cup with a ball rolling inside. A model of the cup-and-ball was rendered in a virtual environment, subjects moved the cup via a robotic manipulandum that haptically transmitted the ball forces. Participants were encouraged to explore the object dynamics to find preferred initial conditions (i.e., ball position and velocity) prior to a continuous 15s movement. Results showed that subjects converged to initial conditions that reduced duration of transients and increased overall predictability of interaction forces. Dynamic simulations confirmed that these initial conditions increased predictability towards theoretically optimal values. The second study investigated the role of haptic and visual feedback in achieving predictability. In the absence of visual feedback subjects were able to converge to predictable interactions, albeit suboptimally. In the absence of haptic feedback, subjects were unable to converge to initial conditions and moved the cup slowly to neutralize ball dynamics. Surprisingly, this strategy increased predictability of interactions, yet to a lesser degree than the haptic feedback condition. A third study investigated if predictability could serve as a measure of functional impairment after stroke. In a custom-developed real-life version of the task, individuals after stroke transported a cup with a rolling ball inside, to targets on a table. Neurotypical and mildly affected subjects prioritized predictability between cup and ball dynamics. Moderately and severely affected individuals showed similarly reduced predictability. This indicates that functionally inspired tasks with novel metrics are sensitive to quantify the ability to complete activities of daily living.

A distributed circuit for regulating feedback control policy

Jonathan Michaels[1], Mehrdad Kashefi[1], Olivier Codol[1], Rhonda Kersten[1], J. Andrew Pruszynski[1]
[1]*Western University*

Although many studies have examined the role of cortical activity preceding voluntary movements, far fewer have examined the neural dynamics underlying rapid responses to unexpected sensory input. Similarly, recent theories of motor cortex describe how neural activity evolves during the initiation of voluntary movements, but generally do not consider the sensory feedback that arises following unexpected perturbations or during continuous control. To address this gap, we trained a macaque monkey to perform a delayed reaching task in which one of two targets must be reached after an unexpected mechanical perturbation pushed the arm either into or out of each target. During behavior we recorded from PMd, M1, and S1 using high-density Neuropixels probes (>1700 single neurons across sessions) and from populations of motor units in relevant arm muscles using novel high-density injectable arrays (>70 single motor units across sessions). Neural population activity prior to the perturbation represented the goal target most strongly in PMd, less in M1, and least in S1. High-density recordings (>100 neurons simultaneously) allowed us to ask how well the trial-to-trial changes in neural state before the perturbation could predict rapid changes in kinematics following the perturbation. Pre-perturbation activity in motor unit populations very strongly predicted kinematics beginning ~30ms after the perturbation on single trials, while activity in PMd and M1 well predicted kinematics beginning ~70ms after the perturbation, implicating trial-to-trial variability in these areas in rapid feedback responses. Expanding on dynamical systems-based models of motor control, we developed neural network models that were trained to control a realistic biomechanical model of the arm including muscle dynamics and delayed sensory feedback, which well recapitulated measured behavioral and neural dynamics. We propose that the distributed neural state observed prior to a perturbation is optimized to align incoming proprioceptive information with ongoing activity such that it drives the correct output to muscles through a combination of continuous delayed feedback and local recurrent dynamics. One prediction of this proposal is that during continuous movement, perturbations not detrimentally affecting the movement goal do not cause large excursions in the neural state, while perturbations that detrimentally affect movement goal rapidly modulate ongoing muscle output through recurrent connectivity. A second prediction is that during continuous movement control delayed sensory feedback is the primary driver of ongoing activity. These simulations provide the basis of a biologically plausible implementation of the principles of optimal feedback control, and ongoing experiments are leveraging our high-density neural and motor unit recording technology in a continuous reaching task with random targets and perturbations to provide the ideal dataset to further test these proposals.

Behaviorally relevant, but not any salient events, inhibit rapid hand movements

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To rapidly adapt our movements to changes in the environment, we need to readily process new information. While a signal indicating that the environment changed might quickly be available, updating movement plans contingent on the behavioral relevance of the change will take longer. How should a motor system behave while a salient change is being processed? Saccadic eye movements pause even after irrelevant salient changes - a phenomenon known as saccadic inhibition (Reingold &

Stampe, 1999; Rolfs et al., 2008). But similar observations about hand movements are not as prevalent. Here, we show that only behaviorally relevant changes in the environment have overt consequences for the execution of hand movements. In our study, participants collected an irregular array of six dots on their smartphone or tablet, by tapping on them in a swift, horizontal sequence of movements. On 50% of the trials, the background of the screen flashed white for 33ms, which constituted a salient, but behaviorally irrelevant change. On another, independently chosen 50% of the trials, all dots suddenly changed their position, resulting in a salient, and behaviorally relevant change. If the flash and position changes occurred on the same trial (25% of all trials), they did so at the same time. Participants were instructed to adapt their responses to the new positions of the dots on the screen. An analysis of participants' errors between the touch position and the dot position revealed that participants adjusted their responses to the new information within about 400 ms after change onset, confirming that behaviorally relevant information was indeed incorporated into movement plans. We computed movement rates - the number of movements per second as a function of time - aligned to the onset of changes. Indeed, we found clear signatures of hand movement inhibition: In trials with behaviorally relevant changes, movement rate decreased by 30% within about 400ms after the change. We did not observe a dip for behaviorally irrelevant changes, nor did a simultaneous behaviorally irrelevant change alter the pattern of response adjustment or inhibition that accompanied a behaviorally relevant change. Pausing a movement can only possibly benefit the accuracy of its execution when the pause shifts the movement to a time window when the motor plan has integrated the new information. In our data, the time window during which participants adjusted their responses to a baseline level of error coincides with the time window of hand movement inhibition. This suggests that the hand movement system achieves accurate responses by delaying the onset of a movement until new, behaviorally relevant information is integrated into the motor plan. Our results suggest that hand movement inhibition is a consequence of adjusting the motor plan to behaviorally relevant information in the environment, but - contrary to saccadic inhibition - is not a general signature of processing novel information.

Emergence of habitual control in a novel motor skill over multiple days of practice

Christopher Yang[1], Noah Cowan[1], Adrian Haith[1]
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When humans learn new motor skills, their behavior can become habitual, or inflexible to changes in the goals/structure of a task. Neuroscientists and psychologists have long debated the nature of habits and their relationship with motor skills, but these debates have been hampered by a dearth of empirical work examining how habits form during motor skill acquisition. Although habit formation has been studied to a limited extent in tasks where one must select between a few discrete choices (e.g., arbitrary visuomotor associations), the extent to which these findings generalize to real-world tasks with a continuum (i.e., infinity) of possible states and actions is unclear. To better understand the nature of habit formation in continuous skills, we performed a multi-day learning experiment to examine the emergence of habitual behavior as participants learned a novel motor skill. Participants learned to control an on-screen cursor using a bimanual mapping where moving the left hand vertically moved the cursor horizontally while moving the right hand horizontally moved the cursor vertically. After practicing this mapping for two, five, or ten days, we altered the mapping by flipping the direction of cursor movement in the horizontal axis. We assessed, using both a point-to-point movement task and a continuous tracking task, whether participants would be able to update their control of the cursor in accordance with the new flipped mapping, or whether they would habitually continue to use the mapping they had originally practiced. We found that, in both tasks, participants became more skillful in using the bimanual mapping with up to five days of practice. However, participants use of this mapping became habitual after only two days of practice. Furthermore, the habit that participants had formed did not become stronger or more resistant to extinction with more practice. These data demonstrate a dissociation between the emergence of skill and habit during learning; motor behaviors can continue to become more skillful with practice even after they have become habitual. Thus, our results suggest that habitual behaviors, despite being defined as inflexible to change, maintain some level of flexibility during learning.

A sensory race between oculomotor control areas for coordinating motor timing

Antimo Buonocore[1], Ziad Hafed[1]
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Successful interaction with the environment requires a fine balance between following internal goals, like planning a movement, and maintaining sensitivity to external events. Because external events necessarily come asynchronously to current internal brain state, a so-called "race condition" can frequently occur in sensorimotor behavior: on the one hand, there is an internal motor plan in progress; on the other, a new competing orienting response is jumpstarted by the external event. Handling such a race condition requires both rapid sensing of the outside world as well rapid inhibition of motor plans. We, therefore, hypothesized that omnipause neurons (OPN's) in the nucleus raphe interpositus (rip), constituting the very final gateway for allowing or preventing saccades, should exhibit classic hallmarks of early sensory areas: these neurons can rapidly regularize the race condition by momentarily interrupting an ongoing movement plan in favor of processing an orienting response to the external event. This would require that OPN's exhibit ultra-rapid, sophisticated visual pattern analysis capabilities. We first confirmed that OPN's had sustained tonic activity during fixation and paused for saccades of any size and direction. We then presented visual patterns during fixation. We used gratings of different spatial frequency, contrast, orientation, and motion speed/direction. Despite their high tonic rates (e.g. 100 spikes/s), OPN's exhibited highly robust short-latency phasic activity increases <50 ms after image onset. Critically, such visual responses were feature-tuned, with preferred stimuli causing an almost doubling of tonic rate. Consistent with another motor structure, superior colliculus (SC), OPN's preferred low spatial frequencies and had clear contrast sensitivity. They also exhibited offset responses, like early visual areas. Despite not having clear spatially-confined receptive fields, OPN's preferred foveal and, sometimes, lower visual field locations. Most intriguingly, OPN visual response latencies were even earlier than in the SC with the same images. What is the functional role of such early OPN visual pattern analysis capability? It allows OPN's to race with the SC for controlling motor timing, as we confirmed with electrical stimulation. We injected short stimulation pulse trains to "simulate" brief phasic visual responses in either OPN's, SC, or V1. In OPN's, visual "bursts" momentarily inhibited spontaneous saccades. Contrarily, SC visual "bursts" increased spontaneous saccade likelihood, and V1 visual "bursts" were consistent with sensing phosphenes. Therefore, OPN's can quickly sense exogenous events and reset oculomotor activity, effectively regularizing the race condition that can otherwise take place between an existing motor plan and a newly initiated one, say, via the SC. Our results provide a highly mechanistic description of why even simple visually-guided saccades can exhibit surprisingly large timing variability.

Express reaching responses are preserved in Parkinsons Disease and insensitive to levodopa treatment

Rebecca Kozak[1], Maggie Prenger[1], Madeline Gilchrist[1], Kathryne Van Hedger[1], Mimma Anello[1], Penny MacDonald[1], Brian Corneil[1]
[1]*Western University*

Parkinson's Disease (PD) is a common movement disorder characterized by slow and stiff voluntary movements, due to dopamine depletion of the dorsal striatum. A growing body of evidence suggests PD patients retain the ability to generate reflexive and/or stimulus-driven movements of the eyes and upper limbs. However, the mechanism of action for such spared responses remains largely unknown. Recent work has suggested that Express Reaching Responses arise from the tecto-reticulospinal tract, which lies in parallel to the corticospinal tract. Express reaching responses are the first phase of stimulus-driven muscle recruitment, appearing ~100 ms after stimulus onset, well before movement onset. The presence and magnitude of express reaching responses are correlated with rapid RTs during visually-guided reaching. Our objective was to test the hypothesis that the tecto-reticulospinal tract is spared in PD by examining express reaching responses. Furthermore, we sought to examine the impact of dopaminergic medication (DA), commonly used to treat motor symptoms in PD. Toward this end, we recorded reach kinematics and electromyographic activity (EMG) from pectoralis major, a muscle involved in cross body reaching, in 16 PD and 18 age-matched healthy-control (HC) participants, as they performed visually-guided reaches in a Kinarm robot, both off and on DA, with session order counterbalanced across participants. Participants reached towards targets in an emerging target paradigm, which has been shown to robustly elicit express reaching responses, and short latency RTs. We found that PD and HC participants differed on two key phases of reaching movements; either volitional movement, or movement initiation. Consistent with a movement disorder, PD patients exhibited lower peak velocities ($p = 0.01$), longer movement durations ($p = 0.001$), and lower peak EMG amplitudes ($p = 0.01$) compared to HCs. However, consistent with spared stimulus-driven movements, there was a trend towards more rapid RTs for PD patients compared to HCs ($p = 0.06$). To better understand the reason for spared movement initiation, we examined EMG activity, and found that express reaching responses were more frequent ($p = 0.017$) and larger (albeit not significantly, $p = 0.07$) in PD patients compared to HC. Furthermore, DA treatment did not affect the express reaching responses or RTs. Our findings indicate that multiple descending motor pathways contribute to key phases of reaching movements toward a moving target. PD patients retain the first phase of stimulus-driven muscle recruitment, while simultaneously exhibiting degraded volitional movement in later parts of the reach. Furthermore, rapid movement initiation was not sensitive to DA manipulation. Taken together, we suggest that a tecto-reticulospinal tract remains intact in PD patients, making this tract an attractive therapeutic target in clinical populations.

15:00 – 17:00 Session 9, Panel III

Motivational influences on motor performance

Vikram Chib[1], Court Hull[2], Amanda Therrien[3], Mati Joshua[4]
[1]*Johns Hopkins University,* [2]*Duke University,* [3]*Moss Rehabilitation Research Institute,* [4]*The Hebrew University of Jerusalem*

Motor performance is motivated by the rewards and costs at stake. Historically the basal ganglia have been implicated in the representation of motivational factors that drive motor performance; however recent studies have also identified motivational signals in cerebellum, suggesting an interaction between cerebellum and basal ganglia to generate motivated motor behavior. In this session we will present recent evidence for the roles of basal ganglia and cerebellum in motivated performance, across human and animal models. We will discuss the similarities and differences between cerebellar and striatal signals and why these seemingly disparate brain regions might encode affective information. First, Vikram Chib will present data that examine how fatigue influences motivational state, making human participants less willing to engage in effortful exertion. Using fMRI data, he will describe how signals related to motor cortical state in premotor cortex influence computations of effort value in the basal ganglia, decreasing motivation and willingness to exert. Vikram's data will provide an account of how the basal ganglia incorporates information about bodily state to motivate motor performance. Second, Amanda Therrien will present a series of studies that examine state estimation and its relationship with reward learning in individuals with cerebellar degeneration. Estimations of body state are hypothesized to depend on computations within the cerebellum. Cerebellar damage in humans significantly impairs state estimation, which in turn impairs motor control and learning. Amanda will show that estimations of body state are incorporated in the processing of reinforcement and reward information, and that the cerebellum mediates this function. Third, Court Hull will present data testing how signals in the cerebellum might convey reward predictions in order to guide motor learning. Using a combination of calcium imaging and electrophysiology in awake behaving mice, he is testing whether cerebellar climbing fibers obey the requirements of reward prediction error, how behavioral context affects these signals, and how these signals might act to shape cerebellar output. Court's data will address the mechanisms of reward signaling in the cerebellum, and how they compare with what is known for basal ganglia circuits. Finally, Mati Joshua will present studies that recorded neural data from eye-movement areas in the basal ganglia and cerebellum of monkeys, while manipulating eye-movement parameters and reward. Recent findings of reward signals in the cerebellum challenge the view that the cerebellum performs error-based learning, whereas the basal ganglia are involved in reward-based learning. While cerebellar reward signals demonstrate some resemblance to those in the basal ganglia, a direct comparison has been lacking. Mati's data will provide a direct comparison between reward and eye-movement signals in the cerebellum and the basal ganglia.

Thursday July 28, 2022

08:00 – 10:00 Session 10, Individual III

Beyond remapping: how is cortical information content altered following hand loss?

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Hand loss is a key model for studying reorganisation in the human brain, but the functional consequences of these large-scale changes in brain activity are still unknown. Specifically, remapping of multiple body-parts (indexed by increased BOLD activity) was reported in the missing hand cortex during arm, face and feet movements of congenital one-handers, and during intact hand movements in acquired amputees (Makin et al., 2013; Hahamy et al., 2017). However, it is not clear whether this dramatic brain remapping bears any functional relevance (Muret and Makin, 2021), and how the developmental stage of remapping (early or late in life) may impact this relevance. As a first step towards answering these questions, we investigate the information content of the remapped activity observed following congenital or acquired hand loss. To this end, we scanned (3T fMRI) congenital one-handers (n=21) and amputees (n=18) as well as two-handed controls (n=22). All participants performed two actions (i.e., squeeze or push) with each of 4 different body-parts involved in hand-loss compensatory behaviour: the intact Hand, residual Arm, Lips and Feet. Data from an independent localiser was combined with anatomical masks of primary sensorimotor cortex to define the Face, Leg and Hand regions in the deprived hemisphere. Univariate activity evoked by the different actions and body-parts was extracted to assess remapping. Representation Similarity Analysis was then used to identify changes in representational dissimilarities between two actions or pairs of body-parts (i.e., information content) in the respective regions. Using conventional univariate analysis, we found an increased activity in one-hander's missing Hand region relative to controls (i.e., remapping) for the Arm, Lips and Feet (all $p < 0.001$) but not in the primary region of each body-part. In other words, the increased activity for each of these body-parts was uniquely expressed in the deprived cortex. However, this was not reflected in increased information content; when comparing dissimilarities between actions performed with these body-parts, we merely observed a trend for the Arm only ($U = 158$, $p = 0.078$). This result calls to question the notion that the widespread remapping due to early life handlessness is functionally relevant. Conversely, similar analyses in acquired amputees revealed significant remapping of the intact Hand ($p < 0.001$) in the missing Hand region relative to controls, with a corresponding increase in action dissimilarity ($p = 0.002$) and thus information content. This suggests that some remapping happening later in life might bear functional significance. To conclude, even though the critical period is a necessary condition for remapping to happen at a large scale, our results challenge the notion that such remapping actually reflects functional relevance, and thus true reorganisation.

The effect of tactile augmentation on force field adaptation

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When exposed to a novel dynamic environment, we adapt by changing our movements' dynamics. Adaptation occurs through the development of an internal representation of the perturbation, which allows us to predict the disturbance and apply compensatory forces. To form an internal representation, the sensorimotor system gathers and integrates sensory inputs, including kinesthetic and tactile information about the external load. Currently, the relative contribution of kinesthetic and tactile information to the adaptation process is poorly understood. In our previous study, we examined the effect of augmented tactile information on force field adaptation, and found that this stimulation had no effect on movement kinematics, but had a pronounced effect on movement dynamics. Here, we aim to further investigate this integration process of kinesthetic and tactile information, by using an innovative approach of probe trials along the adaptation process. Specifically, participants were exposed to a velocity-dependent force field while performing reaching movements, and in random trials during adaptation, we applied a sequence of force channel - force field - force channel trials. Within each sequence, the force field was accompanied with a velocity-dependent tactile stimulation in the form of moving tactor, which induced three types of stretch: (1) same direction as the force field, (2) opposite direction to the force field, and (3) no skin stretch. Then, by examining the difference between the force channel trials before and after the augmented tactile stimulation, we were able to thoroughly assess the effect of the skin stretch on the adaptation process. We found that consistently with our previous results, the skin stretch in the same direction as the force field impaired the adaptation, while skin stretch in the opposite direction slightly improved the adaptation. In addition, we found that the same direction skin stretch caused a short-lasting decrease in muscles activity due to both feedforward and feedback commands. Regarding to grip force control, the reactive component of the grip force was increased for both same and opposite direction stimulations, with higher increase for the same direction stimulation. Moreover, we found an increase of the predictive component for the opposite direction stimulation. Overall, the results lead us to conclude that skin stretch in the same direction as the external load has a strong but short-lasting effect on adaptation, while skin stretch in the opposite direction to the external load has a weak but long-lasting effect on adaptation. This may indicate that the skin stretch has a different effect on the fast and slow components of the adaptation according to the direction it is applied. This study is an important milestone in the process of understanding force adaptation and sensory integration, which can help in promoting the use of tactile stimulation in medical and assistive devices.

Effects of task-irrelevant visual feedback on motor adaptation in a bimanual redundant motor task

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Redundancy is inherent in motor tasks. The minimal intervention principle (MIP) suggests that the motor system focuses on the movement variability in the task-relevant dimension while ignoring it in the task-irrelevant dimension (Todorov, Nat Neurosci 2004). However, it has not been directly tested how the motor system adaptively corrects the movement when it encounters perturbations in both dimensions. Here, we developed a novel stick-manipulating task using a KINARM. Subjects manipulated a virtual stick with both hands (distance: 15 cm) and moved the right tip (a cursor) of the horizontal stick (length: 40 cm) from a starting point to a visual target (10 cm). During the baseline phase (360 trials) to reach each of 9 targets (0° : horizontal direction, ±10° , ±20° , ±30° , ±40°), the subjects tended to tilt the stick slightly while moving the cursor. Typically, CW (CCW) cursor-movement direction (CMD) accompanied CW (CCW) stick-tilting angle (STA). We identified the inherent relationship between the CMD and the STA (CMD-STA map) that reflects the stereotypical strategy for performing this redundant task. During the subsequent adaptation phase (240 trials), visual perturbations were introduced when reaching the target in the 0° direction. In Experiment 1 (N = 20), the CMD was gradually rotated in 1° increment per trial over 30° around the starting point. The implicit adaptation to the CMD rotation accompanied the stick tilt predicted from the CMD-STA map in the baseline phase. Experiment 2 directly tested if the motor system was indifferent about task-irrelevant errors by imposing the STA rotation around the cursor by 6° (CW: N = 10, CCW: N = 10). The MIP predicted that the subjects did not change their movement patterns because this perturbation did not affect the cursor position. However, the subjects implicitly corrected the STA. If the CMD-STA map constrained their relationship as observed in Exp.1, this STA correction should accompany the CMD change. Notably, the STA correction induced the unnecessary CMD error. Experiment 3 examined how the task-irrelevant errors (CW (N=10) or CCW (N=10) STA rotation) influenced the adaptation to the CW CMD rotation. Under the constraint by the CMD-STA map, the CCW (CW) STA rotation might facilitate (interfere with) the adaptation to the CW CMD rotation. Indeed, the facilitating (interfering) effect between the adaptations to CW CMD rotation and CCW (CW) STA rotation decreased (increased) the trial-by-trial variability of the CMD. In summary, we show that the perturbation in the task-irrelevant dimension could influence motor control and adaptation in the task-relevant dimension. This inconsistency with the MIP is likely to arise from the inherent relationship constraining the movement pattern in task-relevant and -irrelevant space. We speculate that, under such a relationship, the motor system cannot ignore the error in the task-irrelevant dimension because it implies the error in the task-relevant dimension.

Distinct functional architectures for implicit and explicit motor learning from reinforcement signals

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Motor learning can be dichotomized based on the level of conscious control into implicit or explicit learning but also based on the nature of the available teaching signal into reward or error-based learning. A fundamental question is the extent to which implicit and explicit adaptive processes learn directly from teaching signals versus from one another. In particular, we tested the idea that implicit learning on a reinforcement task may be primarily driven by the implicitization of explicit learning rather than directly driven by reward information. In Expts 1-4, participants made 10cm reaching movements to a target in a force channel, rewarded based on the pattern of force they applied to the side of the channel. To ensure that the reward feedback (FB) we provided contained useful information even when performance was poor, we rewarded movements that were better than the median match to the ideal force pattern over the last 40 trials. Participants readily learned this task when verbal instructions were provided alongside a diagram illustrating the rewarded force pattern. However, decreasing the instruction quality by withholding the diagram reduced learning, and removing all instructions about the reward contingency so that participants were not told how they could increase reward, completely abolished learning, even when training was continued for 2000 trials over 3 days. The finding that this learning improves when instructions improve, indicates that reinforcement drives explicit learning, and the absence of any evidence for learning when instructions are withheld, suggests that reinforcement induces little implicit learning. In Expts 5-6, we examined the effect of instructions in a different reward-based task. Here we specifically measured implicit and explicit components of learning based on an aim-report paradigm for VMR learning where reward FB was provided in lieu of visual FB about cursor direction, and the VMR was gradually changed from one trial to the next in a sum-of-sinusoids pattern. We again found that learning was dramatically reduced when reward-contingency instructions were withheld, with a greater than 20-fold reduction in overall learning and a more specific 10-fold reduction in implicit learning. This indicates that successful explicit learning dramatically improves implicit learning compared to when successful explicit learning is not present in a reward-based task. We thus uncover a remarkable difference between how implicit and explicit learning interact when learning is driven by reinforcement vs error-based teaching signals. Whereas error-based teaching signals can readily drive both implicit and explicit learning (e.g., Taylor et al 2014, Miyamoto et al 2020), here we find that reward-based teaching signals can readily drive explicit learning, but provide little direct drive for implicit learning, which primarily arises from the implicitization of explicit strategy, perhaps via a use-dependent learning process.

Blocking cerebellar signals increases internal noise and impairs motor adaptation

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The motor system can rapidly adapt to changes in the body or the environment. During adaptation to external perturbations, the motor system continuously calibrates its sensitivity to errors to allow for more efficient adaptation. The cerebellum is considered as a key player in adaptation, but the neural mechanism underlying adjustments of error sensitivity during adaptation remains unknown. We previously showed that high-frequency stimulation (HFS) in the superior cerebellar peduncle (SCP) effectively and reversibly blocks cerebellar outflow and impedes motor timing and coordination. Here we used this approach to study the effects of a cerebellar block on motor behavior and motor cortical activity when monkeys adapt to an external perturbation. Monkeys (n=2) were trained to wear an exoskeleton (KINARM system) and made center-out movements to 1 of 8 pre-cued targets. After training was completed, a recording chamber was attached to the monkey's skull above the hand-related area of the motor cortex, and a chronic stimulating electrode was inserted into the SCP. High-frequency biphasic stimulation pulses (130 Hz, 100-200 uA) were delivered through the electrode to interfere with the outflow of cerebellar signals. The experimental protocol included an HFS stimulation condition (on/off) and a velocity-dependent force field (FF) perturbation condition (on/off). In the presence of FF, hand trajectories deviated from the straight line but monkeys compensated for the perturbation and gradually decreased the amount of the deviation. Applying HFS during FF trials significantly impaired adaptation as was evident in the monkeys' decreased capacity to consistently reduce movement errors and the residual deviations in late adaptation trials were significantly higher than control (p=3.36e-08, computed during late adaptation trials). In addition, we found that HFS alone (in the absence of FF) increases the level of noise as measured by the variability of maximal deviations across trials compared to control trials (t-test, p = 2.6e-11). To identify the mechanism(s) through which HFS impairs adaptation we used a state space mode, which posits that adaptation is an adaptive process driven by the extent of learning from past errors (i.e., error sensitivity) balanced by the amount of forgetting (i.e., retention factor). The results showed that during HFS, error sensitivity was significantly reduced (22.1%, p=1.2e-27) whereas the retention factor was decreased slightly by 4.7% (p=0.003). Next, we tested the possibility that the increase noise caused by HFS acts as a noisy perturbation on top of the external FF that interferes with the learning process. Although HFS significantly increased motor variability compared to the control trials, the increased variability did not trigger an adaptive response, indicating HFS increases internal and not external noise. Finally, error sensitivity for adaptation during HFS was significantly lower than in FF trials even

Probing the foundations of motor learning for physical Human-AI collaboration

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Physical interaction of humans with "dumb" devices have been in recent times well investigated. Much of the motor learning required has been studied in the framework of motor adaptation, and it remains elusive how motor control strategies (i.e. control policies) are being learned in the first place. This is essential for any form of Human-AI physical interaction as we cannot assume that the two entities need to start learning new control policies without being able to rely on an agreed common control policy; a caveat that also applies for human-human interaction. We present an experimental and computational framework to study the learning of collaborative motor policies by human and AI agents. We have created a test rig for real-time, real-world human-human and human-AI motor collaboration. The rig involves a non-trivial motor task, where a ball must roll on a square tray with obstacles, to reach a goal hole it to fall into. The tray motions are limited to two degrees of freedom, as rotations along its lateral and longitudinal axes. We assign the control of each degree of freedom to one entity. In this manner, and by the way in which the obstacles are placed upon the tray, the only way to solve the task is for the two entities to work together; none of them can solve it on their own. Tray motions are controlled by a robotic manipulator, with human commands captured through optical tracking of controller trays they hold in their hands. AI commands are directly applied by the robot on the respective axis. The AI is implemented as a data-efficient, off-policy, deep reinforcement learner, which receives as its states the position and velocity of the ball as well as the tray angle and angular velocities, all along the two axes of the tray. We have run experiments involving human-human and human-AI teams using this setup. Using this framework we have complete access to the AI's control policy as it is evolving and learning, and implicitly, we can also learn a model of the human's control policy as it evolves, providing a rich framework for studying motor control. We are able to show that Humans and AI can learn to collaborate in a short period of time with suitable use of data-efficient reinforcement learning. Crucially we are seeing that different users develop different control strategies, and correspondingly, the AI system learns different cooperative strategies in response to that. We can show that "transplanting" different collaborative AI policies for one user and exposing them to another leads to substantial decrease in overall task performance. Studying human control policies more closely we observe clusters being formed with common approaches, resulting in more similar collaborative AI agents for humans within that cluster. Our collaborative framework provides an ideal window in studying Human-AI, but also Human-Human interaction.

Friday July 29, 2022

08:00 – 10:00 Session 13, Panel IV

Interrogating the neural control of movement during free behavior

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Our nervous system is capable of generating an amazingly rich variety of movements across a diverse set of contexts and environments. Yet, traditionally, the motor system has been studied using constrained paradigms that involve highly stereotyped and overtrained movements. While such approaches are important for the controlled study of individual aspects of motor control, they are unable to capture the underlying neural principles governing naturalistic movements, and are insufficient for determining whether these principles generalize across the full behavioral repertoire of the animal. For example, research has revealed that aspects of motor control may be heterogenous across different movement modalities. Fast optogenetic inactivation of motor cortex revealed different muscle response latencies between reaching and locomotion. How does cortical influence on downstream muscles vary across a wider variety of movements? New paradigms that facilitate motor system study across multiple behaviors in unconstrained animals are necessary to address these questions. One reason for the lack of such studies is due to the historical challenge of obtaining electrophysiological and behavioral data from unrestrained animals. However, recent advances in computer vision, large-scale electrophysiology, and wireless data transfer have enabled the development of novel freely-moving paradigms. In this panel, we will present and discuss recent technical developments in video-based kinematic tracking and the resultant freely-behaving experiments enabled by these advances. We will present the findings of four lines of research, revealing novel principles underlying the neural control of unconstrained, naturalistic movements. First, David Xing will present on the development of a novel freely-climbing paradigm in mice with simultaneous large-scale neural and EMG recordings. Animals in this paradigm perform a variety of motor actions such as dexterous climbing and locomotion, as well as grooming, eating and leaping. Next, Ilka Diester will introduce a virtual head-fixation approach based on 3D motion tracking combined with a model which removes the influence of undesired body movements on neuronal activity. She will report how this strategy allows the analysis of defined behaviors, unveiling an unexpectedly large fraction of neurons in the rat motor cortex tuned to paw movements, which was

previously masked by body posture tuning. Next, Ann Kennedy will present findings indicating preserved covariance patterns among monkey M1 neurons across a range of unconstrained behaviors in a large telemetry cage requiring limb coordination and body posture changes. Finally, Jesse Marshall will discuss recent advances in 3D behavioral measurement tools, and how they facilitate quantitative comparisons between the neural codes underlying natural and learned behaviors.

10:30 – 12:30 Session 14, Individual IV

Postural and volitional signals occupy separate neural dimensions in motor cortex

Patrick Marino[1], Lindsay Bahureksa[2], Carmen Fisac[2], Emily Oby[1], Asma Motiwala[2], Erinn Grigsby[1], Adam Smoulder[2], Alan Degenhart[3], Wilsaan Joiner[4], Steven Chase[5], Byron Yu[2], Aaron Batista[1]
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Motor cortex (M1) generates time courses of neural population activity, or 'neural trajectories,' that drive movement. These trajectories are shaped by inputs from other areas, such as volitional signals encoding movement goals and sensory signals encoding arm posture. How do postural and volitional signals interact to shape neural trajectories in M1? We examined neural population activity across a variety of tasks and found a strikingly simple organization: first, postural and volitional information were isolated in separate neural dimensions, producing a postural representation that was stable across tasks. Second, the interactions between postural and volitional signals were small and depended on task demands. To ask how postural and volitional signals interact in M1, we started with a brain-computer interface (BCI) task in which Rhesus monkeys volitionally modulated M1 activity to drive a computer cursor to a target. To vary postural input to M1, we placed the monkey's arm in different postures while the animal used the BCI. Because this task did not require arm movement, arm posture was fixed during individual trials, and target-specific volitional inputs to M1 did not need to change across postures. Individual neurons exhibited mixed responses, but at the population level, we found that postural and volitional information were isolated in separate neural dimensions. Neural trajectories did not change shape across postures, despite large, posture-driven changes in trajectory starting points. This indicates that postural inputs, which convey critical information for movement control, do not always affect dynamics in M1. Next we asked whether this organization was present during arm movements. We recorded from M1 while monkeys engaged in multi-posture isometric force and delayed center-out reaching paradigms. In these tasks, arm posture was time-varying, and different initial postures required different movements for task success. The organization seen in the BCI task was visible: postural and volitional information occupied separate neural dimensions. When multiple tasks were run within a session, a single classifier could decode posture across tasks. Neural trajectories displayed limited reshaping across postures, reflecting the necessary interactions between posture and movement in these tasks. We found time-varying activity in the posture subspace, consistent with the possibility that arm posture was represented in this space in an ongoing manner. These findings demonstrate that postural and volitional information occupy separate dimensions of M1 activity, allowing for a stable postural representation across tasks. Sensory information is used differently across tasks, and this was reflected in the task-dependent interactions we observed between postural and volitional signals. Our results shed new light on how M1 accomplishes sensorimotor integration and can inform the design of BCI decoders that are robust to changes in user posture.

Vestibular reflexes in neck muscles contribute to stabilizing the head across the range of dynamic motion experienced during everyday life

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The vestibular system senses motion of the head in space and provides rapid reflex responses in muscles throughout the body to ensure stable posture and gaze. The vestibular reflex in neck muscles (vestibulocollic reflex; VCR) can contribute to stabilizing the head in space, which is vital to enable accurate motor control since the head serves as the reference frame for visual and vestibular information. However, to date our understanding of the efficacy of the VCR in stabilizing the head during motion experienced in everyday life is limited. Previously, the function of the VCR has been inferred from modelling the biomechanics of the head-neck system, or by recording neck muscle activity in response to slow, low frequency motion in cats. Meanwhile, frequencies up to 20 Hz are contained in dynamic motion experienced by humans and non-human primates. Thus, to date the functional efficacy of the VCR during motion relevant to everyday life remains unknown. Here we probed the characteristics of the VCR by recording neck muscle activity during passive whole-body motion in the yaw plane in alert rhesus monkeys. First, to examine the characteristics of the VCR, we applied sinusoidal vestibular stimulation at 18 frequencies from 0.5-20 Hz in 2 healthy monkeys in the dark. Phase indicated that motor units increased activity during contralateral motion (e.g., leftward motion activated the right SPL muscle to stabilize the head in space), and gain increased with the frequency of stimulation up to ~15 Hz. To examine if the response was purely vestibular in origin, we applied sinusoidal vestibular stimulation to a bilateral vestibular loss (BVL) monkey in the dark. Responses were strikingly absent in the BVL monkey, confirming vestibular feedback drives the neck motor unit responses. Next, to examined multisensory integration of visual and vestibular information, we compared responses to motion under 3 different visual conditions (dark, world-fixed surround, and head-fixed surround). In comparison to the dark condition, response gain was higher with the world-fixed visual surround at frequencies beyond ~8 Hz, suggesting visual input may modulate the gain of the VCR. Interestingly, when visual information about self-motion was provided to the BVL monkey (world-fixed visual surround), neck motor unit responses were still absent even at low frequencies, suggesting visual information could not substitute for the lack of vestibular feedback. Finally, we investigated whether motor units show non-linear responses to vestibular input by applying broadband white-noise stimulation. In comparison to sinusoidal stimulation, gain was attenuated at low frequencies during white noise stimulation, a phenomenon previously observed in central vestibular neurons. Altogether, our results demonstrate vestibular projections to neck muscles play a vital role in posture and accurate motor control in primates across the range of dynamic motion experienced during everyday life.

Resting-state functional connectivity predicts postural deficits following spaceflight

Heather McGregor[1], Nichole Beltran[2], Yiri De Dios[2], Jacob Bloomberg[3], Scott Wood[4], Ajitkumar Mulavara[2], Roy Riascos[5], Patricia Reuter-Lorenz[6], Rachael Seidler[1]
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During spaceflight, astronauts adapt to sensorimotor changes induced by the microgravity environment. These include altered vestibular signaling, body unloading ("weightlessness"), and reductions in both lower limb motor outputs and somatosensory inputs. When astronauts are reintroduced to gravity, these in-flight sensorimotor adaptations are maladaptive, manifesting as significant post-flight balance impairments. All astronauts exhibit balance deficits immediately post-flight, but there is considerable individual variability in the extent of impairment and the rate of readaptation to gravity. We have recently shown that astronauts compensate for post-flight vestibular deficiency by upweighting visual and somatosensory inputs to maintain their balance. Predicting a crewmember's post-flight balance impairment would offer insights for pre-flight training and countermeasure development. In this fMRI study, we investigated if resting-state functional connectivity (FC) involving sensorimotor and association brain areas prior to spaceflight is associated with post-flight balance impairments. Fifteen astronauts completed pre-flight test sessions approximately 180 and 60 days prior to launch and a post-flight session within 5 days after their return from a 6-12 month mission to the International Space Station. Test sessions consisted of a 10-min resting-state fMRI scan as well as balance assessments using Sensory Organization Tests. During balance tests, astronauts performed three 20-s trials while standing on a sway-referenced (unstable) support platform, closing their eyes, and performing rhythmic head pitches. Per-trial equilibrium scores were calculated based on anterior-posterior peak-to-peak sway angle. We assessed the change in median equilibrium score from pre- to post-flight. Pre-flight neuroimaging data were preprocessed using a standard pipeline followed by a seed-based connectivity analysis. We tested for associations between pre-flight FC and post-flight changes in postural stability. Resting-state FC between a seed region in the left insula and clusters in left primary somatosensory cortex and left lateral occipital cortex prior to flight was associated with post-flight changes in postural stability. Weaker pre-flight FC between these brain areas was associated with larger postural deficits following spaceflight whereas stronger FC was associated with smaller postural deficits -- or in some cases stability improvements -- following spaceflight. These individual differences in pre-flight FC between regions involved in somatosensation and higher-order visual processing suggest that pre-flight training targeting the visual and/or somatosensory systems may help to reduce postural deficits in astronauts following spaceflight. Supported by NASA grant #NNX11AR02G.

Basal ganglia-spinal cord pathway that commands locomotor asymmetries

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Motor impairments in Parkinson's disease are caused by loss of dopamine input to basal ganglia circuits. Although the basal ganglia are important for locomotion in particular, mechanisms underlying basal ganglia control over spinal locomotor networks remain unclear. One hallmark feature of human Parkinsonism is an exacerbated turning gait and failure to negotiate turns. Chx10 gigantocellular (Gi) neurons are required for turning gait asymmetries (Cregg et al., 2020; Usseglio et al., 2020), suggesting that turning deficits in Parkinson's disease may arise via this spinal projection pathway. Using deep brainstem calcium recording in mice, we found that D1 and D2 striatal projection neurons (SPNs) evoke discrete changes in Chx10 Gi activity during locomotor turns. Leveraging Chx10 Gi neurons as an entry point, we used a reverse dissection approach to uncover the dominant basal ganglia-spinal cord pathway for locomotor asymmetries in mammals: striatal projection neurons -> substantia nigra pars reticulata (SNr) --> pontine nucleus oralis (PnO) -> Chx10 Gi neurons -> spinal locomotor networks. PnO was identified using an intersectional viral screening strategy, where a subset of PnO neurons defined by Vglut2 expression and commissural projection proved to act as the critical link between basal ganglia output and Chx10 Gi neurons. Stimulation of this small cluster of neurons evoked contralateral turning, whereas photoinhibition evoked ipsilateral turning. Finally, chemogenetic or optogenetic manipulation of motor targets downstream of the basal ganglia restored contralateral turning in unilateral 6-OHDA lesioned mice. Our results reveal the circuit logic underlying a critical motor program, from action commitment in the basal ganglia to execution by spinal locomotor networks.

Data-driven gait signatures reveal individual-specific differences in gait dynamics post-stroke

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Modeling the neuromechanics of walking, particularly in neurological disorders, is challenging because current biomechanical simulations lack appropriate neural control mechanisms and constraints. Prior work has shown that at least three distinct groups of muscle coordination impairment exist in post-stroke individuals who have similarly slowed walking speeds. However, we do not know how these neural control deficits manifest in movement features. Here we use a Recurrent Neural Network (RNN) to model the neuromechanical dynamics of gait in a data-driven manner based on capturing spatiotemporal dependencies between sagittal plane lower-limb joint angles during treadmill walking, to compare stroke survivors to each other as well as to able-bodied controls (AB). We generated and analyzed individual-specific 'gait signatures': low-dimensional representations of the parameters of a data-driven gait dynamics model that gives rise to an individual's unique kinematic patterns. We predicted that stroke survivors with faster walking speeds would have gait signatures that more closely resembled that of AB but that those with slower walking speeds would deviate from AB gait signatures in a variety of ways, presumably as a result of differences in their motor coordination deficits. We collected continuous, bilateral, lower limb, sagittal plane joint angles (hip, knee, and ankle) from AB (N=5) and post-stroke (N=7, > 6 months after stroke onset) participants who walked on a treadmill at six different speeds. Kinematic data from all individuals served as inputs to an RNN model, which was trained to predict a time-shifted version of the kinematic input data. Internal activations for all individuals' gaits were extracted from the trained model and reduced in dimension using principal components (PC) analysis. The differences between gait signatures were visualized using two-dimensional t-distributed stochastic neighbor embedding (t-SNE) maps. Gait signatures for each individual walking at different speeds were closely clustered to each other, suggesting that individual-specific differences in gait signature representation are relatively invariant across walking speed. AB gait signatures clustered tightly together, whereas stroke individuals were more separated. Higher-functioning stroke survivors (preferred speed > 0.4 m/s) had more similar gait dynamics to AB, as were clustered in close proximity to the AB gait signatures. Conversely, lower-functioning stroke survivors (preferred speed < 0.4 m/s) were most distant and less clustered, indicating more heterogeneity in gait dynamics. We infer that slow walking can result from disparate neural control mechanisms across individuals allowing potential discrimination in underlying neuromechanics. Gait signatures use kinematic information to capture individual-specific dynamic differences irrespective of walking speed and may enable holistic and objective metrics for characterizing post-stroke and other gait deficits.

Movement is governed by rotational dynamics in spinal motor networks

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Although the nervous system is elegantly orchestrating movements, the underlying neural principles remain unclear. Since flexor- and extensor-muscles alternate during movements like walking, it is often assumed that the responsible neural circuitry is similarly alternating in opposition. Here, we present ensemble recordings of neurons in the lumbar spinal cord that indicate that, rather than alternation, the population is performing a "rotation" in neural space, i.e. the neural activity is cycling through all phases continuously during the rhythmic behavior. The radius of rotation correlates with the intended muscle force. Since existing models of spinal motor control offer an inadequate explanation of rotation, we propose a new theory of neural generation of movement from which this and other unresolved issues, such as speed regulation, force control, and multi-functionalism, are conveniently explained.

15:00 – 17:00 Session 16, Panel V

Basal ganglia circuit communication for movement execution and motor learning: The vigorous tutor revisited

Andreea Bostan[2], David Robbe[3], Roxanne Lofredi[1], Wolf-Julian Neumann[1], Robert Turner[2]
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What are the functions of the basal ganglia? Thirty years ago, the answer to this question seemed to be within reach, but lasting efforts in search for a unifying framework were of no avail. Indeed, behavioral correlates of basal ganglia activity seem as diverse as the ever-increasing complexity of their anatomical and molecular circuit characteristics. The basal ganglia network is uniquely positioned at the center of the motor network to integrate widespread cortical and subcortical information and, under the influence of dopamine, distribute the result of these computations to a similarly diverse array of cortical and subcortical outputs. Whatever the function of the basal ganglia, it is likely embedded in the ability of this web of long-range synaptic connections to shape motor control and learning across the brain. Conversely, the power of these network level connections can be observed in the synchronous oscillations across cortex, basal ganglia and thalamus that are pathologically exaggerated in basal ganglia- based movement disorders. The present panel reviews recent advances in pathway-specific functional anatomy and physiological mechanisms of basal ganglia dependent motor control. It aims to integrate findings from rodent, non-human primate and human clinical research spanning a variety of research methods including transsynaptic tracing, behavoiur, invasive electrophysiology, neuroimaging and computational modelling. While these methods are diverse, the studies presented all focus on structural and functional basal ganglia networks for motor learning and kinematic control. Research highlights include the overlap of basal ganglia and cerebellar circuits in non-human primates with neuromodulation induced changes in human trial to trial motor improvement, an interrogation of potential roles of the dorsal striatum in motor learning, effort and cost signalling and dopamine dependent vigor signals reflected in temporal dynamics in human basal ganglia beta and gamma band activity. The findings presented here serve as case studies to challenge the resilience of influential basal ganglia theories such as the vigorous tutor paradigm, habit formation, reward prediction error signals and energy cost discounting. Our studies suggest that basal ganglia computations result in synaptic modulation of distributed motor networks for motor plan invigoration and consolidation. Importantly, input and output feedback loops may prevail at each stage of the circuit from pre- and primary motor cortex, thalamus and cerebellum. Beta and gamma band oscillatory synchronization may reflect a physiological mechanism for communication in these distributed neural populations, through dopamine-dependent changes in excitability and vulnerability for synaptic potentiation. In summary, our panel highlights the importance of circuit-level computations for understanding basal ganglia function and discusses the translational implications for DBS in basal ganglia disorders.

17:00 – 18:00 Distinguished Career Award Talk

How to select the best balance and gait outcomes for clinical trials

Fay Horak, *Oregon Health and Science University*

The technology to collect Balance and Gait Digital Health Outcomes are Ready for Clinical Trials. However, wearable, inertial sensors provide a myriad of potential measures during prescribed tasks and even more measures during passive monitoring in daily life. Studies have shown that both balance and gait are controlled by several relatively independent neural control systems (domains) that can be affected differently by each neurological disease and by each intervention. Clinical validity includes discovery of which, particular domain is affected by a specific cohort. Evidence to support the use of a particular balance or gait measure as an outcome for a clinical trial includes determining the extent to which measures show: Verification of accuracy, Sensitivity/Specificity, Reliability, Face Validity, Related to Patient-Reported Outcomes and/or Fall Risk, Responsive to Progression, Related to Physiological Biomarkers, Responsive to Change (Effect Size). No one measure will be the best in all categories of evidence so we recommend developing a composite score including several, independent measures using Multiple Criteria Decision Analysis (MCDA). MCDA is a systematic approach to determining the best outcome. Experts weigh the relative importance of all available evidence and the weighted sum of evidence is used to determine the most useful outcome. Examples of evidence supporting balance and gait outcomes for Parkinson’s disease, Cerebellar ataxia, Multiple Sclerosis, and other neurological disorders will be discussed. Benefits and challenges of measuring gait passively in daily life compared to prescribed test in the laboratory or clinic will also be discussed.

Blitz Abstracts

Blitz I

Tuesday, July 26, 2022

Where is the target of our movement?

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When modelling the neural control of movement, one generally focusses on how to generate motor commands that bring the hand to the target. In such models, the location of the target is often taken for granted. However, our brain must rely on sensory information to estimate target location. Sensory information has a limited precision, which could lead to imprecise movements, so it might be worthwhile improving sensory judgments by averaging over time. However, if the location is changing because the object moves, averaging will introduce a bias. Do we rely on the latest location information at each instant, or do we integrate information over time to compensate for the limited precision of instantaneous visual judgments? What if the target moves, so the present location is not where we want our movement to end? What information do we use for the extrapolation? To assess when and how visual information is used, we investigated how participants tapped on objects that were stationary, moving at a constant velocity or accelerating. We added some jitter to the trajectories and studied how the movements were influenced by this jitter. We also varied the regularities between subsequent trials. We show that participants continuously control their movements on the basis of the latest available information about the target's location with a delay of 100ms. The gain of this control increases during the movement, the largest gain being found for the jitter 150 ms before the tap. The same control is used when the target is moving. In that situation, participants combine this instantaneous target location with an extrapolation of the location over the remaining time to reach it. This extrapolation is based on the target's velocity during the last several hundred milliseconds, without considering that the target's velocity may be changing within that period. If the target is accelerating, participants do not take this acceleration into account, so they make predictable systematic errors. By adjusting their movements to compensate for errors made in previous trials, they make accurate goal-directed movements whenever the acceleration is constant across trials. Such heuristics can also deal with misalignment between the senses Our finding that participants only use the instantaneous estimate of target location for controlling their movements might suggest that their movements have to be imprecise. However, at every instant a new noisy estimate is obtained. The characteristics of the muscles introduce the low-pass filtering required to ultimately achieve a precise movement. In conclusion, when making a goal-directed movement, humans build an estimate of the location of the target by using instantaneous information on location that is extrapolated using accumulated velocity information and combine this with a heuristic based on performance feedback.

Predicting full-body proprioceptive cortical anatomy and neural coding with topographic autoencoders

Max Grogan[1], Kyle Blum[2], Lee Miller[2], Aldo Faisal[1]
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Proprioception is one of the least understood senses yet is fundamental for the control of movement, its loss producing profound motor deficits. Even basic questions of how pose and movement are represented, as well as how these representations are arranged across the somatosensory cortex, are unclear. To this end, we adopt a task-driven modelling approach, using a variational autoencoder with Poisson distributed latent variables to approximate a population of cortical neurons. We optimize the model to encode natural movement stimuli derived from recordings of human kinematics and impose biological constraints which we hypothesise to be important for reproducing characteristics of proprioceptive neural coding, namely, enforcing a sparse code and implementing lateral effects between neighbouring neurons in the model to produce topographical structure in neural tuning. To evaluate the effectiveness of these coding principles at reproducing empirical observations in neural data (without any direct fitting to recorded firing rates), we task our model with encoding movement kinematics during a centre-out reaching task and compare activity in the cortical grid of the model to recordings from multi-electrode arrays in area 2 of monkeys performing the same centre-out reaching task. The model is able to reproduce several key observations from the empirical data, including the shape and velocity dependence of proprioceptive receptive fields in hand-centred coordinates despite the model having no knowledge of arm kinematics or hand coordinate systems, the distribution of neuronal preferred directions (PDs), and the topographical arrangement of neural tuning across the cortical surface. Furthermore, we are able to demonstrate the importance in training such models on data that reflects the true distribution of natural behaviour, with the model failing to reproduce key properties of the empirical data when trained on data from stereotyped reaching behaviour only. We then highlight two testable predictions made by the model: 1. The distribution of PDs across the cortex has a blob-and-pinwheel-type geometry. 2. Few neurons encode just a single joint. Lastly, we task the model to encode full-body movement statistics to generate further predictions on the somatotopic organisation proprioceptive stimuli. In summary, the topographic VAE (Topo-VAE, Blum et al, 2021) provides a principled basis for understanding the sensorimotor representations and theoretical basis of neural manifolds using deep generative modelling. These basic scientific principles may have application to the restoration of sensory feedback in brain-computer interfaces (Weber et al, 2012) and the control of humanoid robots.

Biomimetic stimuli from a vestibular prosthesis improve postural control in a nonhuman primate

Olivia Leavitt[1], Kathleen Cullen[1]
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Dynamic balance requires rapid and precise integration of vestibular, somatosensory, and visual inputs. Patients experiencing bilateral vestibular loss (BVL) frequently complain of postural imbalance and remain at high risk of falls even following rehabilitation. An innovative solution to replace vestibular function is the vestibular prosthesis, which bypasses damaged neuroepithelial tissue in the vestibular periphery to stimulate vestibular afferents directly. In clinical trials, vestibular prostheses improve posture, gait, and quality of life. However, they do not yet effectively restore natural function. We hypothesize that the utility of the prosthesis may be enhanced by applying mapping functions between head motion and pulsatile stimulation rate that better mimic the response of endogenous vestibular afferents. Thus, here we investigated the effects of applying naturalistic prosthesis mapping functions in a primate model of posture during transient support surface perturbations. We first established that rhesus monkey postural responses to support surface motion resemble those of humans. Motion of the monkey's head was measured using a wearable IMU, ground reaction forces measured by a force plate, and joint positions were estimated using video-based markerless motion tracking (DeepLabCut). The monkey's responses were consistent with those observed in other animals, tilting against the direction of support surface tilt to regain an earth-vertical head and body orientation. To determine the contribution of vestibular signals to dynamic postural responses, we then applied these support surface perturbations to a monkey with BVL. The BVL monkey exhibited misdirected upper body and head movements, reacting in the opposite direction to the normal monkey. Both head movements and torque were also greater in magnitude for the BVL monkey than normal. Finally, we repeated the perturbations while delivering vestibular stimulation to the BVL monkey via vestibular prosthesis using mapping functions derived from the natural responses of regular and irregular vestibular afferents. We also compared these mappings with a static mapping like those used for clinical trial participants. The animal began exhibiting consistent responses to support surface perturbations within 30 trials after starting the stimulation. When vestibular stimulus profiles were generated using irregular afferent mapping, the misdirection of postural responses was corrected, and the animal began responding in the same direction as a normal animal. In contrast, both regular afferent mapping and static mapping reduced the magnitude of postural responses but did not reverse their direction. This result is congruent with prior results which indicate that irregular afferents are the primary contributors to vestibulo-spinal reflex pathways. Thus, leveraging knowledge of the vestibular system's endogenous dynamics improves behavioral outcomes in a clinically-relevant model of vestibular loss.

Characterization of head orientation and heading during everyday activity: Implications for modeling.

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Estimation of head orientation relative to gravity and the direction of linear self-motion (i.e. heading) is necessary for postural control, locomotion, and perception of spatial orientation. While it is accepted that estimation is constrained by natural stimulus distributions, empirical data describing natural distributions of human head orientation and heading is lacking. Here, we measure 6DOF head position, velocity and acceleration over dozens of hours of unprescribed natural activity. The resulting distributions fill an important gap in the literature and are further used in a Bayesian framework to model known biases in perception of both head orientation and heading. Approximately 50 total hours of unprescribed natural activity was recorded across 10 subjects using an Intel Realsense T265 tracking camera that estimates position at 200 Hz via a proprietary visual-inertial fusion algorithm. Accuracy of the T265 has been evaluated previously (Hausamann et al 2021). Subjects completed calibration movements (head nod and shake) every half hour to facilitate transformation of data into a head-centered reference frame. Across-subject distributions of head orientation relative to gravity were non-normal. Roll was symmetrical and leptokurtic; pitch was asymmetrical, with an over-representation of downward head pitch and higher variance than roll. Across-subject distributions of heading azimuth and elevation were non-normal. Heading azimuth was multimodal, with modes at 0 and ± 90 deg. Heading elevation was unimodal with fat tails and high variance. To explore how natural distributions might shape perception, orientation and heading distributions were used as priors in Bayesian models that aim to explain perceptual biases. Free parameters of the models were constant and signal-dependent noise on orientation and heading estimates, which determined the variability on the Bayesian likelihood for each orientation and heading direction. Variability was modeled to increase linearly or sinusoidally with eccentricity from straight ahead (for heading) or from vertical (for head orientation). Models were fit by minimizing the residual standard error (RSE) between biases observed in previous psychophysical studies and modeled biases. Qualitatively good model fits were obtained for previously observed biases in perception of pitch (Cohen & Larson, 1974), roll (De Vrijer et al., 2009), visually-perceived eye level (VPEL) (Hudson et al., 2000), heading azimuth (Cuturi and MacNeilage, 2013), and heading elevation (Crane 2014). Generally, predicted biases increased with eccentricity, like observed biases. In addition, predicted biases were asymmetrical where the natural distributions were asymmetrical, e.g. for head pitch, and asymmetry was reflected in previously reported psychophysical data. Goodness of fit was quantified using RSE: these values were 8.346° for roll, 4.847° for pitch, 1.475° for VPEL, 2.775° for heading azimuth, and 8.476° for heading elevation.

Ocular eccentricity affects subjective visual vertical perception in health and disease

Catherine Agathos[1], Anca Velisar[1], Natela Shanidze[1]
[1]Smith-Kettlewell Eye Research Institute

Body coordination is critical when interacting with our environment, requiring appropriate integration and reweighting of visual, vestibular and somatosensory cues. One's subjective perception of gravity relies on such integration along with prior knowledge about head orientation in space. It is a crucial aspect of space representation and important for static and dynamic postural control. Age-related vestibular deficits affect mobility and contribute to increased visual dependence for postural control. These changes may be exacerbated by eccentric viewing, leading to higher fall risk for older adults with central vision loss (e.g., due to age-related macular degeneration, AMD) who often adopt eccentric eye positions to exploit their peripheral retina. Visual information is transformed, from retino-centric to head- and body-centered coordinates according to task demand. In addition to vestibular signals, the eye-in-orbit position is a reference for egocentric perception. Thus, an incomplete re-referencing of eye/retinal positions with respect to the body in AMD may affect individuals' interaction with their environment. To determine the effect of eye eccentricity alone, we first tested young adults performing subjective visual vertical (SVV) tasks using central and eccentric eye position. Next, we investigated the effect of central field loss (CFL) due to AMD, while controlling for aging and disease progression, by testing individuals with monocular CFL. We compared SVV judgements during binocular (analogous to central viewing in young adults, since foveal fixation is used with the healthy eye) and monocular viewing with their affected eye - as they adopt an eccentric fixation due to CFL. Participants judged the orientation of a briefly flashed rod, tilted with respect to gravity, with and without a misleading visual context. Depending on the viewing condition, young adults fixated a target centrally or eccentrically, to the right. Eye-tracking was used to monitor fixation. The target appeared centrally in both viewing conditions for those with CFL. Responses were analyzed to determine bias in participants' SVV. In young adults, we found a significant effect of eccentricity, with the bias shifting in the direction opposite fixation and of visual context, with the bias shifting in the direction of the visual context. In participants with monocular CFL, there was an influence of monocular versus binocular viewing and of the visual context, with bias shifts of up to 7°. These data suggest that eccentric viewing affects SVV in both healthy younger adults and older adults with CFL. Our data also show that despite visual impairment, those with CFL are still reliant on visual orienting cues. The interaction of eye position and visual dependence will be important to consider further in the design of rehabilitation tools for individuals with AMD who have eccentric fixation and may have increased visual dependence.

Perception of time-varying envelopes begins at the single-neuron level in central vestibular pathways: implications for perception and motor control

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The vestibular system encodes head motion during our daily activities giving rise to vital autonomous reflexes as well as self-motion perception. Recent studies have shown that self-motion experienced during everyday activities consists of a fast time-varying head velocity waveform (i.e., the carrier or 1st order) whose amplitude (i.e., the envelope or 2nd-order). While previous psychophysics studies have shown that humans can perceive differences in the envelope as low as 2 deg/s, how neurons within ascending vestibular pathways encode these has not been investigated to date. Here we recorded from vestibular-only (VO) neurons within the vestibular nuclei that project to the thalamus as well as the spinal cord, thereby mediating self-motion perception as well as vital reflexes to control posture. Neuronal responses were recorded during rotational stimulation consisting of a noisy waveform whose envelope varied sinusoidally at lower frequencies within that seen under natural conditions (0.05 - 1 Hz). The envelope was furthermore varied such that the underlying stimulus waveform only elicited linearly related changes in firing rate for semicircular canal afferents. Overall, we found that VO neurons robustly encoded the time-varying envelope with a gain that decreased as a function of frequency. Interestingly, VO neural responses increasingly lagged the envelope stimulus as frequency increased consistent with a long stimulus-response latency of ~100 ms. Using a linear-nonlinear cascade model we determined that envelope responses in VO neurons could not be explained by static nonlinearities (i.e., cut-off and saturation). Rather, VO neuronal responses could be reproduced only by accounting for long experimentally-observed stimulus-response latency. Finally, to compare our single unit findings with results of prior psychophysical studies, we computed neural amplitude detection and discrimination thresholds. We found that neural detection and discrimination threshold values were an order of magnitude higher than those observed for human perception. Indeed, to account for perception, it was necessary to pool the activities of about 150 to 200 neurons - a value much greater than for thalamus neurons (~10 neurons, Carriot et al. 2021). Overall, our results show that, while encoding of time-varying envelopes begins at the level of the vestibular nuclei, perceptual performance is likely mediated by downstream neurons (e.g., cortex) that first extract the envelope signal and then send this signal upstream to VO neurons. As such, our results have critical implications for understanding how self-motion perception as well as critical reflexes mediating posture control are mediated by ascending vestibular pathways.

Humans optimize energy and time for point-to-point walking movements

Elizabeth Carlisle[1], Arthur Kuo[1]
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Humans often perform voluntary movements such as walking at self-selected speed and duration. The speed trajectories of some point-to-point tasks, such as upper extremity reaching and visual saccades, are thought to minimize objectives such as accuracy or smoothness. Such objectives do not, however, explain point-to-point walking bouts. Steady walking appears to minimize energy expenditure per distance traveled, but there is no governing principle for the speed trajectories of point-to-point walking bouts, nor for how those speeds are influenced by task urgency or movement vigor. We propose an optimization principle for walking that resolves both speed trajectories and durations, by combining energy and time. The energy cost is the total energy expenditure over the whole walking bout, and the time cost is a penalty linear in task duration, with an individual-specific coefficient. This energy-time cost can predict an entire speed trajectory over a given distance, including acceleration, deceleration, and

overall duration. Both energy and time appear important for walking, and could influence arm and eye movements as well. We predicted speed profiles with a computational, dynamic walking model. The minimization objective is expressed as the energy needed for (ankle) push-off each step, plus a cost proportional to task duration, with a coefficient for an individual's valuation of time. The optimal trajectory is dictated by walking dynamics, where the swing leg behaves like a pendulum and the stance leg like an inverted pendulum, and push-off work is needed to power walking and modulate speed. The model predicts a somewhat rounded speed profile, with a gradual acceleration and deceleration, and a peak about halfway through the walk. Steady walking speed emerges as an optimum for longer walks. The objective's coefficient for duration increases or decreases the overall speed, but does not affect the speed profile's shape; it may be considered a time valuation for the energy one is willing to spend to save a unit of time. We tested model predictions with an experiment (N=10) where healthy adults were instructed to walk prescribed short distances (2 - 20 steps). Walking speed for each step was measured using inertial measurement units attached to the feet, and the resulting speed trajectories compared to model. There was good agreement in the overall shape of the speed profiles, as well as the relationships between peak speed and distance (R^2 = 0.8620), and walking duration and distance (R^2 = 0.9835). Individuals differed in walking duration, but their trajectories were consistent with an individual-specific valuation of time. This objective can predict walking speed trajectories, and can potentially apply to reaching and saccade movements as well. Both energy and time could be important for general, goal-directed movements.

Deep brain stimulation frequency affects evoked potential delay, amplitude, and frequency components

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Deep brain stimulation (DBS) is an emerging treatment for movement disorders, including dystonia. While DBS has proven effective, not much is known about the mechanisms of action of the treatment method, nor of dystonia itself, which makes it difficult to provide the ideal treatment for each patient. Hence, this study aimed to shed light on these areas by investigating the effect of DBS frequency on evoked potentials (EPs) recorded in deep brain structures of dystonic patients. Externalized DBS leads were implanted bilaterally in 10 pediatric patients with dystonia selected for DBS treatment. Up to 6 leads per hemisphere were placed in target areas including the thalamus (ventral intermediate, VIM; ventral posterolateral, VPL; ventral anterior, VA; and ventral oralis, VO) and basal ganglia (globus pallidus interna, GPi; and subthalamic nucleus, STN), based on prior studies of clinical efficacy in patients with movement disorders when lesioned or electrically stimulated. Stimulations consisting of 3-V, 90-us pulses ranging between 9 and 250 Hz were delivered through conventional low-impedance macro-contacts. Neural data were simultaneously gathered through high-impedance micro-contacts, allowing us to record high-frequency neural components in the kHz range. Each recording was investigated for the existence of an EP, which, if found, was characterized by its amplitude, delay, and frequency components. These characteristics were then compared between stimulation frequencies. Preliminary results alluded to a clear effect of stimulation frequency on EP delay, amplitude, and frequency components. Stimulation frequency was found to be negatively correlated with EP amplitude, and positively correlated with EP delay - i.e., higher stimulation frequencies typically evoked smaller and more delayed neural responses. Moreover, as the stimulation frequency was increased, any high-frequency components of EPs seemed to reduce, inferring a possible cerebral low-pass filtering effect at higher stimulation frequencies. These trends of decreased amplitude, increased delay, and "low-pass filtering" of EPs at higher DBS frequencies may be related to refractory periods and oversaturation of neural receptors when stimulations are delivered at shorter intervals. Qualitative and/or computational models will be developed with the aim to explain the neural mechanisms behind this frequency dependency. Future work also involves confirming preliminary results through group analyses, including multivariate regression, which will allow us to determine whether these trends are more prominent e.g. in particular stimulation and/or recording regions, in anti- or orthodromic connections, or in certain subjects. These findings will help shed light on the dystonic brain's frequency-dependent response to DBS and provide insight into how we can use stimulation frequency to generate wanted neural response patterns to elicit the most effective clinical response to DBS treatment.

Blitz II

Thursday, July 28, 2022

High-performance kinematic decoding and neural-state estimation that leverages general properties of motor-cortex population geometry

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A common goal in basic research and brain-machine-interface engineering is to infer the most likely neural state, and/or the most likely action, from spiking observations recorded from a small set of neurons. Recent characterizations of population-level properties of neural activity in motor cortex suggest a new set of statistical constraints that allow efficient neural state estimation and subsequent kinematic decoding. Neural trajectories in motor cortex are stereotyped and directed. A neural trajectory is traversed in only one direction - never in reverse. Moreover, neural covariance often changes dramatically across tasks, contexts, or trial epochs, such that neural trajectories explore previously low-variance dimensions. These properties allow neural trajectories to spread out and avoid 'trajectory tangling'; similar neural states never lead to dissimilar future neural states. These properties suggest a revised view of neural activity in motor cortex: the embedding dimensionality of neural trajectories may grow large, yet trajectories remain sparse such that the vast majority of neural state space is empty and unused. Thus, despite relatively high linear dimensionality (tens or even hundreds of dimensions) there are very few locations where the neural state can plausibly reside. Furthermore, because tangling is low, a good estimate of the present neural state typically provides a good estimate of the recent past and near-term future. We present a decode algorithm (MINT: Mesh of Idealized Neural Trajectories) that codifies these properties into statistical assumptions. MINT learns a library of idealized neural trajectories, one per condition, that serves to scaffold a geometrically complex underlying manifold. MINT also learns a library of corresponding behavioral trajectories. Each neural state in the library has exactly one corresponding behavioral state. Kinematic decoding uses this direct mapping, avoiding the need to approximate it with a nonlinear function. During inference, MINT first estimates the probability of every state in the library, given past and present spiking observations. Interpolation is then used to improve the estimate's resolution and generalize between conditions as needed. We evaluated offline performance across multiple tasks and brain areas. Performance rivaled or exceeded that of modern neural network state estimators and decoders. Yet MINT is mechanistically interpretable and orders of magnitude more computationally efficient. As the movement repertoire

desired for brain-machine interfaces expands, decode methods will face the challenge that correlations between neural activity and behavior are strongly task dependent. MINT provides a unified decode strategy that is aided rather than impeded by changing correlations. This generality demonstrates the utility of scientifically grounded assumptions: cutting-edge performance is readily achieved across a broad variety of situations, with minimal computational cost.

Influence of implicit and explicit feedback response to a visual error on visuomotor learning response

Yuto Makino[1], keisyu Inoue[1], Toshiki Kobayashi[1], Daichi Nozaki[1]
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When encountering a movement error, the motor system corrects the movement within a trial (feedback response: FR) and in the subsequent trial (learning response: LR). A theoretical study has proposed that the motor command for FR serves as a teaching signal for LR (Feedback Error Learning (FEL); Kawato et al., 1987). Consistent with the idea, it was demonstrated that the LR is a time-shifted copy of the FR (Albert & Shadmehr, 2016). However, other empirical results contradicted the idea. First, the LR did not preserve the temporal patterns of FR (Fine & Thoroughman, 2006). Second, the LR is present even when the FR is absent (Burge et al., 2008). To test the FEL further, we modified an experimental paradigm developed initially to investigate the FR (Franklin & Wolpert., 2008). Specifically, the visual cursor was laterally shifted when reaching a target 20 cm away. We measured the force against the force channel in the perturbation trial (FR) and the subsequent trial (LR). This method enables us to arbitrarily manipulate the temporal pattern of visual error and directly compare the temporal profiles for FR and LR by the force output. First, Exp.1 examined if the LR was similar to the FR with a constant time shift (N = 10). The cursor was laterally shifted by ±3 cm at 7 different locations. As reported in the previous study (Albert & Shadmehr, 2016), the temporal patterns of FR and LR were similar regardless of the shift location, and the magnitude of LR significantly correlated with that of FR. However, while the onset of FR depended on the shift location, the LR started equally before the movement onset, clearly indicating that the LR is not the FR shifted with a fixed time. Next, Exp.2 examined if the similarity between the FR and the LR was still preserved when manipulating the temporal profile of cursor-shift (N = 10). After ± 3 cm cursor shift at 1 cm, the shift was maintained, removed, or reversed (∓3 cm). Although the temporal pattern of cursor-shift specifically modulated the FR, the LR did not show such temporal specificity: For example, a biphasic FR pattern was observed for a reversed condition, but the monophasic LR was produced. Exp.1 and 2 assumed that the FR was implicitly induced (i.e., the explicit strategy was not used). Although the explicit strategy for motor learning has been widely investigated (Taylor et al., 2014), no previous study has examined how the explicit FR influenced the LR. In Exp.3 (N = 10) with the cursor shift by ± 3 cm at 1cm, depending on the target color, the subjects were instructed either to voluntarily exert the lateral force in the cursor-shift direction (anti-correction), in the opposite direction (pro-correction) or not to use any explicit strategy. Counter-intuitively, the anti-correction enhanced the LR, while the pro-correction reduced the LR. These results indicate that the motor system produced the LR through the complicated computation based on the visual error information and the FR.

Anticipatory force control for skilled manipulation of objects at variable contact points depend on visual feedback at grasp contact

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BACKGROUND AND AIM: Anticipatory force control is key for dexterous hand-object interactions. Visual feedback of an object's physical properties and sensorimotor memories from prior interactions form internal representations that enable anticipatory force control and subsequent dexterous manipulation. Most studies on which this prevalent theory is based used designs that constrain the grasp contact points, which fails to explain a fundamental aspect of dexterous manipulation: our ability to grasp an object at various contact points and adjusting our forces accordingly. This presents a major paradigm shift in that force planning relies not only on sensorimotor memories and visual cues of object properties, but also on where the object is grasped. In this study, we determine how sensory information of the hand from reach onset to grasp contact is integrated online and contributes to force coordination for subsequent dexterous manipulation. METHODS: Right-handed participants lifted a symmetrically shaped object with an asymmetric center of mass (CM) at unconstrained contact points. Sensorimotor learning rates were quantified based on minimizing roll of an object with a left or right CM, with the given CM switching after every block of 8 trials (total blocks: 8). Four between-subjects conditions manipulated the availability of visual feedback at reach onset (OFF-ON), grasp contact (ON-OFF), or both (OFF-OFF; ON-ON). RESULTS: The difference in object roll between the first and last post-rotation trial in each block of trials became smaller with subsequent blocks in all groups, indicating learning to generalize generating a compensatory torque of appropriate magnitude and direction for manipulating an object with a switching CM. Learning was faster and most notable in ON-ON and ON-OFF than OFF-ON and OFF-OFF groups. CONCLUSIONS: Our results suggest that visual feedback at movement onset, but not grasp contact, is used to modulate forces in responses to digit position during sensorimotor learning of dexterous object manipulation. The timing of sensory feedback contributing to successfully manipulating objects is highly relevant to work on brain-computer interfaces and other technologies aiming to restore skilled grasp in patients with a loss of hand function.

Express visuomotor responses in hip abductor muscles: Evidence for an intricate relationship between fast stepping and postural control

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BACKGROUND: Our ability to rapidly interact with our environment has been studied in reaching via the measurement of express visuomotor responses (EVRs). EVRs are directionally tuned muscle activity bursts that aid in the rapid initiation of the goal-directed movement. They occur ≈100ms after visual stimulus onset, hinting at the involvement of a direct subcortical pathway via superior colliculus. Fast stepping responses are equally important as reaching, yet the presence of EVRs in the lower extremities has not yet been demonstrated. Stepping is more complex than reaching due to increased postural demands, which usually need to be compensated for via anticipatory postural adjustments (APAs) that involve muscle recruitment opposite to that of the focal stepping movement. We here aimed to investigate stepping-related EVRs and their interaction with the APAs that precede step initiation. METHODS: We used an emerging target paradigm, during which healthy young subjects (N =16) stepped rapidly towards flashed visual targets presented randomly to the left or right. We recorded surface EMG of bilateral gluteus medius (GMed), a muscle that is oppositely involved in APAs and stepping; and bilateral ground reaction forces. Two target location conditions were introduced. First, in a lateral stepping condition with reduced postural demands prior to step initiation, targets were presented in front of and lateral to the stepping leg. Second, in a medial stepping condition with increased postural demands, targets were presented in front of and medial to the stepping leg. Outcome measures were

EVR presence, magnitude and latency, APA presence, and stepping reaction times. RESULTS: In the lateral condition, EVRs were robustly and strongly present in GMed contralateral to the target (16/16 subjects, M = .12, ML = 108ms). In medial stepping, EVRs were detected in few subjects (3/16) with low magnitude (M = .05, $p < .001$) and slightly longer latencies (ML = 111ms). APAs could only be identified in the medial condition (M = 167ms), following the EVRs by ≈55ms. These observations coincided with significantly faster stepping RTs in the lateral (M = 323ms) compared to the medial condition (M = 442ms; $p < .001$). We found a strong negative correlation between EVR magnitude and subsequent stepping RT in lateral stepping ($r = -0.63$ $p < .001$). This correlation was absent in medial stepping. CONCLUSIONS: Here we provide evidence for an intricate relationship between EVRs and postural control. In the lateral condition, where APAs were absent due to low postural demands, EVRs aided in the execution of a fast step, as strong EVRs correlated with faster stepping RTs. In the medial condition, results were strikingly different: APAs were essential, as postural demands needed to be accounted for prior to making the step. EVRs were barely present in this condition, implying that higher-order areas suppressed the subcortical EVR network, as they would otherwise hinder APA execution.

Sensory tuning in neuronal movement commands

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Movement control is critical for successful interaction with our environment. However, movement does not occur in complete isolation of sensation, and this is particularly true of eye movements. Here, the superior colliculus (SC) plays a fundamental role, issuing saccade motor commands in the form of strong peri-movement bursts that are widely believed to specify both saccade metrics (encoded spatially) and kinematics (encoded temporally). However, practically all models of saccade control by the SC rely on observations with small light spots as saccade targets. Instead, we asked monkeys to "look" at images, akin to more natural behavior. For each recorded SC neuron, we presented different images centered on the hotspot location of the neuron's movement field, and we ensured that the saccade vectors and kinematics were matched across images. We tested gratings of different contrasts, spatial frequencies, and orientations; images of animate and inanimate objects (as well as their non-object scrambled versions); and black versus white stimuli. Despite matched saccades across trials within a given image manipulation, the SC motor bursts were strongly different for different images; that is, they were sensory-tuned, preferring some visual features as the saccade targets over others. Surprisingly, such sensory tuning in the neuronal movement commands could be even sharper than that in passive visual responses: the difference in movement burst strength between the most and least preferred image features (for the same saccade vector) was often larger than that in the visual bursts at stimulus onset during fixation; this is consistent with known pre-saccadic perceptual enhancement. Most intriguingly, even purely motor neurons (without significant visual sensitivity during fixation) exhibited strong sensory tuning in their motor bursts. Sensory tuning was also present in peri-saccadic local field potential modulations. Since SC motor bursts are relayed virtually unchanged to cortex (Sommer & Wurtz, 2004), one implication of our results is that the visual system is primed (via ascending pathways from the SC) not only about the vectors of upcoming saccades, as is traditionally believed, but also about the movement targets' visual sensory properties. Consistent with this, in further human psychophysical experiments, we additionally found that the visual features of a given saccade target significantly modulate the strength of two classic peri-saccadic perceptual phenomena: suppression and mislocalization. Our results provide novel insights about the functional role of SC motor bursts: beyond representing saccade target locations via a spatial code, SC motor bursts also carry information about the saccade target visual features in their temporal profiles. These observations motivate extending theoretical accounts of saccade-related corollary discharge beyond just spatial movement-related reference frames and into the realm of visual feature representations.

Nociception impedes grasping recovery in the spinal cord injured rat

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Significant deficits in motor control and sensory function diminish an individual's quality of life following spinal cord injury (SCI). A top priority of the injured population is regaining upper limb function. It has been shown that descending motor commands and primary afferent input, such as cutaneous feedback and proprioception, drive plasticity and recovery of function after SCI. Our lab and others have shown that primary nociceptors sprout and facilitate the maladaptive plasticity seen in chronic pain development, but their role in motor control is critically overlooked. The purpose of this experiment was to better understand the role of nociceptive input on recovery of motor function after SCI. Mechanosensitive, non-peptidergic nociceptors were ablated in Sprague-Dawley rats via intraganglionic injections of rIB4 -conjugated saporin or unconjugated (vehicle) saporin into the C7-8 dorsal root ganglia (DRGs). During the same surgery, a subset of rats received an ipsilateral C5 hemicontusion and the implantation of a braided multi-electrode probe for recording in the ipsilateral C8 gray matter. The von Frey test for allodynia and immunohistochemistry, in which cervical DRG and spinal cord sections were stained with antibodies against CGRP and isolectin-B4, confirmed nociceptor ablation. This ablation of nociceptors following SCI improved the rats' ability to grasp food pellets when compared to vehicle-treated controls in the Montoya staircase test (x2=4.019, $p=.0449$); however, a cereal manipulation task revealed that individual digit control did not return with ablation. The forelimb mean and max pull force of SCI rats with nociceptor ablation was higher than that of SCI only rats while performing an isometric pull task ($p=.0005$, $p=.0165$). Importantly, the limb extension or "reach" was not impacted by nociceptor ablation at C7-8 as measured by the cylinder paw preference test ($p>0.05$). Furthermore, uninjured rats with nociceptor ablation showed no significant differences in motor control when compared to uninjured rats without ablation indicating that the role of the nociceptor is altered following SCI. Ongoing experiments are focused on measuring changes in neuronal activity within the C7-8 cord in awake behaving rats with and without nociceptor ablation. Multivariate statistical analyses of the behavioral, anatomical, and electrophysiological outcomes are underway. Increasing our understanding of the role nociceptors play in the spinal plasticity related to motor control following SCI will help guide future research and development of rehabilitative techniques.

An intention-based strategy for grasping prosthesis

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Grasping movements are one of the most essential ways primates interact with the environment and they comprise some of our most complex actions. Despite the remarkable recent progress in intracortical brain-computer interfaces (BCI), algorithmic improvements have not considered the special requirements of hand shape control. The act of grasping is determined by the precise execution of non-linear transitions and the attainment of hand configurations in a high-dimensional state space, yet,

existing approaches derive from low-dimensional arm navigation. We introduce the ReMAP (Recalibrated Map to Attempted Path) training algorithm for grasping prostheses. Bred on intention-based training techniques (Gilja et al. 2012; Orsborn et al. 2012), and inspired by variational autoencoders, ReMAP uses the fact that kinematic trajectories during grip type execution tend to stay within a curved state-space manifold. To preserve the subject's intent, the algorithm projects attempted kinematic transitions onto the intended kinematic trajectory and uses the projection as the training objective function. To test our approach, we trained two monkeys to perform a multi-grasp task in a physics-based virtual environment (MuJoCo) while wearing an instrumented glove tracking 32 joint angles of the arm and hand. After the animals proficiently learned the task, they were implanted with microelectrode arrays in three key areas of the grasping circuit (AIP, hand M1 and F5) and trained in an equivalent BCI task with no movement of the native arm. The ReMAP strategy was superior to traditional training methods in a number of metrics, including success rate and accuracy of the BCI grasps. The effectiveness of an intention-based training approach can be measured by the capacity of the BCI to reflect the user's intent in an environment with obstacles (Gilja et al. 2012; Shanechi et al. 2017). When compared under object collisions to a classic intention-based method that only considers kinematic targets, ReMAP produced fewer collisions and achieved higher performance. Offline data analysis revealed that the effectiveness of our decoding method was supported by an asymmetry in the amount of kinematic information present in the neural data: we found abundant position information in contrast to velocity information during BCI- and native arm grasp control, in line with previous work (Vargas-Irwin et al. 2010; Bansal et al. 2011; Stark-Inbar and Dayan 2017) and in comparison to reaching data (Goodman et al. 2019; Okorokova et al. 2020). When looking at the learning process over sessions, we found evidence that there was a tendency of the activity to evolve as position-like patterns. Given the causal nature of BCI control, our results provide compelling evidence for the special nature of the neural representation of grasping to be explored in future studies. Funding: DFG-FOR1847-B3, DFG-CRC889-C09, and EU-Horizon-2020 GA-965044 project B-CRATOS.

Hasty sensorimotor decisions rely on an overlap of broad and selective changes in motor activity

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Humans and other animals are able to adjust their speed-accuracy tradeoff (SAT) at will depending on the urge to act, favoring either cautious or hasty decision policies in different contexts. An emerging view is that SAT regulation relies on influences exerting broad changes on the motor system, tuning its activity up globally when hastiness is at premium. The present study aimed to test this hypothesis. Fifty subjects performed a task involving choices between left and right index fingers, in which incorrect choices led either to a high or to a low penalty in two contexts, inciting them to emphasize either cautious or hasty policies. We applied transcranial magnetic stimulation on multiple motor representations, eliciting motor evoked potentials (MEP) in nine finger and leg muscles. MEP amplitudes allowed us to probe activity changes in the corresponding finger and leg representations, while subjects were deliberating about which index to choose. Our data indicate that hastiness entails a broad amplification of motor activity, though this amplification was limited to the chosen side. On top of this effect, we identified a local suppression of motor activity, surrounding the chosen index representation. Hence, a decision policy favoring speed over accuracy appears to rely on overlapping processes producing a broad (but not global) amplification and a surround suppression of motor activity. The latter effect may help to increase the signal-to-noise ratio of the chosen representation, as supported by

single-trial correlation analyses indicating a stronger differentiation of activity changes in finger representations in the hasty context.

Cerebellar function for recalibrating visual space, motor space and internal movement predictions

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The cerebellum keeps our movements accurate through supervised error-based learning. Accordingly, changes at the Purkinje cell synapse recalibrate an inverse model, i.e. the transformation of a spatial goal position into a motor command. For saccadic eye movements, it was recently revealed that learning is actually a threefold process. Besides motor recalibration of the inverse model, learning also comprises perceptual recalibration of the visuospatial target map, and of a forward dynamics model that estimates the saccade size from corollary discharge. We dissociate cerebellar contributions to the three stages of visuomotor recalibration by fitting a state-space model to the saccades and pre- and trans-saccadic target localizations of eight patients with cerebellar pathology and eight healthy control subjects. Conditions were (1) learning from peri-saccadic inward target steps, (2) learning from peri-saccadic outward target steps and (3) saccade maintenance when the target stayed at its initial position across the saccade. Based on Masselink & Lappe (2021), the model captures recalibration at all three stages of the visuomotor circuitry to reduce postdictive motor error, i.e. the error of the motor command with respect to a postdictive update of visuospatial target position. Results of the learning conditions showed that cerebellar pathology reduces short-term recalibration of the inverse model and completely suspends short-term recalibration of the visuospatial target map. By contrast, the forward dynamics model was well informed about the reduced saccade change in patients. Moreover, the saccade maintenance condition revealed that patients tend to uncompensated oculomotor fatigue. Control subjects sufficiently upregulated saccade duration to counteract a fatigue-induced decline in saccade peak velocity. By contrast, patients compensated by only 46%, resulting in a gradual decrease of saccade amplitudes. According to our model, this could induce long-term compensation at perceptual level, consistent with a significant overestimation of target eccentricity that we observed in the patients' baseline data. Interestingly, this can also explain how saccade amplitudes can recover from initial hypometry induced by cerebellar lesion, as previously observed in monkeys (Takagi, Zee, & Tamargo, 1998; Barash et al., 1999). We conclude that the cerebellum performs short-term learning of the visuospatial target map and of the inverse model and counteracts oculomotor fatigue by within-saccade control of movement duration. The forward dynamics model and long-term perceptual learning may be computed upstream of the cerebellum.

Satellite Posters

SP1.1 Discharge properties of neurons in the 8th nerve, vestibular nucleus and abducens nucleus may explain suboptimal VOR characteristics in response to neuroprosthetic stimulation.

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Introduction: Vestibular neuroprostheses aim to restore vestibular function after the loss of vestibular hair cells. These devices were designed to restore primarily the angular vestibulo-ocular reflex (aVOR) by selectively stimulating afferent fibers of each ampullar nerve. They have been successful in providing controlled vestibular activation in patients, and clinically relevant recovery of function. However, aVOR restoration has been suboptimal in human subjects; e.g., low or pulsatile eye velocity, incorrect timing, and fluctuating direction errors. To understand the mechanisms underlying the suboptimal aVOR response to neuroprosthetic stimulation (eVOR), we recorded eye movement behavior and neural activity during such stimulation. Methods: Rhesus monkeys were implanted with a vestibular neuroprosthesis designed for human use. The device generated biphasic pulse stimulation (BPS) modulated either in current amplitude or pulse frequency. Eye movements were recorded in the dark with scleral coils in awake behaving animals. Unit activity was recorded from 8th nerve afferents, identified vestibular nuclear neurons, and abducens neurons. Results: Neuroprosthetic BPS produced electrically elicited VOR (eVOR) in the plane of the targeted (implanted) canal above threshold current levels. As current was increased, eye movements were elicited out of plane. High eVOR eye velocities could only be achieved at current levels eliciting significant out of plane eye movements. eVOR directions suggested canal-canal or canal-otolith summation. Low pulse rate stimulation elicited brief velocity pulses, while higher pulse rates elicited sustained eVOR velocity. Velocity saturated with high pulse rate, and then decreased at higher rates. Afferent fibers displayed time locked discharge in response to BPS with different thresholds. The probability of eliciting a spike increased with increasing current level. Individual afferent fibers often responded to BPS of sites in multiple canals. Differences were observed between afferents types. Secondary vestibular neurons displayed time locked discharge in response to BPS above current thresholds corresponding to behavioral thresholds. The probability of a spike increased with increasing current amplitude and decreased with increasing pulse frequency, typically saturating well below P=1.0. Changes in current level often changed the timing but not the number of elicited spikes. Most neurons responded to stimulation from multiple canal electrodes at higher current levels. Differences were observed between behaviorally identified neuron types. Abducens neurons displayed complex response characteristics comparable to vestibular neurons, but at longer latency. Conclusion: These results suggest that neural activation with eVOR is qualitatively different than that underlying natural aVOR. These differences limit the ability of neuroprosthetic stimulation to reproduce natural VOR responses.

SP1.2 Binocular coordination of horizontal saccades in mTBI and cerebellar dysfunction

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Mild traumatic brain injury (mTBI) can result in significant problems affecting vision and oculomotor function (Armstrong, 2018; Mani et al., 2018; Stuart et al., 2020), vergence eye movements (Magone et al., 2014; Suhr et al., 2015), saccades (Samadani et al., 2015; Hunfalvay et al., 2019), spatial orientation,

movement, and balance (Wallace and Lifshitz, 2016; Hoffer et al., 2010). These issues can result in problems with gaze control, eye-head-coordination, and visual-motor transformations underlying goal-directed movements. This can occur after multiple head trauma events, and in some cases after a single mild TBI event. Also, symptoms can persist years after the original trauma (Danna-Dos-Santos et al., 2018) and can become progressively worse over time. Effects of the natural aging processes probably interact with the pathophysiology resulting from TBI. The general aims of this study are to characterize the coordinated movement of the two eyes during changes in gaze in response to movement of a visual target and to relate the velocity trajectories of the two eyes to vergence dysfunction in mTBI. For this presentation, the horizontal position and velocity of the left eye versus the right eye were analyzed for the data from 20 control participants and 30 participants with mTBI. Saccade targets were presented 5 to 25 degrees left/right of center. Plots of left versus right horizontal eye velocity were quantified with polynomial regressions of eye velocity toward and away from zero velocity. Discriminant analyses of the regression coefficients identified those subjects with abnormal velocity trajectories. Some patterns included the following. For large saccade amplitudes there could be different velocities for the adducting eye versus the abducting eye in mTBI subjects who have convergence insufficiency or convergence excess. Furthermore, there were differences between the acceleration and deceleration phases of the saccades, with the acceleration phase of horizontal saccades being significantly different in mTBI compared to controls, similar to what is present with cerebellar dysfunction. Simulations of the velocity and acceleration profiles suggest deficits in the motor commands for adduction versus abduction movements. These results have identified eye velocity patterns and possible motor command deficits that show promise for characterizing binocular eye movements in mTBI. Further work will evaluate vertical and diagonal saccades and gaze in three dimensions where there are changes in vergence. The results could provide further insight into underlying the pathophysiology affecting the control of gaze in mTBI and suggest possibilities for vision therapy.

SP1.3 Information transmission in the cerebellum: the role of rate and synchrony during smooth pursuit

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Motor behavior is driven by neural populations that transform and relay information to downstream areas. A common mechanism for information transmission is the coherent modulation of upstream firing rates. However, motor signals may also be encoded in the precise timing of spikes across a neural population. The synchronous firing of multiple units could then faithfully transmit relevant temporal information to downstream populations. We have addressed this issue for a specific neural circuit by recording simultaneously from definitively identified cerebellar Purkinje cells (PCs) via extracellular recordings and isolated the contributions of rate and synchrony for control of motor behavior. The floccular complex of the cerebellum is crucial for the performance of smooth pursuit eye movements, allowing us to assay how changes in PC rates and synchrony contribute to pursuit behavior. Using multi-contact silicon electrodes, we recorded from 32 pairs of well-isolated PCs, definitively identified by the presence of post-climbing-fiber pauses, in three rhesus monkeys. To ensure that we could measure spiking synchrony across simultaneous units with high accuracy, we designed a novel spike sorter that minimizes errors in detection of overlapping extracellular spikes. The likelihood that two simultaneously recorded PCs fired together with millisecond precision was relatively small, with a less than 10% increase relative to chance. These results were consistent across a much larger population of 118 putative PC pairs, where one or both units lacked climbing-fiber responses. Using the measured millisecond correlations between simultaneously recorded units, we simulated a population of 40 PCs, allowing us to assay the impact of the observed correlations on a cell in the cerebellar nucleus. The presence of neuron-neuron correlations in the PC population resulted in only a 6% change in the input to a downstream neuron. We also tested whether PCs actively synchronize only during execution of pursuit eye movements. As simultaneously recorded PCs tended to have very similar preferred directions of pursuit (mean angular distance of 13.4°), changes in their firing rates tended to be strongly correlated. The likelihood of observing synchronous spikes between pairs of PCs was modulated with pursuit, but could be almost wholly accounted for by changes in firing rate. Finally, we assayed whether the rate responses of PCs could predict the firing of downstream units in the vestibular nucleus. Indeed, the responses of individual cells could be well predicted (R² > 0.90) by changes in PC rate signals alone without the need for precise timing of PC spikes. Our results suggest that the synchronous activity of Purkinje cells is unlikely to contribute substantially to motor behavior. Rather, coherent changes in the firing rate of Purkinje cells appear to be relayed faithfully to downstream neurons.

SP1.4 Inferring function from information transfer during coordinated eye and arm movements

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The function of a module embedded within a circuit can be described by the relationship between its output and input, observed across a sufficiently broad range of circumstances. When studying the brain, this sort of information can be difficult to measure and characterize. An alternative approach is to deduce function based on the flow of information between modules. Input and output of a module are difficult to measure but we can infer information flow by looking at shared information across modules. In this study, we apply this approach to the Lateral Intraparietal area (LIP) and the Parietal Reach Region (PRR) to better understand their relative roles in planning coordinated eye and arm movements. We simultaneously recorded spikes and local field potentials (LFPs) from LIP and PRR while rhesus macaques planned and executed different types of coordinated eye and arm movements. We assayed communication between these two areas using time-lagged spike-LFP coherence and LFP-LFP spectral Granger causality. Somewhat surprisingly, we find that PRR transmits more task-specific information to LIP than vice versa, particularly during movements involving a reach. This is true when transmission is assayed using either coherence or Granger causality. It is true in the period immediately following a movement instruction as well as during a prolonged delay interval while the movement is being planned. This suggests that PRR plays a commanding role in determining the spatial goals of coordinated eye and arm movements, instructing LIP of those goals rather than vice versa. This is consistent with LIP playing an oculomotor-specific role rather than a more sweeping role in target selection. More generally, we argue that using either time-lagged spike-LFP coherence or LFP-LFP Granger causality can be informative of the pattern of information flow between brain areas, and that the direction and magnitude of this flow across multiple task types can in turn be informative of the roles that these brain areas play in those tasks.

SP1.5 Ocular eccentricity affects subjective visual vertical perception in health and disease

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Body coordination is critical when interacting with our environment, requiring appropriate integration and reweighting of visual, vestibular and somatosensory cues. One's subjective perception of gravity relies on such integration along with prior knowledge about head orientation in space. It is a crucial aspect of space representation and important for static and dynamic postural control. Age-related vestibular deficits affect mobility and contribute to increased visual dependence for postural control. These changes may be exacerbated by eccentric viewing, leading to higher fall risk for older adults with central vision loss (e.g., due to age-related macular degeneration, AMD) who often adopt eccentric eye positions to exploit their peripheral retina. Visual information is transformed, from retino-centric to head- and body-centered coordinates according to task demand. In addition to vestibular signals, the eye-in-orbit position is a reference for egocentric perception. Thus, an incomplete re-referencing of eye/retinal positions with respect to the body in AMD may affect individuals' interaction with their environment. To determine the effect of eye eccentricity alone, we first tested young adults performing subjective visual vertical (SVV) tasks using central and eccentric eye position. Next, we investigated the effect of central field loss (CFL) due to AMD, while controlling for aging and disease progression, by testing individuals with monocular CFL. We compared SVV judgements during binocular (analogous to central viewing in young adults, since foveal fixation is used with the healthy eye) and monocular viewing with their affected eye - as they adopt an eccentric fixation due to CFL. Participants judged the orientation of a briefly flashed rod, tilted with respect to gravity, with and without a misleading visual context. Depending on the viewing condition, young adults fixated a target centrally or eccentrically, to the right. Eye-tracking was used to monitor fixation. The target appeared centrally in both viewing conditions for those with CFL. Responses were analyzed to determine bias in participants' SVV. In young adults, we found a significant effect of eccentricity, with the bias shifting in the direction opposite fixation and of visual context, with the bias shifting in the direction of the visual context. In participants with monocular CFL, there was an influence of monocular versus binocular viewing and of the visual context, with bias shifts of up to 7°. These data suggest that eccentric viewing affects SVV in both healthy younger adults and older adults with CFL. Our data also show that despite visual impairment, those with CFL are still reliant on visual orienting cues. The interaction of eye position and visual dependence will be important to consider further in the design of rehabilitation tools for individuals with AMD who have eccentric fixation and may have increased visual dependence.

SP1.6 Predictive steering: integration of artificial motor signals in self-motion estimation

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Perception of self-motion depends on the integration of vestibular and visual signals and, when the motion is self-generated, also relies on motor efference copies. The brain's computations for both active and passive self-motion estimation can be unified with a single model that optimally combines vestibular and visual signals with sensory predictions based on motor efference copies (Cullen, 2019; Laurens & Angelaki, 2017). However, it is unknown whether this theoretical framework also applies to the integration of sensory signals with indirect motor feedback, like the motor signals that occur when driving a car. Here, we examined if training humans to control a self-motion platform would lead to the construction of an accurate internal model of the mapping between the steering movement and the vestibular reafference. Participants (n = 15), seated on a linear motion platform, manually steered a wheel to control the platform's velocity in order to translate their body midline sideways to align with a memorized visual target. Thus, in this self-motion condition, there was not only sensory (vestibular) feedback about the motion available, but also an internal motor signal, i.e., a cognitively mediated signal of efferent nature. A second group (n = 15) remained stationary and handled the steering wheel to translate a line from their body midline to the remembered target location. Only the final location of the translated line was shown to the participants. Participants were not informed about the gain between the steering wheel angle and the displacement of the platform or line (cm/s per degree). This gain changed twice during the experiment (high gain - low gain - high gain). For both the self-motion and stationary condition, participants only received visual feedback about their error after the movement had ended. Results show that gain changes are virtually undetectable in the displacement error during the vestibular whole-body steering condition. This suggests that in this condition, with the indirect motor signals, the vestibular signals are continuously monitored to correct for unexpected changes in the control dynamics of the platform and to update the internal prediction of self-motion within a single trial. In contrast, when participants did not receive any sensory feedback during the movement, gain changes resulted in considerable displacement errors that only reduced across a number of trials. This suggests that participants adjusted their steering movement only between trials based on the displacement error feedback. Overall, our results suggest that the brain integrates and anticipates the sensory consequences of an indirect motor signal to accurately estimate self-motion.

SP1.7 Head stabilization strategies across adulthood during stepping in place: insights on aging and adaptation

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The vestibular system drives the optimal head-in-space stabilization strategy (HSSS), where the head is articulated with respect to the trunk, as opposed to the rigid, en bloc strategy where the head and the trunk move as one unit. The HSSS allows for better sensory integration, multi-limb coordination, and to maintain stable gaze. Individuals with vestibular dysfunctions (and associated upweighting of visual cues, or visual dependence) tend to adopt the en bloc strategy while walking. More visually dependent healthy young and older adults also adopt this strategy under demanding motor tasks. Indeed, a more rigid head stabilization strategy may serve to reduce the number of degrees of freedom to be controlled during movement and accentuate visual and vestibular feedback. This rigid strategy, however, may be a maladaptive, rendering individuals more susceptible to falls. We have previously demonstrated increased visual dependence in older adults for verticality perception and that this visual dependence was associated with a greater reliance on visual cues for self-motion perception while stepping in place (SIP) - a task creating sensory discordance as compared to normal walking. In the current study, we investigated whether age-related differences in sensory reliance would manifest in differential head stabilization strategies in the same participants. Young, middle-aged and older adults stepped in place under natural or enhanced optic flow - a moving cobblestone pattern projected on the ground. Participants gazed straight ahead and their head and trunk orientations in pitch and roll were recorded. Head stabilization strategy was determined according to the anchoring index between the head and trunk (based on their orientations), revealing the adoption of the HSSS, the en bloc strategy, or no consistent strategy adoption. Overall, older adults most frequently showed no consistent strategy. Compared to the other age groups, they adopted the HSSS significantly less frequently and the en bloc strategy more frequently. Middle-aged adults showed similar behavior to young rather than older adults, frequently adopting the HSSS. In addition, all participants showed an improvement in head stabilization under enhanced as compared to natural optic flow. Our findings reveal changes in head stabilization strategies and adaptation to sensorimotor discordance across adulthood. Older adults seem to lose the ability to consistently adopt the HSSS, possibly associated with vestibular aging and a compensatory visual dependence. Future studies should investigate whether this loss in motor skill is due to reduced vestibular function or a consequence of age-related changes in sensory reweighting. The overall improvement in head stabilization under enhanced optic flow suggests an adaptation through the exploitation of dynamic visual stimuli, which persists to some extent in older age. This phenomenon could be leveraged in rehabilitation protocols for older adults.

SP1.8 Tail motoneurons are targeted by vestibular complex axons in mice

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Tails are a defining characteristic of chordates and play multiple roles critical for animal survival, such as balancing (Schwaner et al., 2021). Previous studies in mice have suggested that their prominent tail is important for balance (Buck et al. 1925, Ewer 1968). However, little is known about its neuronal control in the spinal cord and the relation to balance related brain structures. One of such structures is the vestibular complex in the brainstem, which comprises of 4 main nuclei and several accessory nuclei. As previously shown, the vestibular complex (VC) generates motor programs in the hindlimbs muscles in response to a balance perturbation (Murray et al, 2018). In this work we asked 1) where in the spinal cord the tail motoneuron (tail-MNs) pool is located, and 2) determine if tail motoneurons are targeted by vestibular complex axons, analogously to the motoneurons involved in hindlimb balancing responses.\\ Here, the tail-MNs pool was localized in the sacro-coccygeal part of the spinal cord using retrograde viruses and tracers. Within the labeled neuronal pool, we characterized their sizes in order to identify putative alpha motoneurons. Roughly 60 per cent of these putative alpha MNs were contacted by vestibular complex-originating axon terminals, similarly to what was previously described for other MNs pools (such as hindlimbs extensors). Intriguingly, we also showed previously (Lacava and Uusisaari, JNS 2020) that mice use their tails in movements phase-locked to hindlimbs stepping, suggesting that the vestibular complex may play a role in whole body coordination of fine movements during locomotion as well. Because of the conserved properties of the vestibular complex across many species, our results could lead to a new understanding of the neuronal control of balance in other vertebrates as well.

SP1.9 Longitudinal Volume Loss after Traumatic Brain Injury Predicts Vestibular Dysfunction

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Introduction: Traumatic brain injury (TBI) nearly always results in vestibular dysfunction impairing balance and vestibular perception. We recently identified brain regions predicting vestibular dysfunction in acute TBI, however, it remains unknown whether longitudinal structural brain changes predict recovery from vestibular dysfunction. Methods: The data was collected as part of an MRC-funded prospective study (Calzolari et al., 2021). Structural T1 MRI was acquired from 39 acute TBI patients with preserved peripheral and reflex vestibular function during acute admission and then after 6 months. Imbalance was measured with Posturography on soft surface with eyes closed. Vestibular perception was measured via self-motion perceptual thresholds during passive yaw rotations in dark. After accounting for missing scans at any timepoint, and quality control of MRI scans, 33 subjects' longitudinal data were analyzed and Voxel Based Morphometry we looked at the volume change over time and its link with recovery from vestibular dysfunction. Results: We found an interaction (FWE corrected) between recovery of balance and vestibular perception and the left Calcarine and right Supplementary Motor Area. Conclusion: Volume loss in left Calcarine and right Supplementary Motor Area are linked to poor recovery of balance and vestibular perception in patients with TBI. This is the first prospective acute TBI follow up study to show structural changes to be directly associated with vestibular recovery which is a core clinical function that improves quality of life and return to work.

SP1.10 Remote Assessment of Stroke in Acute Vertigo: Preliminary Results of a Feasibility Study

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Vertigo is the commonest symptom in posterior circulation stroke. Early treatment of stroke improves outcome, however, diagnosing stroke presenting with vertigo is usually delayed since clinicians find vertigo difficult to diagnose. Delayed diagnosis results in either missing life-threatening stroke or over-investigating benign vertigo diagnoses. Although prospective studies show that expert clinical assessment outperforms brain MRI in the first 24hrs in diagnosing stroke, expert vestibular neurologists constitute a limited resource. Remote clinical assessment may widen access to such experts. Hence, we assessed the feasibility of comparing the efficacy in acute vertigo diagnosis of remote versus face-to-face assessment by a vestibular neurologist. The on-going study is prospective and single blinded and explores patients admitted to one of the largest hyperacute stroke units (HASU) in the UK with an acute vestibular presentation. Inclusion criteria of patients was any one or all of dizziness, vertigo, and imbalance. The primary outcome measures were the sensitivity and specificity of experts' remote assessment via high resolution video technology of acute vertigo patients compared to the gold standard of the final diagnosis via direct clinical assessment and additional investigations. Secondary outcomes included measures investigation burden, and duration of in-patient stay. In the initial 3-month period of this one-year study, 360 cases were admitted and screened. Of these 360 cases, 35 were vestibular presentations, with 15 of these 35 cases undergoing remote assessment. The other 20 vestibular cases were not recruited for reasons ranging from refusing to participate to unavailability of an expert to perform the remote assessment. All 15 assessed cases had neuroimaging (CT+/-MRI) with 5/15 scans confirming stroke (3 ischemic and 2 hemorrhagic). Remote assessment was 100% specific for differentiating between stroke and non-stroke and all stroke cases were correctly identified by remote assessment (i.e., sensitivity 100%). In 13 of the 15 cases, remote assessment and the gold standard assessment led to the same diagnosis/outcome rendering an accuracy of 87%. Preliminary results indicate that remote assessment of vertigo by an expert is highly sensitive and specific for diagnosing stroke. Further refinement of the process will occur over the coming year. A remote acute vertigo service has the potential to reduce inequalities in healthcare by providing timely access to expert assessment, improve efficiency by reducing unnecessary investigations, and enhance safety via early correct diagnosis and correct treatment for stroke with vertigo.

SP1.11 Assessing Human Pedunculopontine Nucleus Activity & Link To Postural Control

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The PPN (Pedunculopontine Nucleus) is intimately involved in postural control and PPN neurones are heavily vestibular responsive. We have shown that deep brain stimulation of the PPN in Parkinson's Disease patients modulates vestibular perceptual function and postural control. In the current study we assessed Prepulse inhibition (PPI) as a non-invasive means of probing PPN function involved in postural control. PPI is a paired-pulse neurophysiological paradigm in which any subthreshold stimulus induces significant changes in the response to a subsequent suprathreshold stimulus. Measuring changes in the R2 area of the blink reflex is a reliable method to quantify PPI. More inhibition is observed when PPI is tested while standing, suggesting that PPI may be modulated in different postural conditions. Here we describe how somatosensory PPI (sPPI) from the leg is modulated in four different balance conditions. We also correlated it with sway measured on a balance platform. We divided the experiment into four parts. In the first experiment, we record an input-output curve testing 11 interstimulus intervals (ISI) in 20 healthy subjects. In the second experiment, we investigated the effect of two different intensities of the subthreshold stimulus. In the third experiment, we tested sPPI in four different conditions (lying down, standing on hard surface, standing on soft surface, and standing on hard surface during tandem stance). In the fourth part, we collected data on sway on a force platform. For experiments 1 to 3, intensity for evoking a blink reflex was set at 3 times the motor threshold for R2, while the peripheral stimulus was delivered over the lateral aspect of the right ankle. No significance differences between each ISI were noted. ISI 110 showed a consistent inhibition across all subjects, and it was chosen for experiment 2 and 3. An intensity of twice the sensory threshold was chosen for experiment 3. In standing on hard surface and, to less extent, on soft surface, R2 area was more reduced than in supine condition. Inhibition in tandem gait did not differ significantly from the supine condition. A correlation between sway in the antero-posterior plane and PPI was noted. PPI is differentially modulated according to the posture. This observation may relate to the differences in integrating tactile, vestibular, and proprioceptive inputs involved in posture and balance control while standing on different surfaces and under different circumstances. Our data also support the notion that PPI is a measure of PPN activity, given the pattern of PPI modulation we observed in the specific postural tasks. It follows that PPI - a putative marker of PPN activity - can be used to interrogate PPN modulation in neurological diseases with postural imbalance such as Parkinson's Disease.

SP1.12 The effects of subclinical neck pain on cerebellar processing as measured by the cervico-ocular and vestibulo-ocular reflexes

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BACKGROUND: Subclinical neck pain (SCNP) refers to, untreated, recurrent episodes of mild-to-moderate neck pain with pain-free days, allowing for assessment of physiological alterations in central processing without pain being a confounding factor on the day of collections. Previous literature has found that there are neurophysiological alterations in cerebellar processing in individuals with SCNP such as disruptions in sensorimotor integration (SMI), motor control processes, proprioception, and cerebellar inhibition (CBI), all assessed indirectly. Cerebellar processing in these individuals have not been assessed directly, which can be examined via the cervico-ocular and vestibulo-ocular reflexes (COR & VOR). These two oculomotor reflexes act to keep images stable on the retina in response to trunk and head movements. Thus, due to this altered cerebellar processing, it is possible that individuals with SCNP may experience alterations in both their COR and VOR as well. OBJECTIVES: This study aims to investigate the relationship between SCNP and the cerebellum by measuring changes in COR gain and VOR gain adaptation in individuals with SCNP. METHODS: 38 right-hand dominant participants (20 SCNP: 9M &11 F; 18 Healthy controls: 8M & 10F) between the ages of 18 and 35 performed two eye-tracking tasks. COR: participants were seated in a motorized chair and fitted with an eye-tracking device. They were instructed to stare at a visual target projected on a monitor 3 meters away from them. Once the target appeared on the screen, the motorized chair began a series of oscillations at a frequency of 0.04 Hz, with an amplitude of 5º, for 120 seconds. 10 trials were completed, with each trial lasting two minutes. VOR: participants were seated 90 cm away from a monitor and were instructed to make active head rotations while tracking a target projected on the screen in-front of them. Participants performed 390 trials divided into 13 blocks (pre-adaptation, 10 adaptation, & 2 post-adaptation blocks) in which the target would move at different speeds during each block. RESULTS: The SCNP group demonstrated significantly higher COR gain values than the healthy control group (p = 0.006, d = 0.833). No statistical between-group differences in VOR gain adaptation between the SCNP and healthy control groups (p = 1.00). The healthy control group did demonstrate higher VOR gain values at baseline, though this was not statistically significant (p = 0.487, d = 0.229). DISCUSSION: These results suggest that SCNP may alter proprioceptive input towards the cerebellum, thus altering cerebellar processing. Future work is needed to determine if treatment of neck pain can reverse these neuroplastic changes in cerebellar processing.

SP1.13 Effect of Post-Training Sensory Input on Systems Consolidation of a Motor Skill

Trace Stay, Eunice Chan, Solmih Kim, Victoria Xin, Alex Somera, Dong Cheol Jang, Jennifer Raymond

Systems consolidation is the process whereby the way a memory is stored is transformed over time. In oculomotor tasks, the expression of a learned eye movement response to a vestibular or visual input requires the cerebellar flocculus immediately after training, but not 24 hours later. A hypothesis is that plasticity in the flocculus during training alters the activity of the sole output neurons of the flocculus, which, in turn, triggers secondary, persistent plasticity in the downstream vestibular nucleus. Previous studies indicate that modifications in the vestibular nucleus occur within four hours after oculomotor learning. We tested how manipulation of the sensory input to the flocculus and vestibular nucleus during the post-training consolidation period modify the amount of learning that was retained at 24 hrs. Modeling suggested that vestibular afferent activity might increase the amount of oculomotor memory consolidation relative to no vestibular activity. Accordingly, we trained three groups of mice to make larger eye movements in response to a vestibular input, i.e., to increase the gain of the vestibulo-ocular reflex (VOR), and then gave each group a different level of vestibular input during the post-training period. One group was returned to their home cages immediately after VOR training. A second group was head-restrained on a stationary vestibular turntable for one hour after training, to minimize vestibular input. The third group was head-restrained and given continuous 1-Hz sinusoidal passive vestibular stimulation for one hour after training. All three groups were tested for retention of the VOR-increase learning at 1 hour after training, then kept in darkness overnight and tested again for retention at 24-hours. We found that while the home cage group showed high levels of retention of VOR-increase learning at 24 hours, the other two groups showed significantly impaired retention of learning. These results identify a behavioral manipulation that can be used to analyze the patterns of neural activity in the VOR circuit that are necessary and sufficient to support the systems consolidation process.

Poster Session 1

Tuesday July 26, 2022

A – Control of Eye & Head Movement

1-A-1 Information transmission in the cerebellum: The role of rate and synchrony during smooth pursuit

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Motor behavior is driven by neural populations that transform and relay information to downstream areas. A common mechanism for information transmission is the coherent modulation of upstream firing rates. However, motor signals may also be encoded in the precise timing of spikes across a neural population. The synchronous firing of multiple units could then faithfully transmit relevant temporal information to downstream populations. We have addressed this issue for a specific neural circuit by recording simultaneously from definitively identified cerebellar Purkinje cells (PCs) via extracellular recordings and isolated the contributions of rate and synchrony for control of motor behavior. The floccular complex of the cerebellum is crucial for the performance of smooth pursuit eye movements, allowing us to assay how changes in PC rates and synchrony contribute to pursuit behavior. Using multi-contact silicon electrodes, we recorded from 32 pairs of well-isolated PCs, definitively identified by the presence of post-climbing-fiber pauses, in three rhesus monkeys. To ensure that we could measure spiking synchrony across simultaneous units with high accuracy, we designed a novel spike sorter that minimizes errors in detection of overlapping extracellular spikes. The likelihood that two simultaneously recorded PCs fired together with millisecond precision was relatively small, with a less than 10% increase relative to chance. These results were consistent across a much larger population of 118 putative PC pairs, where one or both units lacked climbing-fiber responses. Using the measured millisecond correlations between simultaneously recorded units, we simulated a population of 40 PCs, allowing us to assay the impact of the observed correlations on a cell in the cerebellar nucleus. The presence of neuron-neuron correlations in the PC population resulted in only a 6% change in the input to a downstream neuron. We also tested whether PCs actively synchronize only during execution of pursuit eye movements. As simultaneously recorded PCs tended to have very similar preferred directions of pursuit (mean angular distance of 13.4°), changes in their firing rates tended to be strongly correlated. The likelihood of observing synchronous spikes between pairs of PCs was modulated with pursuit, but could be almost wholly accounted for by changes in firing rate. Finally, we assayed whether the rate responses of PCs could predict the firing of downstream units in the vestibular nucleus. Indeed, the responses of individual cells could be well predicted (R2 > 0.90) by changes in PC rate signals alone without the need for precise timing of PC spikes. Our results suggest that the synchronous activity of Purkinje cells is unlikely to contribute substantially to motor behavior. Rather, coherent changes in the firing rate of Purkinje cells appear to be relayed faithfully to downstream neurons.

1-A-2 Discharge properties of neurons in the 8th nerve, vestibular nucleus and abducens nucleus may explain suboptimal VOR characteristics in response to neuroprosthetic stimulation.

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Introduction: Vestibular neuroprostheses aim to restore vestibular function after the loss of vestibular hair cells. These devices were designed to restore primarily the angular vestibulo-ocular reflex (aVOR) by selectively stimulating afferent fibers of each ampullar nerve. They have been successful in providing controlled vestibular activation in patients, and clinically relevant recovery of function. However, aVOR restoration has been suboptimal in human subjects; e.g., low or pulsatile eye velocity, incorrect timing, and fluctuating direction errors. To understand the mechanisms underlying the suboptimal aVOR response to neuroprosthetic stimulation (eVOR), we recorded eye movement behavior and neural activity during such stimulation. Methods: Rhesus monkeys were implanted with a vestibular neuroprosthesis designed for human use. The device generated biphasic pulse stimulation (BPS) modulated either in current amplitude or pulse frequency. Eye movements were recorded in the dark with scleral coils in awake behaving animals. Unit activity was recorded from 8th nerve afferents, identified vestibular nuclear neurons, and abducens neurons. Results: Neuroprosthetic BPS produced electrically elicited VOR (eVOR) in the plane of the targeted (implanted) canal above threshold current levels. As current was increased, eye movements were elicited out of plane. High eVOR eye velocities could only be achieved at current levels eliciting significant out of plane eye movements. eVOR directions suggested canal-canal or canal-otolith summation. Low pulse rate stimulation elicited brief velocity pulses, while higher pulse rates elicited sustained eVOR velocity. Velocity saturated with high pulse rate, and then decreased at higher rates. Afferent fibers displayed time locked discharge in response to BPS with different thresholds. The probability of eliciting a spike increased with increasing current level. Individual afferent fibers often responded to BPS of sites in multiple canals. Differences were observed between afferents types. Secondary vestibular neurons displayed time locked discharge in response to BPS above current thresholds corresponding to behavioral thresholds. The probability of a spike increased with increasing current amplitude and decreased with increasing pulse frequency, typically saturating well below P=1.0. Changes in current level often changed the timing but not the number of elicited spikes. Most neurons responded to stimulation from multiple canal electrodes at higher current levels. Differences were observed between behaviorally identified neuron types. Abducens neurons displayed complex response characteristics comparable to vestibular neurons, but at longer latency. Conclusion: These results suggest that neural activation with eVOR is qualitatively different than that underlying natural aVOR. These differences limit the ability of neuroprosthetic stimulation to reproduce natural VOR responses.

1-A-3 The surprising inter-subject stereotypicality by which limb movements quantitatively predict eye movements in real-world tasks

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Visuomotor behaviour is structured around gathering relevant visual information to address one s underlying goals or sub-goals, to inform how one acts on the world. Typically, attempts to model visual attention have either been more qualitative, via top-down saliency models (goal-driven), or quantitative, through the use of bottom-up saliency models that combine visual features to produce gaze probability distributions over an image. Both approaches have limitations in applicability to understanding visuomotor behaviour however, in that qualitative top-down models are rarely computationally tractable, and bottom-up models are confounded by inclusion of task context. To study visuomotor behaviour we take a novel approach that places gaze into the context of the kinematics of the body, tasks and objects. We capture visual information from subjects performing a freely-moving task in the real world, using head-mounted eye tracking glasses (SMI ETG 2W) with a built-in scene camera and a full-body motion capture suit (XSENS, 69 degrees-of-freedom). Subjects were asked to prepare ingredients and cook a predefined meal in a real-world kitchen environment. Using the behavioural data recorded from this experimental setup, we build deep autoregressive models that capture the intrinsic dynamics of limb movement and eye movements, and show that we can predict to within 4 degrees of visual angle where a subject is looking. To capture the external factors driving eye movements, we also process egocentric visual information using a deep-learning-based object detection pipeline for pixel-level object segmentation, and gaze-objects from a subject s field-of-view on a per-frame basis. In this way, we obtain the temporal structure of visual attention allocation over objects in complex environments. From this, we can build sequence models (Hidden Markov and grammar induction models) to make predictions about external drivers of eye movements. Sequence models are constrained by the limited number of object-labels available in common object detection frameworks however, so to address this we allocate objects into functionally-similar higher-order groups using semantically-similar wordsets from the common lexical corpus WordNet, and also generate data-driven groupings using Latent Dirichlet Allocation. In capturing both the internal and external factors driving visuomotor behaviour, we can show how kinematics of the body modulate eye movements in natural tasks, and also how both eye movements and limb activity are modulated by objects in a subject s environment. This significantly improves our ability to predict eye movements, several seconds ahead of time. Preliminary sequence modelling also reveals a structure to natural eye movements that is invariant across subjects in our task. Taken together, our work in this area showcases how we can use multimodal ecologically-valid datasets to investigate real-world visuomotor interactions.

1-A-4 Neural substrates for generation of oblique saccades -Branching patterns of single tectofugal neurons-

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It is generally accepted that voluntary quick eye movements (saccades) are organized in the horizontal and vertical eye movement systems. Therefore, oblique saccades are considered to be generated by the vector sum of the outputs from the coordinated horizontal and vertical saccade systems, but the precise neural mechanism of generation of oblique saccades remains unresolved. The superior colliculus (SC) is known to be the center for saccades. Our previous studies show that many single efferent neurons in the SC project to the midbrain and the pontine reticular formation, but their branching patterns and exact terminal areas in the brainstem are not known. In our previous studies, both horizontal and vertical ocular motoneurons receive disynaptic excitation and inhibition in a reciprocal manner from both SCs. These excitation and inhibition are mediated by the last-order excitatory and inhibitory premotor neurons, respectively. In this study, we used an electrophysiological method for investigating branching patterns of single tectofugal neurons that project to various last-order premotor neurons for horizontal and vertical saccades in the brainstem of the cat. We recorded extracellular spikes from neurons in the SC and examined whether they were activated antidromically by stimulation of the vertical and horizontal last-order premotor neuron areas (excitatory burst neuron (EBN) region in Forel's field H, FFH for vertical saccades; EBN region in the paramedian reticular formation (PPRF) and inhibitory burst neuron (IBN) region in the paramedian pontomedullary reticular formation for horizontal saccades) and the second cervical (C2) spinal cord. A spike collision test was carried out, when necessary, so that we excluded the possibility of the inadvertent current spread from the EBN area in

the PPRF to the descending axons that project to the spinal cord. The results showed that there were four types of branching patterns of single tectofugal neurons that projected to the last-order horizontal and vertical premotor neuron areas, and the upper cervical spinal cord. Among the 70 tested tectofugal neurons, two types of the tectofugal neurons (about 69%) had axonal branches that projected to the ipsilateral FFH and the contralateral EBN region in the PPRF, and furthermore, about 69% of them had another axonal branch that extended to the spinal cord. Twenty-two tectofugal neurons were related to only horizontal eye movements but not to vertical eye movements and 17 of them further projected to the spinal cord. These findings indicate that single tectofugal neurons innervating both horizontal and vertical saccade generators with their axonal collaterals can easily synchronize the onsets of the horizontal and vertical saccade generating systems, and provides evidence that the branching patterns of single tectofugal neurons determine the functional synergies for coordinated oblique eye and head movements.

1-A-5 Neck EMG and Head Stabilization by Vestibulocollic Reflexs (VCRs) during Walking

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Vestibulocollic reflexes (VCRs) play a critical role in successful locomotion by compensating for head-on-body movement to stabilize the head in space. To stabilize gaze and heading as the body rotates and translates during locomotion, neck muscles engage in order to maintain the orientation of the head relative to the torso. Previous studies have showed that the head is well-stabilized in both pitch and roll by VCRs during quadrupedal locomotion in rhesus monkeys. However, no work to date has directly examined neck muscle activity during walking. Accordingly, using a combination of head and body 3D motion capture and acute intramuscular EMG recording, we studied head stabilization and the functional activity of neck muscles during walking in two rhesus macaques with intact vestibular systems and compared these results with those from a bilateral vestibular loss monkey. A head-mounted 6D gyroscope/accelerometer was used to record head motion, while 6 high-speed cameras were used for synchronized motion recording. DeepLabCut, an open-source markerless pose estimation system, was then used to extract the animals' 3D posture for gait analysis. Separately, an open-source, marker-base tracking system was used to extract the animals' head and trunk 6D positions. Acute intramuscular EMG recordings were performed bilaterally in the splenius capitis (SPL) muscles. Single motor unit activity was identified in the EMG recordings. We found that, in healthy monkeys, the head was well-stabilized, with head-on-body movement compensating for the movements of the body. Both left and right SPL EMG and single motor unit activity showed phase-dependent during locomotion, which acted antagonistically. On the contrary, without vestibular sensory input, the bilateral vestibular loss monkey showed much larger head oscillations, which did not compensate for the swings of the body. In this animal, the neck muscles did not show phase-locked activity or antagonism. Overall, the findings of the present study suggest that when acting normally to enhance head stability, neck muscles exhibit phasic activity during locomotion, and that vestibular sensory inputs play a key role in organizing this activity and ensuring compensatory head movement during locomotion.

B – Fundamentals of Motor Control

1-B-6 Dissociation between stiffness perception and action during uncoupled bimanual interaction

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While interacting with an object, we can assess its stiffness by squeezing it between our hands or by placing it on a rigid surface and squeezing it with only one hand. Such interaction with the object leads us to create our perception and then to react according to it. But what are the relation between those two prosses that happened in our brain? Previous studies have shown that there is a dissociation between action and perception during grasping and lifting tasks. However, there are studies that support the idea that action and perception might be intertwined. Although most of our daily interactions with the environment are conducted during bimanual movements, bimanual tasks are rarely studied. Here, we investigate perception and action during uncoupled independent bimanual interaction, in which the two hands act separately in manipulating different virtual objects. To do so, we performed two experiments. In both experiments, right-handed participants examined the stiffness of pairs of virtual elastic objects, standard and comparison objects. They either touched both objects with the same hand (left or right) or touched each object with different hand. Participants held a robotic device in each hand, and experienced force feedback proportional to the amount of object deformation. After interaction with both objects, participants were asked to report which object felt stiffer. In the first experiment (N=10), we examined free interaction with the objects. The results of this study showed that participants perceived the objects that were probed with the left hand to be harder than objects that were probed with the right hand. In the second experiment (N=15), participants hands were fixed such that the probing was conducted by wrist movement only (rather than elbow and shoulder movement that was observed in the first experiment), and additionally, the inactivated hand was fixed by the robot. We found different biases for each participant: Some of the participants had the same result as the participant from the first experiment, while the others perceived objects that were probed with the left hand to be softer than objects that were probed with the right hand. However, in both experiments we found that participants applied higher grip force with the left hand than with the right hand for the same load force. Those results together indicate that the two limitations of fixed bimanual interactions cause to different biases in participant stiffness perception but doesn't affect their action. Therefore, we concluded that there is a dissociation between them. Our results support previous suggestion for unimanual interactions also for bimanual interactions; information processing in our brain occurs in two independent separate neural streams, one for creating perception and the other for creating an action. This insight can be useful for real world applications such as design of a force feedback bilateral teleoperation controller for both hands.

1-B-7 Evidence for dual processes in motor working memory

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Working memory is the active maintenance of information to serve an ongoing task. While working memory has been comprehensively studied in sensory domains such as vision, less attention has been given to motor working memory (MWM), which involves the use and maintenance of movement information. To date, the limited research on this subject has taken a bottom-up approach, examining effector-specific sensory representations. However, there has also been evidence for a concurrent top-down process in which movement information is represented in a more abstract, effector-independent format, such as a goal or trajectory. While it is intuitive that top-down processing is present in MWM, it has only been studied indirectly. Our goal was to develop a more comprehensive framework of MWM that dissociates bottom-up and top-down processes. To that end, we conducted two experiments in which participants first encode reaching movements with one hand (guided by a robotic manipulandum), and then reproduce the movement with either the same hand or the opposite hand. We reasoned that by transferring hands between the encoding and recall of movements, participants could no longer rely on the effector-specific sensory representations (bottom-up process), and thus would solely rely on abstract representations (top-down process). Experiment 1 (n = 21) examined MWM effects by manipulating the number of distinct movements that had to be remembered (i.e., the set size). As expected, subjects' recall errors reflected classic working memory effects such as recency, primacy, and anterograde interference. Critically, in the high set size trials (i.e., 4 movements encoded and one later recalled), there was a significant and substantial gap in performance between the hand switch and no-switch conditions, but only for the two most recently encoded reaches. This key result suggested that two factors may contribute to MWM - an effector-specific representation that rapidly decays, and a effector-independent representation that does not. Next, we asked if decay of the effector-specific process was time-based, interference-based, or some combination of both. In Experiment 2 (n=20) we used the same design as Experiment 1, but participants only encoded a single movement and held that information in mind for either 3, 6, or 12 seconds before the recall phase. As we predicted, hand switching between movement encoding and recall had a strong effect on performance on the short delay trials (3s), but not the longer delay trials (6 and 12s). Importantly, the temporal decay we observed was attenuated relative to the large set size effects seen in Experiment 1. This suggests that the putative effector-specific component of MWM is susceptible to both temporal decay and interference from other movements. Taken together, our results support a dual process theory of MWM. A better understanding of the MWM system may reveal important insights into the flexible nature of human motor skill.

1-B-8 The relevance of identity-specific action-effects, sensory attenuation and the sense of agency: An EEG study

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Sensory processing of self-initiated action-effects leads to less intense perception and reduced neural responses compared to externally triggered stimuli (sensory attenuation). It is suggested that this sensory attenuation might help agents to differentiate between the sensory consequences of self-generated actions, because they are predicted and suppressed, and externally initiated actions, which are unexpected and enhanced (Hughes, Desantis, & Waszak, 2013). However, the link between sensory attenuation and the sense of agency remains unclear. For instance, it is unclear if sensory attenuation occurs in all cases of action-effect prediction (AEP). Specifically, we ask whether action-effects are attenuated when they are relevant to determine and plan follow-up actions. Lacking sensory attenuation in cases of AEP with enhanced behavioral relevance of the action-effect would contradict an immediate link of sensory attenuation to AEP and agency. Here, we quantified auditory evoked potentials in electroencephalography (EEG) when human participants created two-sound sequences by pressing keys on a keyboard. We assessed sensory attenuation using identity-specific AEP, as prediction-congruent sounds have previously been found to be attenuated in the event-related potential (ERP) N1 compared to prediction-incongruent sounds (Hughes et al., 2013). The first sound of each sequence corresponded to (congruent) or violated (incongruent) a previously learned key-sound association. The identity of the first sound was either relevant for the selection of the second sound (keypress) to complete the sequence (Relevance) or irrelevant (No-Relevance), or there was only one keypress and sound (Baseline). In the event-related potentials, we found the P2 component to be modulated by congruency and condition. Post-hoc tests revealed a decrease in the incongruent P2 amplitude from Baseline to Relevance condition, as well as from No-Relevance to Relevance condition. Incongruent sounds resulted in a suppressed P2 compared to congruent sounds. Pupil size data yielded similar findings, with an increase for incongruent pupil size for the Relevance condition compared to Baseline and No-Relevance and an increased pupil size for incongruent compared to congruent sounds in the relevance condition. Contrary to our expectation, we did not observe an N1 ERP modulation by congruency in any condition. These findings indicate that identity-specific action-effect prediction does not necessarily lead to sensory attenuation in N1. However, identity-specific action-effect prediction led to a modulation of the P2 ERP and pupil size, if coupled with the relevance of the action-effect. This modulation was especially apparent in changes for incongruent stimuli. This might indicate an effect of relevance on the (conscious) processing of incongruent auditory stimuli.

1-B-9 Deciding how to move in the face of uncertainty

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When faced with multiple potential movement options, individuals are faced with two critical decisions that influence the motor response. First, individuals must select which of the available options is more desirable. This is typically thought to occur by comparing the subjective desirability of each option as a function of at least two factors: the relative likelihood of each option being correct (i.e., endogenous success), and the reward associated with each choice (i.e., exogenous reward). Second, individuals must also select a strategy for dealing with choice uncertainty. Previous research has identified two such strategies: commitment to one option before moving and aiming for it directly, or delaying the choice by initiating a movement intermediate between the options until more information becomes available. People often generate a mixture of direct and intermediate reaches, and it is currently unclear how people decide which motor strategy to favor. We examined these two motor decisions and their interaction by asking two key questions. First, do people indeed compute subjective utility by weighing success and reward when choosing between two options, and is this weighting consistent across direct and intermediate reaches? That is, do direct and intermediate reaches reflect distinct movement strategies, or are they simply examples of a more general response to choice uncertainty? Second, what drives individual differences in whether people generate direct or intermediate reaches? To address these questions, we asked individuals to complete a series of experiments involving the go-before-you-know task (commonly used to study behavior under choice uncertainty). We found that people do account for both success and reward when choosing between uncertain options. Importantly, however, the weighting of success and reward differ when making direct or intermediate reaches: direct reaches tended to be more strongly biased by success, whereas intermediate movements were more strongly biased by reward. This suggests that direct and intermediate movements are distinctly planned, and the computation of subjective value may depend on the choice of movement strategy. Finally, we found that risk/reward attitude contributed to the choice of motor strategy: more risk/reward-seeking individuals tended to favor an intermediate reach strategy, and were more responsive to reward-related task manipulations. Together, these findings support the idea that choosing a motor strategy in response to uncertainty can influence how the relative desirability of the choice options is computed, and that intermediate movements reflect a distinct strategy to maximize reward over success. More broadly, such findings highlight the complex decision-making processes that underlie seemingly simple motor behaviors.

1-B-10 Effects of implicit and explicit motor learning on the pre-and post-movement cortical beta rhythm

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We act to produce desired effects. The perception of these effects guides subsequent moves. Motor learning is partly driven by explicit strategies, for which action selection is deliberately revised following a discrepancy between the actual and the desired movement, and partly by implicit adaptation, which occurs automatically, without deliberation. The extent to which explicit and implicit learning overlap or diverge in their neurophysiology remains unclear. Results from previous visuomotor rotation studies indicated that the amplitudes of the post-movement beta synchronization (PMBS) and foreperiod beta power (FB) decreased when a rotation was introduced. Do these changes in cortical beta rhythm relate to explicit or implicit learning? In ongoing EEG studies, we investigate whether the PMBS and FB modulations are influenced by explicit learning, and whether they persist when explicit strategies are eliminated, and learning is purely implicit. Participants perform centre-out movements with their right hand to reach through a target; Their hands are out of sight, but their movement trajectories are displayed on a monitor. Veridical feedback is frequently provided, while rarely and unpredictably, the feedback is rotated, either relative to the target (error-clamped feedback), or relative to their own movements (visuomotor rotation). In both cases, the rotated feedback is provided for 2 consecutive trials. In visuomotor rotation blocks, participants are asked to compensate for the perturbation in the second trial by developing a compensatory aiming strategy (explicit learning). In error-clamping blocks, they are asked to ignore the perturbation and keep on aiming directly at the target (purely implicit learning). Our first hypothesis is that the FB reflects implicit learning (internal model recalibration) leading to a power decrease in anticipation of the 2nd rotation in both conditions (compared to unrotated trials), i.e., including where learning can only be driven implicitly. According to our second hypothesis and to preliminary results, the PMBS may reflect strategic re-aiming, as revealed by stronger power decrease in the "compensate" than in the "ignore" condition, in the first rotated trial. In a variant of this paradigm, we test the extent to which behavioural relevance, operationalized as prior knowledge regarding the number of consecutive rotations (2 vs. 1), further modulates the PMBS magnitude. We further hypothesize a stronger PMBS decrease to the first rotated trial when this is followed by a second rotated trial (high behavioural relevance), than when it is not (low behavioural relevance). This series of results describing the electrophysiological correlates of implicit vs. explicit motor learning could have implications for learning in the context of rehabilitation, and for the pathophysiology of disorders such as cerebellar ataxia and obsessive-compulsive disorder which are accompanied by alterations to peri-movement beta power.

1-B-11 Explicit and implicit learning in the wild: sensory prediction error learning occurs outside the laboratory

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Sensorimotor adaptation is supported by at least two parallel learning systems: an explicit strategy, and an involuntary implicit learning system. Curiously, in laboratory settings, these systems are driven by different errors (Mazzoni & Krakauer 2014). The explicit system responds to errors in task outcome whereas implicit learning is driven by sensory prediction errors (SPE): difference between observed and expected outcomes. Though implicit and explicit adaptation occur in naturalistic settings (Martin et al. 1996; Leukel et al. 2015), the errors which drive each system "in the wild" are currently unknown. Do SPEs drive implicit adaptation in everyday life, or is this process specific to well-controlled laboratory conditions? To answer this question, subjects rolled a tennis ball to a small target 20 ft away. Following a baseline period, we next altered visual feedback with prism goggles that rotated the visual field by 30°. Participants rapidly adapted to the visual shift, adjusting their reach angle to mitigate the discrepancy between the ball and target. As in lab-based experiments (Albert et al. 2021), participants showed a persistent 1.3° residual error. To measure implicit and explicit learning, we removed all visual feedback (the room was darkened immediately after ball release) and told participants to aim their throw directly to the primary target. Participant ball rolling angles (relative to the perceived target) decreased from about 28.7° on the last 3 rotation trials, to about 6.2° (implicit aftereffect). This implicit reach angle decayed gradually both in the absence of error, and during an ensuing washout period (with feedback reinstated). Overall, implicit and explicit learning patterns in this ecological skill-based task had a remarkable correspondence to lab-based studies. To test whether SPEs, shown to drive implicit adaption in laboratory experiments, also contribute to learning in ecological settings, a second group completed a paradigm similar to Mazzoni and Krakauer (2006). After the first two throws with rotated vision, participants were given an aiming target to use that would result in the ball moving through the task-related target. Unsurprisingly, this aiming group achieved similar implicit learning (t(9)=0.31, p=0.77), but developed a larger explicit strategy than the control group (t(9)=-2.87, p=0.0019). Remarkably, after rapidly bringing their target error to zero (~9 trials), throwing angles in the aiming group gradually drifted over time, resulting in a 2.62° overcompensation past the target (t(9) =3.28, p=0.0095). This involuntary drift in reaching angle is a well-documented (Mazzoni & Krakauer 2006) hallmark of obligatory SPE-driven implicit learning, which proceeds despite worsening task performance. These results show for the first time, that SPE-driven implicit processes studied in the laboratory actively contribute to short-term adaptation in naturalistic skill-based tasks.

1-B-13 Contact instability of fingers in precision gripping

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Stable precision grips using the fingertips are crucial for human hand dexterity. However, the mechanics of the multi-link chains, like our fingers, make them intrinsically prone to a postural buckling instability induced by fingertip forces. This instability manifests as a sudden snapping of the joints into hyperextension, but is rare among healthy adults. How the nervous system suppresses the fingers from buckling under tip forces is unknown. Here we present the results of experimental and mathematical analyses to show that the nervous system uses muscle co-contraction to suppress finger buckling, and that stability, not strength, limits the maximal force that can be applied. We recorded rare events of finger buckling by instructing human volunteers (n=9, age: 24-47 years) to apply maximal tip force with their index finger, while holding it in a flexed posture. The distal interphalangeal joint buckled in 28 trials and its angle grew exponentially with a time-constant of 38±20 ms (mean±SD). Sensorimotor feedback latencies for the hand are 65 ms at the fastest. So we hypothesized that muscle-induced stiffness may underlie stability rather than neural feedback control. However, by analyzing a biomechanical finger model, we found that muscle stiffness does not automatically guarantee stability at maximal force unless extra stiffness is provided at the joints. We tested this prediction in 38 volunteers by adding external stiffness to their index finger joints and found that the maximal force increased by 34±3%, and muscle electromyography (EMG) readings were 21±3% higher for the finger flexors (mean±SE). An analysis of flexor and extensor EMGs showed that subjects who reduced their co-contraction produced more force. Without external stiffness, the subjects limited their force to sub-maximal levels so that the muscles had the leeway to co-contract and stabilize the finger. We conclude that the neural system uses the spring-like action of muscles to suppress the postural instability, and relying on muscle stiffness limits the maximal force they could apply. More stiffness may help stability, but highly stiff fingers cannot adapt to complex object geometries or precisely regulate force. Therefore, the motor skill of precision grip is the result of careful muscle co-contraction that balances the competing demands of finger stability versus strength and flexibility. The finding of postural instabilities, and the importance of muscle co-contraction, extend beyond fingers and apply to previous work on leg stability in cats, horses, and humans. By analyzing the equations of equilibrium and stability of general systems of constrained mechanical linkages driven by actuators, we derive the necessary conditions for stability and derive minimally stiff co-contraction strategies that guarantee open-loop stability. Thus, our results generalize to any actively driven mechanical linkage network for achieving compliant, adaptive, and open-loop stable contacts.

1-B-14 Kinematic adaptation to a normal but negative gravitational field: feedforward or feedback control?

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As humans, our ability to move is a vital and essential function whose refinement results from years of adaptation and evolution. Since gravity is ubiquitous, our central nervous system (CNS) has naturally learned to make the most of it by optimising its effects to minimise the cost of our actions. Amongst other results, the optimal integration of gravity in motor control is highlighted by variations in the temporal organisation of arm kinematics according to movement direction (Gaveau et al., 2016). Indeed, gravity assists downward movements and resists upward movements which translates in longer and shorter acceleration phases, respectively. Accordingly, acceleration, velocity and deceleration peaks are reached earlier during upward compared to downward movements. This direction-dependent difference is called Directional Asymmetry and has been shown to reflect how much motor patterns optimize gravity effects to minimize muscle effort (Gaveau et al. 2016). Motor control in altered gravity demonstrated that arm kinematics rapidly adapts to new gravity conditions (Papaxanthis et al., 2005; Gaveau et al., 2016). Surprisingly, very few studies focused on the effects of inverted normal gravity. Eighteen volunteers (aged 23,9 ± 5,8) were alternatively standing Head-Up and Head-Down, during 12 phases of 35s, while asked to do vertical one degree of freedom discrete arm pointing movements. To compare motor patterns between orientations and phases, directional differences on times to peak acceleration, velocity and deceleration (ΔRtPa, ΔRtPv and ΔRtPd) and repeated measures ANOVA were computed. In Head-Down, we found an absence of DA at the acceleration peak (ΔRtPa Vs 0: $p = 0.64$) and an absence of adaptation (Phase x Orientation interaction: $F(5,85) = 1$; $p = 0.42$). Moreover, we observed an inversion of the Directional Asymmetry in an allocentric reference frame at both velocity (Phase x Orientation interaction: $F(5,85) = 10.34$; $p = 9e-8$) and deceleration peaks (Phase x Orientation interaction: F(5,85) = 9.55 ; p = 2e-7) compared to what was observed in the Head-Up condition. This reversed DA faded out over time (Phase effect: ΔRtPv: F(5,85) = 4.29 ; p = 2e-3 ; ΔRtPd: F(5,85) = 2.63 ; p = 0.03). Overall, results in the Head-Down condition support a control process that does not optimally integrate gravity effects to minimize muscle effort. Hitherto, only sparse results exist on the effect of an inversion of gravity in the egocentric reference frame. Recent ones reveal a reoptimisation of gravity effects (Opsomer et al., 2021). Our contribution further suggests that this reoptimisation occurs during the latest movement phases, as shown by ΔRtPv and ΔRtPd. This supports the implication of feedback mechanisms and also that our brain uses a representation of gravity effects that not only involves an allocentric but also an egocentric representation (Le Seac'h & McIntyre 2007).

1-B-15 Startling acoustic stimuli hasten choice reaching tasks by strengthening express visuomotor responses without changing their timing

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When we make a voluntary movement to an external cue, such as lifting our foot from the brake when the traffic light turns green, it typically takes ~200ms to react to the external stimulus. Yet, when the cue is paired with a startling acoustic stimulus (SAS), an individual's reaction time can be shortened to ~120ms. This earlier release, and concomitant augmentation, of the motor response is referred to as the StartReact phenomenon. StartReact latencies appear too short to allow cortical processing, which has led to the hypothesis that the startling stimulus releases a prepared movement at the brainstem level, with the motor command being conveyed to the spinal motoneurons through the reticulospinal tract. The StartReact phenomenon has been demonstrated in many simple reaction time tasks. In most choice tasks however, reaction times below 200 ms have not been observed, presumably because a movement has not been prepared. However, presentation of a SAS can hasten the already short reaction times of on-line movement corrections to unpredictably displaced stimuli, supposedly due to a direct mapping between visual input and motor output by a fast sub-cortical visuomotor network. This has led to an alternative hypothesis that intersensory facilitation within the reticular formation may produce the StartReact phenomenon. Here we aim to test these ideas by examining the effect of SAS on express visuomotor responses, another class of movements that is likely governed by a fast sub-cortical visuomotor network. In express visuomotor responses changes to muscle activity occur in response to a newly appearing visual target at short latencies (~100ms). For reaches towards visual stimuli, larger express visuomotor responses precede shorter reaction times. If the StartReact effect hastens choice task reaction times due to intersensory facilitation within the reticular formation, we predict that a SAS with a salient visual go stimulus shortens reaction times of reaching movements in a choice reaction task, by enhancing the magnitude of express visuomotor responses without influencing its timing. To test this, we used a paradigm known to elicit express visuomotor responses and paired a SAS to target emergence on a small proportion of the trials. We found that adding a SAS expedites reaction times towards the target (leftward or rightward) and enhances magnitudes but has no effect on the latency of express visuomotor responses. Furthermore, in an anti-movement condition where subjects move away from a stimulus, we found the SAS-induced enhancement in express visuomotor response magnitude resulted in more frequent early-onset wrong-way movements. Overall, these findings show there may be an important role of intersensory facilitation within the reticular formation between a non-localizable SAS and an express motor program relayed through the tectoreticulospinal tract.

1-B-16 A network information theoretic framework to characterise muscle synergies in space and time

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Objective Current approaches to muscle synergy extraction rely on linear dimensionality reduction algorithms that make specific assumptions on the underlying signals. However, to capture nonlinear time varying, large-scale but also muscle-specific interactions, a more generalised approach is required. Approach Here we developed a novel framework for muscle synergy extraction that relaxes model assumptions by using a combination of information and network theory and dimensionality reduction. We first quantify informational dynamics between muscles, time-samples or muscle-time pairings using a novel mutual information formulation. We then model these pairwise interactions as multiplex networks and identify modules representing the network architecture. We employ this modularity criterion as the input parameter for dimensionality reduction, which verifiably extracts the identified modules, and also to characterise salient structures within each module. Main results This novel framework captures spatial, temporal and spatiotemporal interactions across two benchmark datasets of reaching movements, producing distinct spatial groupings and both tonic and phasic temporal patterns. Readily interpretable muscle synergies spanning multiple spatial and temporal scales were identified, demonstrating significant task dependence, ability to capture trial-to-trial fluctuations and concordance across participants. Furthermore, our framework identifies submodular structures that represent the distributed networks of co-occurring signal interactions across scales. Significance The capabilities of this framework are illustrated through the concomitant continuity with previous research and novelty of the insights gained. Several previous limitations are circumvented including the extraction of functionally meaningful and multiplexed pairwise muscle couplings under relaxed model assumptions. The extracted synergies provide a holistic view of the movement while important details of task performance are readily interpretable. The identified muscle groupings transcend biomechanical constraints and the temporal patterns reveal characteristics of fundamental motor control mechanisms. We conclude that this framework opens new opportunities for muscle synergy research and can constitute a bridge between existing models and recent network-theoretic endeavours.

1-B-17 Comparing Latent Dynamics Extraction Methods on Movement Decoding for Brain Machine Interface Applications

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Cortical neural activities can be used for decoding movement parameters for brain machine interface (BMI) applications (Collinger et al, 2013). Instabilities associated with high dimensional neural activities can result in degradation of BMI decoders. One potential solution to overcome BMI decoder instabilities, is to stabilize low dimensional components of the neural data, latent dynamics, obtained by different dimensionality reduction algorithms across different sessions/days or subjects (Gallego et al, 2020). The combination of the dimensionality reduction algorithms such as Principal Component Analysis (PCA) and demixed Principal Component Analysis (dPCA) and manifold alignment techniques such as CCA have shown stable decoding performance. But, Comparing the effectiveness of different dimensionality reduction algorithms for movement decoding in BMI applications is an open question. In this study we compare the effectiveness of two dimensionality reduction methods, PCA and dPCA for

movement decoding in motor BMI applications. We also investigated the effect of different numbers of low dimensional components obtained from PCA and dPCA for movement decoding. The PCA obtains neural manifolds by extracting lower dimensional components presenting the highest variance of the data. The dPCA is a modified version of the PCA method that extracts neural manifolds considering the task parameters in the principal component extraction. In this study, firing rate activities of 400 trials from the primary motor cortex of a male Rhesus macaque during a two-dimensional center-out cursor task was used (Degenhart et al, 2020). First, we extracted weight matrices of PCA and dPCA using a different number of trials. By applying the weight matrices separately to 400 trials, all trials were transmitted to new space and latent dynamics for each trial were obtained. PLS regression was used for decoding velocity from latent dynamics. We used 50% of the trials in the session to train the decoder and the remaining 50% to test. We repeated this procedure 100 times, randomly selecting the non-overlapping training and testing trials in each iteration. We averaged the R-squared (R2) and averaged correlation coefficient (R) values in different numbers of train and test trials, different number of latent dynamics and different number of trials that were used for obtaining weight matrices of PCA and dPCA methods. PCA showed better decoding performance than dPCA for different number of latent dynamics. Increasing the number of latent dynamics from 2 to 5 increases R2 from 0.61 to 0.72 for PCA and from 0.57 to 0.65 for dPCA. Also, R changes from 0.78 to 0.85 for PCA and from 0.76 to 0.80 for dPCA ($P<0.001$, two-sided Wilcoxon's rank-sum test). Our study showed that although dPCA extracts latent dynamics with better separation for different direction of movement, the PCA produce better latent dynamics for continuous decoding of movement trajectories.

1-B-18 Aging decreases the lateralization of gravity-related effort minimization during vertical arm movements

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Motor lateralization refers to differences in the neural organization of cerebral hemispheres, resulting in different control specializations between the dominant and the non-dominant motor systems. Multiple studies proposed that the dominant hemisphere is specialized for open-loop optimization-like processes. Recently, comparing arm kinematics between upward and downward movements, we found that the dominant arm outperformed the non-dominant one regarding gravity-related motor optimization in healthy young participants. The literature about aging effects on motor control presents several neurophysiological and behavioral evidences for an age-related reduction of motor lateralization. Here, we compare the lateralization of a well-known gravity-related optimal motor control process between young and older adults. Thirty healthy young (mean age = 24.1 ± 3 years) and twenty healthy older adults (mean age = 73.0 ± 8 years) performed single-degree-of-freedom vertical arm movements between two targets (upward and downward). Participants alternatively reached with their dominant and non-dominant arms. We recorded arm kinematics and electromyographic activities of the prime movers (Anterior and Posterior Deltoids) and we analyzed parameters thought to represent the hallmark of the gravity-related optimization process (i.e directional asymmetries and negative epochs on the phasic EMG activity). We found strong age x arm interaction effects on all parameters; i.e., relative durations to peak acceleration ($F(1, 46) = 9.34$; $p = 0.004$) and peak velocity ($F(1, 46) = 7.94$; $p = 0.007$) and the negativity of antigravity muscles' phasic signals ($F(1, 44) = 5.05$; $p = 0.03$). Although all three parameters showed a lateralization effect where the dominant arm was superior to the non-dominant arm in young adults, we found no such effect in older adults. With both arms, the results of older adults lied between those of the dominant and non-dominant arm of young adults. These results add to those of recent literature showing that feedforward motor control remains functional in older adults. More, the results obtained with the non-dominant arm may support a previously hypothesized increased reliance on predictive mechanisms in older adults.

1-B-19 Motor vigour and motor sequence learning are differentially affected by dopamine modulation

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Accumulating evidence points to dopamine being involved in both invigorating movements and shaping motor skill learning. However, it is unclear if the same dopaminergic mechanism underlies both aspects of motor control. Recent findings suggest that both are shaped by similar dopamine-mediated computations, whereas others identify distinct dopamine pathways involving different brain areas. Importantly, the role of dopamine to movement vigour and motor skill learning has predominantly been assessed in isolation using different reward and feedback structures. This may account for the diverging results seen in the literature. Here we used a complex sequential reaching task in which rewards were based on movement times (MT). Crucially, MTs could be reduced via both: 1) movement vigour related to increased muscular effort and 2) a reduction in dwell times through movement fusion. Movement fusion describes the learning-dependent process of blending discrete movements into skilled, continuous actions and represents a hallmark of skilled sequential behaviour. Therefore, this task enabled us to use the same reward structure to simultaneously investigate movement vigour and motor skill learning. 92 participants were randomly assigned to a reward and no reward group and were given either 1.5mg of haloperidol or a placebo. In line with previous work, our results show that reward invigorates performance and that the D2 antagonist haloperidol affects MT irrespective of reward. Importantly, it impaired movement vigour only when reward was available and had no modulatory effect on movement fusion. Thus, we illustrate that whilst both strategies are reward sensitive, they rely on dissociable dopaminergic mechanisms. These results have important implications for understanding dopamine-linked movement disorders.

1-B-20 Modulation of corticospinal excitability while preparing to intercept a moving target

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Accurate interception of a moving target relies on internal estimates of the target's visual motion properties, such as object speed, changing position, and motion duration. Existing behavioral theories of target interception suggest that humans continuously integrate temporal and kinematic information about the target to optimize performance. Previous evidence from non-human primates has shown that neural activity in the primary motor cortex (M1) is sensitive to the time-varying aspects of the visual target motion and motor planning while preparing to intercept. These findings suggest that M1 has access to relevant visual information to help guide the preparation of interceptive responses; however, it is unclear how this information is integrated in M1 to facilitate accurate performance. Here, we applied single-pulse transcranial magnetic stimulation (TMS) over M1 to investigate the influence of target motion parameters on human corticospinal excitability while preparing to intercept a moving target. Participants were instructed to abduct their right index finger to intercept a target moving

horizontally at a constant velocity toward a fixed interception zone. Target speed (Fast or Slow) and distance traveled (Far or Close) were manipulated across trials. Importantly, target speeds and distances were selected so that motion duration was matched across two of the conditions (i.e., Fast-Far and Slow-Close), allowing us to isolate the effects of target kinematics, independent of preparation time. Motor-evoked potentials (MEPs) in response to TMS were elicited from the right first dorsal interosseus muscle at five different latencies relative to the time the target reached the interception zone. We hypothesized that MEP amplitude, a marker of corticospinal excitability, would depend both on the timing of stimulation and the motion kinematics of the target. Consistent with previous behavioral findings, our preliminary results show that movement initiation occurred sooner for higher target speeds and were delayed when the TMS pulse was administered closer to the ideal interception time. MEPs were reduced relative to baseline at earlier TMS timepoints and increased closer to movement initiation, similar to the time course observed in delayed response time tasks. Notably, we observed evidence that the extent of MEP suppression and facilitation depended on target speed. Together, this suggests that the pattern of M1 activity during interception preparation may reflect differences in internal estimates of visual motion properties of the target to-be-intercepted.

1-B-21 Manipulating movement related brain activity with mechanical stimulations

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The dynamics of neural oscillations in the beta band (13-30 Hz) are closely linked to human movement and form a key neural signature in motor control, motor learning, and movement disorders. Specifically, the post-movement beta rebound (PMBR) is a sharp elevation in the amplitude of beta band activity immediately following the termination of voluntary movement. The scale of the PMBR response has been correlated to models of motor learning and as a marker for symptomatic severity in neurodegenerative conditions such as Parkinson's disease. Here, we present a novel robotic device used in conjunction with a simple tracking task to artificially manipulate wrist rigidity, facilitating the investigation of associated beta band dynamics. Our paradigm consists of differing models adjusting factors such as the number, amplitude and distribution of perturbations before completing a one-dimensional, voluntary wrist movement. We investigate the impact of different factors on physiological metrics using EMG and force sensors, in addition to assessments of neural activity using a 19-channel EEG system. Principle neural assessments have focussed on the C3 electrode placed under the International 10-20 system to evaluate activity in the contralateral M1 in a population of healthy, right-handed participants (n=14). Preliminary findings have indicated that paradigms composed of a greater number of perturbations result in an increased magnitude of PMBR when completing a voluntary movement following perturbation. Our preliminary results demonstrate the potential of controlling and manipulating beta activity via mechanical perturbations.

1-B-22 Learning high dimensional hand control of a robot arm is largely independent of mapping structure

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Our study investigates how to turn a healthy person's body into a high-dimensional "joy-stick" to operate an embodied robot, and how the mapping that translates user motion into device action affects skill acquisition. Specifically, a human subject operates a 5 degree of freedom robot arm using the 19 joint angles of their hand. We choose this method of control because a.) the mismatch between the dimensionality of the human hand joint angles and the robot arm degrees of freedom enables the user to specify any robot configuration with a theoretically infinite number of hand postures (Mussa-Ivaldi et al. 2011) and b.) the task is completely novel so all subjects must learn the high dimensional control from scratch. The subject's hand joint angles map to a 5-dimensional latent space that represents the configuration of the robot arm. We compare the performance of three groups of adult human subjects operating the robot with different joint-to-robot mapping strategies to identify how the mapping structure affects the user's performance. We construct the mappings using either Principal Components Analysis (PCA), Non-linear Principal Components Analysis (NLPCA), or our novel Egalitarian Principal Components Analysis (EPCA). Each of the selected methods create a distinct latent space of the hand joint angles, computed using the subject's unstructured finger movement data. PCA solves for a subspace whose basis vectors are ordered by the amount of variance they account for. NLPCA solves for a manifold that captures both linear and non-linear relationships in the data (Pierella et al. 2018), and EPCA solves for a subspace whose basis vectors have equal variance accounted for. Using these methods, we investigate how the geometry of the latent space, the amount of information captured by the latent space (in terms of the ability to reconstruct the joint angle data), and the distribution of variance throughout the latent space affect the user's performance. All subjects pilot the robot to pick up objects randomly positioned throughout the robot's workspace and deposit them into a target bin. Subjects are evaluated based on the time it takes them to reach subsequent trial stages (gripper contact with object-> object grasp -> object lift -> deposit in bin). Preliminary findings show no difference in performance between the groups. Our results indicate that the effect of inter-subject variability dominates any effects of mapping structure on skill acquisition; suggesting that, for body machine interfaces, optimizing feedback and learning environment may yield greater performance returns than optimizing the body-to-device map.

C – Posture and Gait

1-C-23 Faithful encoding of locomotor coordination by individual Purkinje cells

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Complex whole-body movements like locomotion require timely and precise coordination of muscles across the body. The cerebellum is critical for coordinating movement, and for ensuring that control is robust and flexible to changes in the state of the body and environment. During locomotion, the cerebellum is particularly important for interlimb and whole-body coordination. Decades of electrophysiological recordings have consistently shown that Purkinje cell modulation (the sole output of the cerebellar cortex) is broadly correlated with the overall locomotor stride cycle. However, much of the firing rate variability has remained unexplained, and it is still unclear how Purkinje cell activity could be read out to control coordination. Here we performed cell-attached recordings from individual Purkinje cells in head-fixed mice during locomotion, along with continuous, high-speed 3D tracking of limb and body kinematics. We analyzed simple spike activity of 115 Purkinje cells from mid-right cerebellar Lobules IV/V/VI/simplex. Consistent with previous work, we find that most Purkinje cells in this region were modulated by the locomotor cycle. Comparing responses across strides while taking into account stride-to-stride variability further reveals that beyond representing the locomotor stride cycle, Purkinje cells are exquisitely sensitive to stride-to-stride kinematic variation. Moreover, analyzing responses with respect to movements across the body reveals that many individual Purkinje cells

respond to multiple behavioral events, including movements of multiple limbs. We used several approaches, including Generalized Linear Models, to disentangle the contribution of individual body parts from the highly correlated locomotor pattern and establish their influence on neuronal activity. The analyses reveal that a majority of Purkinje cells simultaneously encode movements of multiple limbs to provide precise representations of interlimb coordination during locomotion. This finding resolves long-standing controversies surrounding the role of Purkinje cells in locomotor control. We also observe that many 'locomotor' Purkinje cells also represent the movement of additional body parts, such as tongue movements during licking. Further analysis using Generalized Additive Models allows us to simultaneously approximate even highly non-linear contributions of various body parts to the overall activity of individual neurons. With this approach, we find that Purkinje cells simultaneously encode movements of multiple body parts to provide precise representations of temporal coordination across diverse combinations of behavioral events. The high prevalence and heterogeneity of this non-linear mixed selectivity across the Purkinje cell population could allow for a simple linear decoder to generate flexible readouts: in this case, diverse sets of motor commands for the control of interlimb and whole-body coordination in dynamic environments.

1-C-24 Running development follows walking age. A longitudinal case study

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Children start to run after they master walking. In a previous study on treadmill running, we found no direct agreement between chronological age and the maturity of the running pattern in children aged 59 to 106 months (Bach, Daffertshofer, & Dominici, 2021). This, however, does not exclude that the emergence and development of the running pattern depends on walking experience. We investigated whether walking experience indicates the development of running and whether specific features of running are already present in or develop slowly during the first period after the emergence of walking. We also ask: does the ability to run with a flight phase indicate mature running? We present preliminary results of a case study with two participants recorded multiple times between two weeks after the first independent steps until 32 months of walking experience while walking and running overground and on a treadmill. We recorded 3D kinematics and EMG in two typically developing children with a mean (±std) of 133 (± 73) strides per session. Both participants underwent six recording sessions within a period of three years to assess the development of running after the onset of independent walking. We recorded walking during the first session (at the age of 11.9 and 10.6 months) and fast walking/running for the subsequent sessions. 102 kinematic and spatiotemporal parameters were determined for each session, stride, and leg. The data of five young adults served to define mature running. The sets were reduced via principal component analysis to eliminate covariation. Subsequently a cluster analysis was employed which allowed for using the average pairwise correlation distance to the adult running cluster as a measure for maturity. Walking experience could be confirmed as an indicator for running development, despite the absence of a direct linear relationship between maturity of running and walking age. Our preliminary analysis revealed substantial difference in the ability to run with a flight phase between the two participants. Yet, the cluster analysis did not separate participants, suggesting that running with a flight phase is not the only feature to consider, even in very young children. Monitoring two participants over a period of almost three years with extensive measurements such as bilateral leg and trunk 3D kinematics, spatiotemporal parameters, and bilateral leg and trunk muscle activity provided new insights into the development of running at very early stage after reaching independent walking. FUNDING: This project was funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (no 715945 Learn2Walk), from the Dutch Organisation for Scientific Research (NWO) VIDI grant (016.156.346 FirSTeps). REFERENCES: Bach, M. M., Daffertshofer, A., & Dominici, N. (2021). The development of mature gait patterns in children during walking and running. Eur J Appl Physiol, 121(4), 1073-1085.

1-C-25 Generalization of learning to stand with unexpected sensorimotor delays

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To maintain an upright posture in changing environments, the brain must monitor how motor actions influence body movement and learn new motor actions to balance the whole-body. Generalization of learned behaviors can be observed through transfer, where training in one context benefits motor performance in novel contexts. The presence and extent of transfer may depend on the similarity of the sensorimotor and mechanical characteristics involved in each task. During bipedal standing, the nervous system actively modulates forces and torques to control whole-body motion in anterior-posterior (AP) and mediolateral (ML) directions. These balancing motor actions are generated from multiple muscle effectors that contribute to both directions of standing. As a result, adapting the control of muscles in one direction may benefit whole-body standing behavior in the orthogonal direction. Here, we investigate how the brain learns to balance with unexpected delays and generalizes this learning across the two directions of balance and different muscle effectors. In our first experiment, we examined whether learning to stand with an imposed delay in one direction of balance generalizes to balancing with the delay in the orthogonal direction. While standing in a robotic balance simulator, one group of participants trained with a delay imposed in the AP direction of balance and another group trained with the delay imposed in the ML direction. Before and after the training sessions, participant whole-body sway was quantified in both groups with delays imposed in AP and ML directions of balance. Despite only training with a delay in a single plane of balance, sway variability decreased in both the trained and untrained directions. We next tested whether learning to balance with delays generalizes in absence of lower limb biomechanical interactions, which if it occurs, would suggest transfer at the level of the neural controller. In a second experiment, participants balanced their whole-body in AP by modulating the torque generated by abducting/adducting the extended index finger against a fixed load cell. Participants then trained to balance their whole-body using their finger while a delay was imposed in ongoing balance control. Despite the absence of biomechanical coupling between the intrinsic hand and leg muscles, pre-post comparisons following training revealed that whole-body sway variability decreased in both the trained finger delayed-balance and untrained leg delayed-balance conditions. Our results demonstrate that learning to balance with imposed delays generalizes to different directions of standing and across independent actuators that contribute to balance control. Through training, the brain learns to associate delayed whole-body motion with self-generated motor commands and generalizes motor actions to accommodate for novel sensorimotor delays and maintain balance.

1-C-26 Uneven terrain walking costs differ from dual-task walking in older adults: Preliminary results of the Mind in Motion study

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The cognitive resources associated with walking and differences with age are often probed via dual-task walking. These paradigms require walking while also completing a concurrent cognitively challenging task (e.g., word generation; memory recall; visual cue response). Dual-tasking experiments have indicated that walking behavior in older adults is disproportionately compromised by dual versus single task, relative to younger adults. Although dual-task walking performance could be predictive of fall incidents in older adults, results have been inconsistent. To date, studies have shown that 30% of fall incidents in older adults occur during single-task walking, especially when they walk on uneven terrain in the community. Uneven terrain (UT) walking may challenge mobility in ecologically relevant respects that differ from the cognitive challenges imposed by dual-task walking and could be a more accurate predictor for falls in older adults. Whether UT walking is an equally valid method of assessing challenges during walking has not been studied. To investigate this possibility, we examined walking behavior as walking difficulty increased in 25 high functioning (SPPB >10) older adults. Walking behavior was quantified via walking speed and step duration (time difference in heel strikes of opposing feet). Adults performed overground single-task walking (i.e., normal paced walking) and verbal dual-task (VDT) walking on a flat GaitRite walkway system. The VDT condition asked them to walk while concurrently verbalizing aloud as many words as possible starting with a pseudorandom letter. They also performed UT walking with four terrain difficulty levels (Flat, Low, Med, High), on overground terrain mats (self-selected walking speed) and on a modified treadmill (fixed speed). Unevenness was modified via rigid foam disks attached on the walking mats for overground walking and attached on the treadmill belt. The Flat condition did not have any rigid disks added (i.e., normal walking). The Low, Medium, and High conditions had varying amounts of rigid foam disks (up to 3.8 cm tall). For UT treadmill walking, the belt speed was set to 75% of the walking speed from the overground UT walking. Our results showed that walking speed decreased as walking difficulty increased during both VDT (Single vs VDT; 13% decrease) and UT overground walking (Flat vs High; 22% decrease). Step duration increased during VDT walking (Single vs VDT; 8%), while step duration decreased across UT treadmill walking (Flat vs High; 27%). With increased UT difficulty, walking speed decreased almost twice of VDT walking. Our results suggest that increased terrain unevenness may increase costs to different systems (e.g., sensorimotor) in addition to the cognitive processes challenged during VDT walking. Our Future work will explore if sensorimotor measures (e.g., grip strength; two-point threshold) can predict these changes in UT walking behavior.
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1-C-27 PPN-stimulation induced freezing-response and its impact on the activity of spinal motor circuits in freely moving rats

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It is well known that stimulation (either electrical or optical) of the midbrain locomotor region (MLR) induces locomotor networks resulting in walking and running gaits (Shik et al 1966). Nevertheless, it was recently discovered that optically stimulating a subset of neurons in the pedunculopontine nucleus (PPN), which is a part of the MLR, paradoxically induces a whole-body halt of movement rather than movement initiation (Carvalho et al., 2020). To investigate this new phenomenon and the effect of this PPN stimulation on spinal motor circuits, we chronically implanted Multi-Electrode Arrays (128-channels, Neuronexus) in the lumbar spinal cord of adult rats. Further, we stimulated the PPN using the

CamKIIα-dependent expression of an opsin (ChrimsonR) in an AAV virus, that was injected along an implanted optical fiber (200 µm diameter). Contrary to the anticipated locomotor response, the photo-stimulation induced a strong arrest of movement where the whole body of the rat "completely froze". The lumbar units were recorded before, during, and after PPN stimulation. The majority of the spinal units had a reduced neuronal spiking activity during the freezing response. Measurements of motion were performed using accelerometers and video recording. The neuronal subtypes in PPN responsible for freezing response were investigated using immunohistochemistry, tissue clearing and in-situ hybridization.

1-C-29 Longitudinal Volume Loss after Traumatic Brain Injury Predicts Vestibular Dysfunction

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Introduction: Traumatic brain injury (TBI) nearly always results in vestibular dysfunction impairing balance and vestibular perception. We recently identified brain regions predicting vestibular dysfunction in acute TBI, however, it remains unknown whether longitudinal structural brain changes predict recovery from vestibular dysfunction. Methods: The data was collected as part of an MRC-funded prospective study (Calzolari et al., 2021). Structural T1 MRI was acquired from 39 acute TBI patients with preserved peripheral and reflex vestibular function during acute admission and then after 6 months. Imbalance was measured with Posturography on soft surface with eyes closed. Vestibular perception was measured via self-motion perceptual thresholds during passive yaw rotations in dark. After accounting for missing scans at any timepoint, and quality control of MRI scans, 33 subjects' longitudinal data were analyzed and Voxel Based Morphometry we looked at the volume change over time and its link with recovery from vestibular dysfunction. Results: We found an interaction (FWE corrected) between recovery of balance and vestibular perception and the left Calcarine and right Supplementary Motor Area. Conclusion: Volume loss in left Calcarine and right Supplementary Motor Area are linked to poor recovery of balance and vestibular perception in patients with TBI. This is the first prospective acute TBI follow up study to show structural changes to be directly associated with vestibular recovery which is a core clinical function that improves quality of life and return to work.

D - Integrative Control of Movement

1-D-30 Neural encoding of proprioception of the limbs in the mouse primary somatosensory and motor cortices

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Rodents rely on proprioceptive information from the periphery to guide and coordinate precise forelimb and hindlimb movements, a process called sensorimotor integration. Mouse locomotor patterns are degraded when proprioceptive sensory feedback is attenuated (Akay et al., 2014), and both primary somatosensory (S1) and primary motor (M1) cortices are necessary for adapting motor commands to new sensory environments (Mathis et al., 2017; Heindorf et al., 2018). However, we do not know how proprioception of the limbs is represented in S1 and M1. To address this question and to isolate pure somatosensory responses (proprioception and touch) from motor commands that would be present in awake animals, we recorded neural responses to passive movement of ipsilateral and contralateral limbs in eight mice under anesthesia. Using stereotaxic coordinates to locate S1 and M1 forelimb and hindlimb areas, we performed unilateral two-photon imaging over these two regions simultaneously in

mice expressing GCaMP6s, a highly sensitive fluorescent indicator of neuronal activity. A brushing motion was used to provide cutaneous and proprioceptive stimulation to each limb (blocks of five trials per limb were repeated across three cycles). Altogether, we recorded the activity of 12,895 neurons, of which 2,053 neurons (16%) were significantly modulated by passive movement of at least one limb ($p < 0.02$, Wilcoxon rank-sum test on single trial responses vs. baseline). Of significantly modulated neurons, 48% responded to movement of the contralateral hindlimb, 15% to the ipsilateral hindlimb, 30% to the contralateral forelimb, and 7% to the ipsilateral forelimb. A subset of neurons (9%) was significantly modulated by more than one type of limb movement, most often ipsilateral and contralateral hindlimb movement. In terms of response amplitude, neurons that were significantly modulated by contralateral movements had larger responses than those modulated by ipsilateral movements (hindlimb: dF = 0.90 ± 0.01 SEM contralateral vs. dF = 0.79 ± 0.01 SEM ipsilateral, p = 5.1 x 10^-39; forelimb: dF = 0.78 ± 0.01 SEM contralateral vs. dF = 0.74 ± 0.01 SEM ipsilateral, p = 0.012). In summary, we found evidence of proprioceptive signals related to both ipsilateral and contralateral limbs across primary somatosensory and motor cortices of the mouse. The distributed nature of these responses, across cortical regions and limbs, could be an indication of how proprioception guides the formation of motor commands within the mouse cortex.

1-D-31 An immutable control policy governs fingers closure during reach-to-grasp coordination

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An unexpected movement of the target object, or a sudden bump on the arm, rarely gives us pause because we are so deft at rapid online adjustments of reach-to-grasp actions to all sorts of perturbations. The sensorimotor control policy that makes these actions robust to perturbations has remained elusive. Identifying this control policy is critical to devising an accurate metric to evaluate the development and disease-related changes in reach-to-grasp coordination. We reported previously that the finger-aperture closure is initiated at a specific distance from the object to be grasped--and not at a specific time during the transport--based on a control policy that entails multisensory integration of the internal state estimates of aperture, transport velocity, and transport acceleration (Mangalam et al., Experimental Brain Research, 2021). Here we investigated whether this control policy is robust to unpredictable visual perturbations of task goals during reach-to-grasp coordination. Thirty-five distinct visual perturbations of object size (the object increases in width) and distance (the object moves farther) requiring rapid online adjustments were applied as ten healthy adults reached to grasp virtual objects in an immersive haptic-free virtual environment (hf-VE) after informed consent. The use of hf-VE allowed us to apply object size and distance perturbations instantaneously (< ~11 ms) and seamlessly (i.e., without any mechanical friction, sound, etc.), which is not feasible in the physical world. Perturbations involved graded changes in object size (ranging from 1-4 cm at 1 cm increments) and object distance (ranging from 5-20 cm at 5 cm increments) and were applied at three different latencies after movement onset (100 ms, 200 ms, and 300 ms) for all combinations of the three to investigate whether the control policy holds across perturbations of different types, magnitudes, and timing. The Akaike Information Criterion (AIC)-based model selection approach confirmed that irrespective of the perturbation's type, magnitude, and timing, the aperture closure was always initiated at a distance from the object to be grasped defined by a specific control policy. Monte-Carlo simulations confirmed that the relationship between model-predicted and actual values of this closure distance observed for each perturbation type did not occur by chance and that hand transport velocity was the most critical determinant of finger-closure initiation. One remarkable feature about reach-to-grasp coordination revealed in our data is the existence of an independent transport-aperture relationship in the opening and closure phases of the movement. This feature makes the transition between the two movement phases a fairly distinct waypoint for control during reach-to-grasp coordination. Our findings encompass the clearest demonstration of an immutable closure policy governing finger-closure initiation for robust reach-to-grasp coordination.

1-D-32 Activity in mouse motor cortex reflects action and its expected sensory consequence

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In addition to controlling movement through its descending projections to the brainstem and spinal cord, the motor cortex also sends copies of motor-related signals, termed corollary discharge, to sensory regions of the cortex. Within sensory cortex, corollary discharge signals can be integrated with ascending sensory input to augment neural responses to self-generated sensory cues. Traditionally, models of motor-sensory learning presume that corollary discharge signals stably reflect movement regardless of its sensory outcome, while learning and encoding the expected outcome of an action happens downstream areas that receive corollary discharge signals (e.g. within sensory regions). Here, we show that in addition to encoding movement, motor cortical corollary discharge signals explicitly encode the expected sensory consequences of an action. We recorded neural activity in a prominent motor-related input to the auditory cortex -- secondary motor cortex (M2) -- as mice operated a lever that produced a predictable sound. During a sound-generating movement, many M2 neurons exhibit mixed selectivity of movement and sound signals, consistent with local motor-auditory integration within M2. Although activity in the broader M2 population tiles time throughout the duration of a sound-generating movement, M2 cells that send axons to the auditory cortex concentrate their activity in a narrow window around the time of the expected self-generated sound. This temporally precise concentration of sound-anticipating activity in M2-to-AC cells matches the temporally precise movement-related signals observed in auditory cortex and is not present in naïve mice, indicating that it is learned through motor-sensory experience. Together, these findings reveal that M2 integrates signals related to movement with the acoustic consequence of action and exhibits learned sound-anticipating activity that it selectively routes to auditory cortex.

1-D-33 Drawing performance with the non-dominant hand is supported by bilateral parietal cortex

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Motor compensation refers to the use of the alternative hand (non-dominant hand) after motor impairments in the dominant hand. Compensation is critical for patients with unilateral impairments of the dominant hand, such as stroke and peripheral nerve injury, because approximately 40% of these patients never adequately recover dominant hand function. However, compensation does not occur in daily life or traditional therapy: patients with nerve injury continue to use their injured dominant hand, even when their unaffected non-dominant hand is more dexterous. However, it remains unknown what neural mechanisms drive non-dominant hand compensation and performance, even in the healthy brain. To address these issues, we conducted an fMRI study with healthy right-handed volunteers (currently n = 6). Participants underwent functional MRI scanning while performing a previously published Precision Drawing Task. The task involved using a pen stylus to draw a line inside the path of pre-determined geometric forms. Movement performance was quantified as endpoint (pen tip) velocity smoothness. The task was delivered in a block design, alternating between 20 sec drawing and 20 sec rest, one hand per block. Our primary analysis identified BOLD activity that was hand-specific and correlated with each hand's average performance. Preliminary results indicate that bilateral parietal areas show performance-correlated activity during left non-dominant hand drawing (vs. right dominant hand drawing). Specifically, these posterior parietal areas include left inferior parietal lobule, left superior parietal lobule, and right intraparietal sulcus. Conversely, we found no clusters of performance-correlated activity in posterior parietal cortex during right dominant hand drawing (vs. left non-dominant hand drawing). Therefore, drawing only involved performance-related bilateral parietal activation when drawing with the left non-dominant hand. This left hand drawing network is consistent with previous theories suggesting that interhemispheric parietal connections play a critical role in supporting skilled movement with the non-dominant hand. Ongoing experiments are aimed at determining whether the same neural mechanisms also support compensatory hand movement after chronic injury to the dominant hand.

1-D-34 The role of motor commands in modulation of auditory evoked responses

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Previous studies have shown that the magnitude of auditory EEG evoked responses (N100) is reduced for sounds that are the consequence of voluntary actions compared to the responses evoked by identical sounds from an external source. Although the reduced amplitude is ascribed to motor commands associated with voluntary actions, it is not clear what information such motor commands convey. One 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 sound generation and passive listening. Another type of associated information is expectation of sensory consequences. When learning an audio-motor task, such as generating a sequence of tones on a keyboard, the association between specific actions and the tones they produce is strengthened during the learning process. Thus, if modulations in evoked responses represent expectations of sensory consequences, their magnitude should change during learning. Here we examined the influence of each of these types of information on auditory evoked responses. We recorded the EEG N100 component while participants learnt a new coupling between cues and tones across eight repetitions. The mapping between cues and tones was randomized such that participants had to learn new associations in each trial. During each trial, participants learned to associate between specific visual cues (visuo-auditory condition) or key presses (motor-auditory condition) with corresponding tones. To assess the degree of association, each trial ended with a test phase in which participants were presented with the learnt tones in random order and were instructed to indicate the corresponding sequence of keys or visual cues in the correct order. Preliminary results (n=13), indicate that participants successfully learnt the mapping between cues and tones equally well across conditions (85.73% / 86.22% correct responses in motor/visual conditions respectively). At the neural level, N100 amplitudes in the motor-auditory condition were less negative than in the visuo-auditory condition, in agreement with previous literature. In addition, we find an effect of learning such that the magnitude of the N100 decreases across repetitions, as the mapping between cues and tones is strengthened. Notably, we do not see an interaction effect on the magnitude of N100 between cue type (motor/visual) and learning phase (repetition number during training). Our preliminary results suggest that the N100 evoked response is independently sensitive to both agency and expectation level in an independent manner. This may imply that the N100 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 tones.

1-D-35 Neural mechanisms underlying expectations and feedback of reward-based task performance

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To plan, execute, and evaluate our actions, we must generate expectations of our action outcomes. Both our motor skills and the external environment contribute to our outcome and therefore, to our expectations of such outcomes. However, there is a limited understanding of how the brain integrates information about motor performance and environmental factors when generating expectations and assessing the consequences of our actions. To dissociate these factors, we had participants play a skilled motor task where the outcome depended on both their performance and external probabilistic factors. We scanned participants' brains with functional magnetic resonance imaging (fMRI). Participants controlled a cursor into a variable size target, and if successful at the task, the external environment determined the success of the trial with varying probability. The probabilistic outcome was thus independent of the participants' performance. Before starting each trial, we presented participants with visual cues corresponding to the task difficulty and the external probabilistic outcome, at separate time points. We found regions of the reward and salience network, including the ventral striatum and insula, to be modulated by participants' expectations of outcomes. Specifically, at the time of cue presentation, both the ventral striatum and the insula exhibited reduced activity with easier task difficulty but increased activation with a greater likelihood of success in the probabilistic outcome. At times of performance feedback, ventral striatum activity was greater for successful trials, whereas the insula showed an increased response for failed trials. Violation of prior expectations modulated the activity in both regions during feedback. Specifically, succeeding in the hardest task difficulty evoked the greatest response in the ventral striatum whereas the insula exhibited the greatest activity when failing tasks with the easiest difficulty. At the time of probabilistic outcome, the ventral striatum did not show preferential encoding for successful or failed outcomes and was modulated by the degree of unexpectedness while the insula showed evidence of encoding the unexpectedness of outcome as well as failed probabilistic trials. Finally, functional connectivity analysis showed that the posterior insula exhibited decreased connectivity with the ventral striatum for successful task performance while the connectivity between the anterior insula and ventral striatum was decreased for unexpected probabilistic outcomes. These results suggest that the ventral striatum and the insula may utilize different encoding strategies for feedback based on whether the outcome depended on a participant's performance or the environment. Our findings demonstrate that the ventral striatum and the insula differentially integrate performance and environmental factors when generating expectations and evaluating the consequences of actions.

1-D-36 Distinctive Motor Neuron Recruitment with Intracortical Microstimulation and Wireless Cortical Stimulation using Targeted Delivery of Magnetoelectric Nanotransducers

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Magnetic nanoparticles are a promising substance for clinical diagnostics and therapeutic applications. One benefit of magnetoelectric nanoparticles and magnetoelectric nano transducers (MeNTs) is the ability to activate neural tissue remotely without the need for more invasive techniques (references). Here, we injected MeNTs directly into the forearm region of the primary motor cortex (M1). This allowed us to test their ability to evoke responses from corticospinal neurons in electrical and electromagnetic (EM) fields. We used high density and bi-polar surface electrodes to evaluate the evoked electromyographic (EMG) activity across 18 forearm muscles. To evaluate the electrical responses, we applied intracortical microstimulation (ICMS) to 111 sites in M1 of three rhesus macaque monkeys. Sixty-seven of those sites (60%) produced EMG activity in one or more of the recorded muscles. We selected 20 sites to inject MeNTs based on low threshold responses with ICMS. We found a reduction in the threshold to recruit EMG activity with ICMS after MeNT injection. We performed a systematic comparison of ICMS evoked muscle activity with shared stimulus conditions pre-injection and post-injection at 90% of sites (18/20). Overall, 69% of EMG recordings from surface electrodes showed an increase in the amplitude of the evoked response post-injection. After injection of MeNTs we also observed different patterns of muscle activation from those recruited at the same site pre-injection. We also placed an electromagnet over the MeNT injection sites and compared EMG responses from EM field stimulation conditions pre-injection and post-injection. No responses were observed prior to MeNT injection. Post-injection, the electromagnet evoked EMG responses in 2 out of 3 animals but generated different recruitment patterns compared to the patterns generated by ICMS. This study demonstrates that MeNTs have the potential to enable a non-invasive and contactless cortical stimulation method.

E – Disorders of Motor Control

1-E-37 The positive dimension of schizotypy is associated with a reduced attenuation and precision of self-generated touch

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The brain predicts the sensory consequences of our movements and uses these predictions to attenuate the perception of self-generated sensations. Accordingly, self-generated touch feels weaker than externally generated touch of identical intensity. In schizophrenia, this somatosensory attenuation is substantially reduced, suggesting that patients with positive symptoms fail to accurately predict and process self-generated touch. If an impaired prediction underlies the positive symptoms of schizophrenia, then a similar impairment should exist in healthy nonclinical individuals with high positive schizotypal traits. One hundred healthy participants (53 female) scored for schizotypal traits and underwent a well-established psychophysics force discrimination task to quantify how they perceived self-generated and externally generated touch. The perceived intensity of tactile stimuli delivered to their left index finger (magnitude) and the ability to discriminate the stimuli (precision) were measured We observed that higher positive schizotypal traits were associated with reduced somatosensory attenuation and poorer somatosensory precision of self-generated touch, both when treating schizotypy as a continuous or categorical variable. These effects were specific to positive schizotypy and were not observed for the negative or disorganized dimensions of schizotypy. The results suggest that positive schizotypal traits are associated with a reduced ability to predict and process self-generated tactile stimuli. Given that the positive dimension of schizotypy represents the analogue of positive psychotic symptoms of schizophrenia, deficits in processing self-generated tactile information could indicate increased liability to schizophrenia.

1-E-38 Impaired Sequential but Preserved Motor Memory Consolidation in Multiple Sclerosis Disease

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Studies investigating motor learning in patients with multiple sclerosis (MS) disease highlighted that MS patients exhibit similar learning performance than healthy controls, but that learning can be hampered by the progression of MS eventually leading to impaired efficiency of subcortical-cortical networks. We aimed at investigating whether the long-term, overnight consolidation of sequential motor memories is preserved in MS disease. Thirty-one patients with MS and two healthy control groups (27 young and 14 middle age) were tested over two consecutive days using a serial reaction time task. Performance was tested (a) 20 min after the end of learning at Day 1 to monitor transient offline, short-term increase in motor and sequential performance and (b) after 24 h on Day 2 to quantify overnight delayed changes in performance reflecting memory consolidation. Besides a slower overall RT in patients with MS, motor performance similarly evolved in all groups. Sequence learning as assessed by interference effects was similar in patients with MS and both control groups on Day 1 (Learning and 20-min test). In contrast, while interference effects keep increasing on Day 2 after 24 h (Relearning) in healthy control groups, it reverted to levels reached at the end of learning for patients with MS. Long-term consolidation of sequential knowledge is impaired in patients with MS. At the motor level, learning and overnight consolidation abilities are preserved in MS disease.

1-E-39 Impaired inter-joint coordination in sub-acute stroke participants contribute to performance impairments but cannot be explained by intrusion of pathological synergies

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Motor impairments in post-stroke subjects suffering from hemiplegia can be divided into negative signs - weakness and impairments in motor control, and positive signs - intrusion of pathological synergies and spasticity. In order to examine the contribution of negative and positive signs to motor impairments following stroke, we utilized a novel approach for analyzing movement kinematics using a video-based 3D pose-estimation kinematic model. Twenty-eight post-stroke subjects in the sub-acute stage and 16 healthy controls performed two functional tasks: A cup to mouth, requiring shoulder and elbow flexion (within the pathological synergy), and a reaching task, requiring shoulder flexion and elbow extension (outside the pathological synergy). We estimated functional and obligatory inter-joint coordination based on angular velocity profiles of shoulder and elbow angles. Strength, spasticity and sensation were also estimated. A regression analysis with performance measures such as movement extent, velocity, and smoothness as dependent variables and sensation, strength, spasticity and coordination as independent variables, indicated that the only significant predictors were inter-joint coordination and weakness. Coordination impairments in the reaching task (outside the synergy) were significantly correlated with Fugl-Meyer scores. However, when searching for indications of intrusion of pathological synergies by examining the time spent within a pathological flexor synergy during the movement, or the correlation of shoulder and elbow angles while the shoulder was flexed, no group differences were found. In conclusion, we demonstrate that coordination impairments affect performance in functional tasks in the early sub-acute stage. Nevertheless, intrusion of abnormal synergies have little to no contribution to inter-joint coordination impairment. We therefore suggest that coordination impairments in sub-acute stroke subjects are mainly driven by negative signs such as control impairments. Furthermore, our results indicated that contrary to the common assumption that the Fugl-Meyer assessment is driven by intrusion of pathological synergies, this scale may manifest other impairments or coordination deficits. Decomposition of coordination deficits according to their positive and negative signs may be essential for characterizing hemiparesis after stroke.

1-E-40 Using movement data to classify autism: Challenging an algorithm built for autism classification with Parkinson's data

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Autism Spectrum Condition (ASC) is a neurodevelopmental condition affecting social reciprocity and communication. It was first described as a childhood condition and was treated like this for many years. Nowadays, we know that ASC is a lifelong condition and that autistic adults are a much understudied population across many aspects including diagnosis. Currently, adult diagnosis is based on subjective observations with no validated diagnostic tool, resulting in many autistic adults remaining undiagnosed or waiting a long time for diagnosis. Motor control impairments, and especially imitation difficulties, are present in ASC and research has indicated that they are a potential biomarker of the condition. In our previous work, we used Machine Learning (ML) and a simple imitation task to build a classification model to classify between autistic and non-autistic participants without any other known condition. The model achieved a relatively high classification performance of 73% when it was applied to a new unseen dataset containing autistic/non-autistic data. However, an ideal diagnostic tool has to be condition specific. The aim of the current study was to determine if the aforementioned classification model is autism specific. To investigate this, we included data from people with Parkinson's disease (PD), a condition with movement patterns and motor difficulties that overlap with autism. We expected the classification accuracy of the model to drop when applied to data from both conditions. To test that hypothesis, we used the pre-trained classification model and applied it to a 'challenge' dataset which contained new unseen data from both ASC and PD. Our results indicated drop in classification accuracy of the model as it achieved only 48% classification accuracy. The model accurately classified all of the autistic data points, misclassified as autistic approximately half of the non-autistic participants without PD, and misclassified most of the non-autistic participants with PD as having autism. The model treated the majority of non-autistic participants with PD as autistic in line with previous findings. The fact that it accurately classified all autistic participants is an indication that the model can be used as a screening tool for autism rather than a diagnostic tool. Our results indicate that 'challenging' a ML model to make sure it is condition specific is essential before clinical use.

1-E-41 Directional and general impairments in initiating motor responses after stroke

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Visuospatial neglect is a disorder commonly characterized by an impairment of spatial attention. Reaching can provide a useful framework to quantify one's ability to respond to stimuli in different spatial directions. Previous studies suggest individuals with visuospatial neglect can exhibit delayed reaction times (RT) when reaching towards the contralesional side of space. However, few studies have explored neglect beyond reaching left or right. Further, few studies have examined individuals with left hemisphere lesions. In this study, we used an 8 target centre-out reaching task on the Kinarm Exoskeleton lab to quantify the ability of 265 individuals with stroke (162 right (RHD) and 103 left hemisphere damage (LHD)) to reach in different spatial directions using both arms (days since stroke; mean, range: 11, 1-59). We recruited individuals with stroke that were 18 years and older with a first time reported ischemic or hemorrhagic stroke. The exclusionary criteria were previous stroke, non-stroke related neurological disease (e.g. Parkinson's disease), upper extremity musculoskeletal injury, or were unable to understand task instructions. We developed measures to quantify RT across spatial directions: RT Asymmetry to quantify how RT varied across all spatial directions (slower in a specific direction) and RT General to quantify the fastest response across all directions. Impairments were defined as scores greater than 95th percentile of controls. Individuals with RHD were impaired in at least one measure of RT (48%). 34% displayed impairments in RT Asymmetry, commonly for movements to the left. 32% were impaired in RT General, highlighting longer RT when reaching in all spatial directions. Less individuals with LHD were impaired in at least one of the RT measures (30%). Of note, impairments in RT Asymmetry (24%) were more common than impairments in RT General (12%). Interestingly, assessing both arms presented a clockwise rotation in the direction of RT Asymmetry impairment between the left and right arms, suggesting a systemic rotation in RT impairments. RT impairments were commonly observed for individuals who were diagnosed with visuospatial neglect. However, many individuals without visuospatial neglect were impaired in one of the RT measures (35% for RHD and 28% for LHD). Lesion analysis identified distinct cortical regions that was correlated with RT Asymmetry and RT General. Impairment in RT Asymmetry was associated with lesions to the right inferior longitudinal fasciculus, inferior frontal occipital fasciculus, insula, and optic radiations, whereas impaired RT General was associated with right superior and middle temporal lesions. Using a simple reaching paradigm, we demonstrated almost half of individuals following stroke have impairments responding to environmental stimuli. RT impairments can range from a limited spatial direction or span all spatial directions, and are commonly associated with specific lesion locations.

1-E-42 Robotic assessment of unilateral and bilateral upper limb performance in adults living with hemiparetic cerebral palsy

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Most studies of upper limb function in hemiparetic cerebral palsy (HCP) have focused on unilateral performance in children. Existing studies focusing on bilateral coordination suggest that bilateral deficits can exceed the ones that would be expected based on unilateral performance, but studies in adults with HCP are still scarce. Therefore, the evolution of bilateral coordination with neurodevelopment remains unknown. The aim of this study was to describe the impairments in unilateral and bilateral upper limb (UL) performance in adults living with HCP and to assess relationships between the unilateral performance of each limb and bilateral performance. Methodology: Nineteen adults with mild to moderate HCP (34.3 ± 11.5 years, 11 women, MACS 1-3) performed a unilateral and a bilateral task in the Kinarm Exoskeleton Lab (BKIN Technologies). In the unilateral task (Visually Guided Reaching), the participant had to quickly and accurately moved from a central target to four peripheral targets that appeared successively. In the bilateral task (Object Hit), the participant used paddles to hit and pushed away virtual balls that were moving randomly towards them from various locations at a gradually increasing speed. Several kinematic variables were expressed in Z-score and a composite score (task score) was also computed (based on Kinarm normative data considering age, sex and laterality). A score with an absolute z-score > 1.96 (i.e., 2 standard deviations) was considered as indicating a deficit. Association between variables were tested with Spearman correlations. Results: As expected, many participants (58%) exhibited deficits in the unilateral task score for the more affected UL, with 32% also showing a deficit for the less affected one. When looking at specific kinematic variables, the most impaired variables for the more affected UL were the initial direction angle (63% of participants), the initial distance ratio (47%) and the reaction time (37%). A larger proportion of participants exhibited deficits in the bilateral task score (63%), with the most impaired kinematic variables being the hand speed of the more affected UL (47%) and the movement area covered by the more affected UL (42%). The bilateral task score was found to be significantly (but moderately) associated to the more affected UL unilateral task score (r= 0.5, p=0.02), but not with that of the less affected UL. Discussion: The use of a complex bilateral task revealed sensorimotor deficits in a larger proportion of adults with HCP than the use of a unilateral task. This and the fact that only a moderate association was found between unilateral and bilateral performance suggest that there are specific impairments in bilateral coordination. However other differences between the tasks, for instance the requirements in terms of visuomotor skills, need to be considered.

1-E-43 Pallidal Deep Brain Stimulation on Kinematics of continuous movement and Beta Burst Dynamics Across the Motor Circuit in Parkinson's Disease

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Motor symptoms of Parkinson's disease have been associated with beta (β) oscillations in the basal ganglia-thalamo-cortical network. Recent studies suggest that the beta band activity is not sustained but may occur as transient burst-like events. However, it is not clear whether behavioral symptoms follow the fluctuations of beta oscillation and synchrony and whether DBS affects it. To study neural dynamics of movement velocity and the effects of DBS on it, we recorded local field potentials from hand motor (M1) and premotor cortical (PM) area and internal Globus Pallidus (GPi) of Parkinson's disease (N=21) during deep brain stimulator implantation surgery. Subjects performed 30-seconds blocks of hand opening-closing movement alternating with rest periods. Pallidal DBS was performed in a subset of rest and movement blocks. We analyzed the hand movement pattern and extracted the width and height of an opening-closing cycle as a measure of the continuing movement velocity. 28.8% of recorded movement blocks in all patients (24/93 blocks) showed a significant positive correlation between the width of the movement and time, indicating that the hand movement slowed gradually. The percentage of significant positive correlations decreased to 16.9% of blocks (12/71) with DBS. The average correlation coefficients between the movement width and time were also significantly (ttest $p < 0.001$) shifted toward negative nonsignificant correlation values with DBS. We fit the data to a linear mixed-effect (LME) model with time as fixed and subjects and blocks as a random effect to exclude the random effect of individual subjects and blocks. The LME model confirmed the correlation results. We calculated the correlation between movement width and electrophysiology measures using Pearson linear regression. We calculated the Oscillation measures, including β Burst Percent (time in burst per total), β Burst Rate (number of bursts per time), β Burst Duration, and Power. We also calculated the functional connectivity measures: β Burst Overlap (synchronous bursting in two areas), Coherence and dwPLI. All measures were calculated in M1, PM, and GPi. Among all measures, Only M1 low beta Burst duration, rate, and percent showed significant average positive correlations ($p<0.05$) with velocity. In addition, using LME, we found that among all measures, the fixed effect of burst duration and burst percent was significant ($p<0.01$) with a positive coefficient. This effect became insignificant ($p>0.01$) with negative coefficients during DBS. Our findings showed that the movement velocity variations are associated with ongoing fluctuations of motor cortex beta bursts. DBS not only decreases the cortical beta oscillations but also decorrelates cortical oscillations with behavior parameters. However, synchrony and functional connectivity between nodes of the motor network are not directly correlated with velocity-related symptoms like bradykinesia.

F – Adaptation & Plasticity in Motor Control

1-F-44 The Effect of Detuning on Interlimb Coordination

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Bilateral in-phase and anti-phase coordination modes represent two basic movement patterns with distinct characteristics--homologous muscle contraction and non-homologous muscle contraction, respectively. These movement patterns have a strong tendency to be in a stable phase relationship even under conditions of greater task difficulty. A method to understand the contribution of each limb to the overall coordination pattern involves detuning ($\Delta\omega$) the natural eigenfrequency of each limb. In the present experiment, we measured the effect of detuning on coordination stability as human participants performed bilateral in-phase and anti-phase movements using their left and right hand in 1:1 frequency locking mode. Differences between the uncoupled frequencies were manipulated via the application of viscous (velocity dependent force) & elastic (position dependent force) forcefields and by using a fast and slow oscillation frequency based on a custom task developed using the KINARM robotic exoskeleton (BKIN Technologies, Ltd. Ontario, Canada). The effects of manipulating detuning were measured through relative phase (Φ) from 0° to 180° and the standard deviation of relative phase ($SD\Phi$). We found that when applying matched forces to each arm, participants tended to deviate less from the intended relative phase irrespective of coordination mode. Second, we found that when the forcefields were mismatched (different forces applied to each arm) participants exhibited a larger deviation from the intended relative phase. Overall, there was increased phase deviation during anti-phase coordination compared to in-phase coordination. Finally, participants exhibited higher variability in relative phase in mismatched force conditions compared to matched force conditions, with overall higher variability in the anti-phase coordination mode. We extend previous research by empirically demonstrating that detuning between limbs disrupts stability in each coordination mode, and that this effect is larger when detuning is larger (i.e., when forces are mismatched).

1-F-45 Electrical and optogenetic stimulation for stroke recovery in rats

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The work presented in this poster develops approaches to neurostimulation and examines factors which may influence motor plasticity in rodents. Neurostimulation has significant potential to strengthen residual motor circuits after stroke, leading to enhanced functional motor recovery. However, few validated tools exist to assess motor cortical excitability in rats, a crucial intermediary to develop effective stimulation protocols in humans. Our understanding of the principles behind neuronal plasticity and how it can be harnessed is also not fully understood. Both components require advances to develop meaningful and effective therapeutic applications. Toward these goals, we first developed a set of tools which facilitate neurostimulation in the awake, behaving rodent. Investigators can perform electrical and optogenetic interrogation of the corticomotor system in a closed-loop fashion, based on the level of electromyographic activity (EMG) in pseudo real time. This platform can be used to probe the excitability of the nervous system during consistent levels of spontaneous activity without prior training or restraint, and to deliver paired neurostimulation protocols for associative plasticity. Here, we describe the system in brief and demonstrate the reduction of motor evoked potential variability, a potential confounder for reliable assessment of corticomotor excitability over time. Temporal association of neural activity through paired associative stimulation of two neuronal elements is one potential method of driving beneficial plasticity. This protocol stems from spike-timing-dependent plasticity (STDP), a well validated phenomenon in vitro. However, the inter stimulus interval between paired stimuli has seldom been systematically explored in humans; a potential advantage here lies in animal models. We completed such a study, aiming to recapitulate STDP-like plasticity curves in the healthy rat by pairing single pulse orthodromic electrical stimulation of the primary motor cortex with antidromic activation of the motoneurons via intramuscular stimulation. We did not find that associative stimulation induced consistent changes in corticomotor plasticity across all the timings tested; some potential reasons why we observed these results may include interference from ongoing motor activity, and competition of plasticity between the motor cortex and the spinal cord with a single inter-stimulus interval, among others. Finally, selectivity of neural elements activated may also be a key factor affecting MEP variability as well as for driving plasticity and functional recovery in the rat. To further examine this element, we are in the process of performing a study comparing electrical and optical neurostimulation of the rats' rostral forelimb area after a photothrombotic stroke to the caudal forelimb area. We present early results from the pilot cohorts tested towards this goal.

1-F-46 Using tools as cues for dual adaptation to opposing visuomotor rotations in virtual reality

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In response to unexpected perturbations during a motor task, we modify subsequent movements to compensate for errors and improve performance. Motor adaptation to a visuomotor rotation is characterized by reduced errors over time and aftereffects (errors in the opposite direction) following removal of the perturbation. In dual adaptation, participants adapt simultaneously to two opposing visuomotor perturbations. For dual adaptation to be successful, the sensorimotor system relies on relevant contextual cues that are each associated with one of the perturbations. While intrinsic cues (related to the state of the body) have been shown to facilitate dual adaptation, extrinsic cues have yielded mixed results. Humans are experts at using multiple tools and switching between them in various tasks. We thus hypothesized that the use of distinct tools as contextual cues would allow the formation of specific motor memories to each of two opposing visuomotor rotations. If so, participants will exhibit concurrent adaptation to these perturbations. We designed a task in a virtual reality environment where participants (N = 40) used two different tools to move a ball towards targets. Each tool was associated with a different visuomotor perturbation applied to the moving ball (either a 30° clockwise or counterclockwise rotation). Importantly, the mapping between the hand and its visual representation always remained veridical; only the path of the ball was rotated. In addition, participants had to manipulate each tool differently (using forward or backward arm movement) to move the ball to

the target. Therefore, each tool was also associated with a distinct state of the limb (i.e., intrinsic cue). We investigated dual adaptation by having participants switch between both tools every 8 trials. Our results indicate that participants were able to concurrently adapt to two opposing perturbations, each associated with a different tool. However, dual adaptation was not complete as errors did not go back to baseline levels by the end of the exposure phase, and limited aftereffects were observed when perturbations were removed. These findings suggest that the formation and the recall of separate motor memories is slower when using tools as contextual cues for dual adaptation.

1-F-47 Updates of explicit re-aiming to a visuomotor rotation occur via reinforcement learning

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Multiple processes contribute to successful goal-directed movements, such as top-down decision processes for movement selection and planning, along with lower-level processes that ensure the movement is properly calibrated. A large body of empirical work using visuomotor rotation tasks has inspired sophisticated computational models that characterize gradual, lower-level implicit recalibration processes underlying motor adaptation. However, there has been limited development of computational accounts of the flexible, strategic processes that can facilitate learning. Here, we propose that the emergence of a re-aiming strategy can be understood within a reinforcement learning framework, seen as an iterative process that explores an action-value space to maximize reward. We considered three models of re-aiming: 1) Updating of action-value associations occurs only for the selected action via trial-and-error ("local update" model); 2) Updating of action-value associations occurs for all possible actions after each trial based on inference about the underlying rotational relationship between the cursor and the hand ("global update" model); 3) Updating an inference about the rotational relationship between the cursor and hand in an incremental manner ("rotational update" model). To arbitrate between the three models, we examined two visuomotor rotation learning datasets in which participants strategically re-aimed to counteract a rotation imposed between their unseen hand and a visual cursor. Within 30 reaches, participants learn to re-aim in the opposite direction of the rotation, bringing the rotated cursor to the target. For both datasets, the global update model provided a better account of the group data and idiosyncratic individual re-aiming behaviors. These results indicate that re-aiming after unsuccessful movements is neither a trial-and-error process, one that could be implicit and oblivious to the underlying rotation, nor an inferential process that explicitly updates an estimate of the rotation size. Rather, the data point to an iterative reinforcement learning process that involves the scaffolding of an explicit inference about the size and direction of the rotation. Moreover, the fine-tuning of this inference may operate in an implicit manner. These results provide a computational perspective on a flexible, strategic process that allows the sensorimotor system to respond to rapid changes in the environment.

1-F-48 Learning in a mirror reversal task provides distinct mechanisms between de novo learning and motor adaptation

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When people encounter movement errors, they process these errors to correct for subsequent movements. Such error processing contributes to learning when we are either adapting well-known movements or acquiring new motor skills (de novo learning). Previous studies have compared these two types of motor learning, however, several aspects of de novo learning, including its retention and generalization, still warrant investigation. Here, participants completed an online version of the mirror reversal task, a paradigm that captures de novo learning mechanisms, across two sessions. In session 1 (N = 63), participants reached to three targets located in the upper-right quadrant of the workspace (5, 45, 85 degrees in polar coordinates), with the mirror located along the vertical midline axis. Although targets farther from the mirror axis produced larger errors, we found that asymptotic learning did not differ across target locations. Moreover, we observed quick progression in learning and no reach aftereffects, which are persistent deviations in reaches after perturbation removal and are indicative that adaptation has occurred. Interestingly, participants make faster and shorter movements towards the 5 degree target, while taking the longest amount of time and path to reach the 45 degree target. Participants returned for a second session (N = 48; days apart: M = 4.77, SD = 2.52), and showed retention of learning upon re-experiencing the perturbation. They then reached for corresponding target locations within the lower-right and upper-left quadrants of the workspace, followed by reaches using their opposite and untrained hand. We observed almost complete and near immediate generalization of learning to targets across the workspace and the opposite hand. Taken together, these results provide further behavioral mechanisms that distinguish de novo learning from adaptation.

1-F-49 Non-invasive temporal interference stimulation of the human striatum at 80 Hz, but not 20 Hz, disrupts reinforcement motor learning

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Reward is a strong modulator of human behavior. In particular, when applied during training, reward can boost motor learning in healthy subjects and clinical populations and modulate learning-related brain plasticity. Despite the potential clinical relevance of these observations for motor rehabilitation, the underlying brain mechanisms remain largely unexplored. A prevalent hypothesis in the field is that the striatum, a region known to be crucial for both motor and reinforcement learning, may be important to implement reward-related benefits in motor learning. However, because of its deep localization in the brain, modulating striatal activity to understand the causal role of this structure has not been possible in healthy humans non-invasively. Here, we leverage an innovative, non-invasive transcranial brain stimulation technique called temporal interference stimulation (TIS; Grossman et al., 2017, Cell) to target the striatum during reinforcement motor learning in humans. In this randomized, sham-controlled, double-blind study, we applied TIS while 24 participants were practicing a force-tracking task with or without real-time reinforcement feedback (i.e., a form of intrinsic reward) and with concurrent functional magnetic resonance imaging (fMRI). Based on previous studies showing a preferential involvement of high gamma striatal oscillations in reward processing (Berke 2009, EJN), we compared the behavioral and neurophysiological effects of 80Hz TIS (TIS80Hz) with those of 20Hz TIS (TIS20Hz) and sham stimulation (TISsham). As expected, participants learned more when reinforcement feedback was provided in TISsham. Consistent with our hypothesis, these benefits were abolished by TIS80Hz, but not by TIS20Hz. Moreover, in line with a role of striatal beta oscillations in motor function, motor learning

without reinforcement was reduced with TIS20Hz, but not with TIS80Hz. We also find that the impairment of reinforcement-related benefits in motor learning with TI80Hz was related to individual changes of neural activity in the putamen and caudate nucleus, suggesting that the observed behavioral effects were indeed related to neuromodulation of striatal activity. Finally, we show that TIS modulated functional connectivity between the striatal target and a series of motor- and reward-related brain regions, and that this modulation critically depended on the frequency of stimulation and the presence of reward. Overall, these results provide causal evidence for an involvement of the striatum in reward-related benefits in motor learning. Moreover, they also demonstrate that TIS can non-invasively alter specific striatal functions depending on the frequency of stimulation, and the state of the underlying neuronal network.

1-F-50 The effect of combining punishment and reward can transfer to opposite motor learning

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It has long been established that punishment and reward are potent modulators of human and animal behavior. However, until recently how punishment and reward influence human motor learning has not been extensively studied. Although using different tasks, previous research seems to reach a similar result that negative and positive feedback have dissociable effects on motor learning. The conclusion is drawn when aversive and positive approaches are imposed separately in different conditions. But in real world, they are usually used in combination to improve human's behaviour. It is not clear how people are motivated when combining punishment and reward together. For practical applications such as sports training and motor rehabilitation, motor learning is more useful if it transfers to untrained scenarios. Previous studies indicate that the effect of punishment and reward can last till when people relearn. However, it is not clear whether the effect of punishment and reward could transfer to other situations. Here in the present study, we used a motor adaptation task to answer the abovementioned questions: what the effect of combining punishment and reward is in motor learning and whether the effect could transfer to other situations. Specifically, we recruited four groups of participants who learned a visuomotor rotation task under pure punishment, pure reward, punishment and reward combination, or neutral control conditions. In addition, we adopted task A → task B → task A paradigm to check whether negative or positive feedback on initial learning could transfer to the following opponent learning and relearning. We found a distinct effect of combining punishment and reward comparing to the summation of their separate effect. Specifically, during initial learning when there is motivational feedback, combining punishment and reward can not only accelerate learning rate, but also increase learning extent. More interestingly, the effect can even transfer to the following opposite learning. The findings suggest that the combination of punishment and reward has a distinct advantage over pure punishment or reward on motor learning and motor transfer. This distinct motivational effect may result from enhanced sensitivity to directional errors through an explicit learning mechanism. Acknowledgement: This work is supported by National Natural Science Foundation of China (32000745).

1-F-51 Implicit reward-based motor learning

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People can modify a movement based on binary feedback indicating success or failure. Previous research has shown that this form of learning is largely explicit. For example, performance deteriorates under distraction and participants can rapidly switch between the acquired and original behavior. The present study was designed to test whether binary feedback could be sufficient for implicit learning in response to a visuomotor rotation. Participants made fast, center-out movements, with the goal to make an invisible cursor intersect a visual target. The hand was occluded and feedback was limited to a tone, indicating success or failure. 150 no-feedback baseline trials were followed by 700 perturbation trials. In the small perturbation group (n=20), the cursor was shifted by 1.5º every 100 trials until the rotation reached a maximum of 7.5º. In the large perturbation group (n=28), the cursor was shifted by 2.5º every 50 trials to a maximum of 25º. The experiment ended with 150 no-feedback aftereffect trials. Prior to this block, we told participants that the feedback might have been perturbed in the previous block, and that they should now reach straight to the target. These instructions were to encourage participants to stop using an aiming strategy if they had become aware of the perturbation. Perturbation size induced differences in awareness of the perturbation. In the Small group, there was little evidence of awareness: 40% reported that the feedback was perturbed, and of these 25% reported the correct direction of the perturbation. In contrast, 80% of the participants in the Large group reported that the feedback was perturbed and 75% of these reported the correct direction. Both groups showed a change in reach angle to compensate for the perturbation. Over the last 50 feedback trials, the mean reach angle was 6.6º (Small) and 17.2º (Large). The groups showed similar aftereffects: 5.1º (Small) and 3.5º (Large). These results demonstrate that binary feedback can induce implicit adaptation and that the magnitude of this implicit effect does not scale with perturbation size. Interestingly, adaptation generalized to reaches to targets flanking the training location by 15º, with reaching angles biases in the same direction as adaptation to the training target (Small: 4.0º; Large: 3.1º). The fact that generalization to both flanking locations was in the same direction argues against the hypothesis that implicit learning in response to binary feedback is a form of use-dependent learning: use-dependent learning would predict probe reaching biases in opposite directions (towards the training location). Rather, the overall pattern of results points to an implicit learning mechanism that responds to binary feedback to calibrate a sensorimotor map. While qualitatively similar to that observed in response to sensory prediction errors (i.e., error-based learning), the magnitude of the implicit change resulting from binary feedback is smaller.

1-F-52 Changes in interlimb corticospinal facilitation between upper and lower limbs after interlimb coordination task

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It is well-known that voluntary upper-limb muscle contractions facilitate corticospinal excitability of lower-limb muscles and vice versa. This interlimb corticospinal facilitation has been considered the neural basis of interlimb coordination. To our knowledge, however, no studies have examined the relationship between the interlimb corticospinal facilitation and interlimb coordination function. Since interlimb coordination requires neural interactions between upper and lower limbs, we hypothesized that interlimb corticospinal facilitation will increase after improving interlimb coordination function. To test our hypotheses, we investigated changes in lower-limb corticospinal excitability during voluntary upper-limb muscle contractions after an interlimb coordination task, and vice versa. Seven right-handed healthy persons (2 females, mean age ± standard deviation: 24.5 ± 4.2 years) performed the interlimb coordination task or the single-limb motor task approximately a week apart. The interlimb coordination task was to simultaneously coordinate ankle dorsiflexion and wrist flexion forces in 0-30% of the maximum voluntary contraction (MVC) range. In contrast, the single-limb motor task was to exert wrist flexion or ankle dorsiflexion in 0-30% of MVC range alternately. Each task consisted of six sets of eight trials, and in the single-limb motor task, one trial included both ankle dorsiflexion and wrist flexion (i.e., one set consisted of eight ankle dorsiflexions and eight wrist flexions). Corticospinal excitability was assessed through motor evoked potentials (MEPs) evoked by transcranial magnetic stimulation (TMS). MEP amplitudes of tibial anterior (TA) and flexor carpi radialis (FCR) muscles were measured at rest and during 30% of MVC of FCR or TA muscles, respectively, before and after each motor task. TMS intensity was adjusted to a 1.2-fold resting motor threshold, which was set each time before and after the motor task. Results showed that the ratio of TA MEP amplitude during wrist flexion to that at rest were facilitated after the interlimb coordination task (132 ± 30%; one-sample t-test: t(6) = 2.78, p = 0.032), not the single-limb motor task (101 ± 65%; t(6) = 0.059, p = 0.95). On the other hand, the ratio of FCR MEP amplitude during ankle dorsiflexion to that at rest were unchanged after either of the two tasks (coordination: 113 ± 39%; t(6) = 0.87, p = 0.42; single-limb: 111 ± 17%; t(6) = 1.66, p = 0.15). The results suggest that interlimb corticospinal facilitation relates to interlimb coordination function. The increased corticospinal excitability only in the lower limb during voluntary upper-limb muscle contractions after the interlimb coordination task may reflect that humans daily perform precise control of the upper limb while contracting the lower limb (i.e., standing), but are not accustomed to controlling the lower limb precisely while contracting the upper limb.

1-F-53 Strategic re-aiming decreases perceptual precision during motor adaptation

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The precision, or reliability, with which we perceive sensory consequences of our own motor commands is thought to depend partly on an internal model that predicts these consequences. When sensorimotor contingencies change, and predictions are violated, e.g., early during sensorimotor adaptation, perceptual precision should decrease. Here, we test this idea. In four experiments, healthy young volunteers repeatedly adapted to a 45° visuomotor rotation for 2-4 reaches (rotation mini-block), followed by 2-4 washout reaches (washout mini-block). In different experiments, individuals were instructed either to use an aiming strategy that fully compensated for the rotation, or to ignore the rotation, and to "aim directly" at the target. Any adaptation was therefore implicit. Across all experiments, visual feedback was omitted on the second, third, or fourth trial of each mini-block, and participants localized their unseen hand. We estimated the precision of position sense by computing variability of hand localization across mini-blocks. We found implicit motor adaptation as indicated by reach after effects as early as after a single rotation trial. Importantly, we observed an increase in inter-quartile-range of angular localization errors, as evidence of a decrease in perceptual precision, in rotation blocks, compared to washout blocks, but only when participants used an instructed aiming strategy. Inter-quartile-range did not change when participants ignored the rotation, and aimed directly for the target. Different methods for reporting hand location did not influence our results. We conclude that a change in sensorimotor contingencies alone does not alter the precision of positions sense, while a re-aiming strategy, or the presence of aiming targets, decreases precision. We attribute this decrease to a down regulation of proprioceptive acuity due to the visual demand of the task. A decrease in perceptual precision due to strategic re-aiming may have important implications for implicit motor adaptation, and shape the interplay between implicit and explicit learning.

1-F-54 Differential contributions of task performance errors and sensory prediction errors to motor learning

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Humans adapt their movements to minimize errors induced by changing environments. Such learning is believed to be driven by two prominent error sources: task-related performance errors and limb-related sensory prediction errors. Whether these two sources stimulate independent learning mechanisms, or interact in some way, remains an open question. Some early work suggested a separation, with task errors triggering the use of cognitive strategies to reduce error and sensory prediction errors driving implicit recalibration. However, recent studies have suggested that task errors might also influence implicit learning in two potential ways: they might drive a different implicit process, or they might modulate sensory prediction error-driven implicit learning. To test the first hypothesis, we required participants to compensate for task errors induced via target jumps in the absence of any prediction errors. Participants showed no aftereffects - a signature of implicit recalibration - indicating that task errors alone do not drive implicit learning. To test the hypothesis that task errors modulate implicit learning in presence of sensory prediction errors, we employed a visuomotor adaptation task in which the feedback cursor was clamped in a fixed direction, independent of actual hand motion. Cursor feedback was eliminated after the initial portion of the movement, but it was shown again at the end of the movement (endpoint feedback) at different distances from the target; this enabled us to experimentally manipulate information about task error while keeping prediction error magnitude constant. We found that learning was the same in all the groups and there was no modulation of learning rate or amount based on task error magnitude, suggesting that task errors have little influence on implicit learning. So, how do task errors contribute during motor learning? To address this question, we designed a task where the reach target was jumped upon movement initiation, but cursor feedback was clamped in the direction of the original target. Participants were instructed to ignore the cursor feedback and reach the new target. This created task errors initially, but once subjects started aiming to the new location to cancel them out, sensory prediction errors emerged. We found that the change in hand angle was, not so surprisingly, correlated with the magnitude of the target shift during the initial phase of learning, but was surprisingly similar across target shift magnitudes thereafter, i.e. once the sensory prediction errors emerged. This again suggested that implicit learning remained invariant to the size of the task error, and was expressed in a relatively rigid, inflexible manner. Collectively, these results show that task errors and sensory prediction errors exert independent influences during motor learning with task errors likely driving strategic processes and sensory prediction driving implicit recalibration.

1-F-55 Does ipsilateral remapping following hand-loss impact motor control of the intact hand?

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Hand loss, either due to congenital malformation or amputation later in life, profoundly alters motor ability, due to reliance on one intact hand. Based on anecdotal evidence, amputees rely on their intact hand more than individuals born without a hand (one-handers), that prefer to use other body parts for their daily activities. Would this prolonged over-practice of the intact hand in amputees result in increased motor abilities and enhanced sensorimotor representation of the intact hand, as some theories suggest? Previous studies reported increased activity in the missing-hand territory when amputees performed simple movements with their intact hand, compared to two-handers and one-handers. However, it is still unclear whether these changes in overall activity reflect changes in the recruitment of neural resources when using the intact hand and in motor control. Here, we investigated motor learning and neural representation of the intact/dominant hand in amputees, one-handers, and two-handed using behaviour as well as univariate and multivariate fMRI. Participants pressed keys of a piano-like device with either a single finger (Single-Digit easy task) or a chord-like configuration of three fingers (Multi-Digit difficult task) with five levels of complexity as increased ipsilateral processing associates with demanding motor tasks. Results show that motor performance did not differ for the Single-Digit task across groups, while congenitals performed worse than the amputees and controls in the Multi-Digit task, especially for more complex configurations, suggesting that hand loss might compromise motor control only when occurring early in life. This reduced performance was not associated with differences in univariate activity relative to the two-handers either in the intact- or missing-hand territory. However, we observed reduced information content in the (contralateral) intact hand area relative to two-handers and amputees. This suggests that intact sensorimotor patterns of complex actions and fine motor performance are potentially interrelated. In contrast, amputees did not differ from the control group in motor performance at any level of difficulty. However, we replicated the increase in ipsilateral univariate activity relative to controls in the Single-Digit task, as well as relative to controls and one-handers in the Multi-Digit task. Contrary to previous suggestions, this boost in ipsilateral activity may not be functionally related to motor performance. We further observed a consistent (but not significant) reduced univariate activity in the (contralateral) intact hand area of amputees. We speculate that hand loss later in life could promote a redistribution of resources from the intact- to the missing-hand area. In summary, enhanced ipsilateral activity did not seem to benefit (or impair) intact hand function; However, contralateral information content may reflect motor performance of fine motor configurations.

1-F-56 Is the human body the best model for controlling artificial limbs? Comparing biomimetic vs arbitrary motor control strategies

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For individuals missing a limb, the development of robotic prosthetic limbs and their control often centers on embodiment as the ultimate goal: focusing on becoming more like the biological system (biomimetic). The untested assumption is that by using control strategies that are biomimetic, the user is likely to recruit already existing motor skill to control the prosthesis. However, given clear differences between a biological and a prosthetic limb, biomimetic control strategies might actually be hindering usage, due to known neurocognitive bottlenecks. We compared two motor control strategies for a robotic hand: biomimetic (mimicking the desired movement with their own hand) versus arbitrary (pairing an unrelated hand gesture with the desired movement). We focused on i) skill learning, ii) generalizability, and iii) the neural representations supporting control of biological and robotic hands. To accomplish this, we trained two groups of able-bodied participants (n = 40) to use a multi-articulating myoelectric robotic hand over the course of five days (2 hours/day). The robotic hand was attached to participant's left arm and was operated by an 8-channel EMG pattern recognition system, positioned around the forearm. Additionally, a separate control group (n = 20) was tested with the robotic hand without training. We used pre- and post- comparison measures to assess brain and behavioural outcomes of robotic hand usage. Questionnaires for explicit sense of embodiment revealed increased embodiment over the robotic hand specifically in the trained users, with no differences between the two trained groups. We found that the biomimetic group performed better than the arbitrary group on speed tasks, but both groups performed similarly on other aspects of robotic hand control (i.e. grasping precision and gesture switching). Crucially, when assessing how well the training generalized to a novel hybrid control strategy, the biomimetic group showed no benefits of training, and performed similarly to the no-training control group. In contrast, the arbitrary users showed significant behavioural gains which were further reflected in subjective ratings for control difficulty, relative to both other groups. Overall, we suggest that biomimetic and arbitrary control strategies may provide different benefits. The best strategy likely depends on the strengths of the technology, training opportunities and user requirements.

G – Theoretical & Computational Motor Control

1-G-56 Investigation of the effect of an external input in executed movement

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The motor cortex is essential for motor planning and execution. Researchers have focused on the neuronal state at movement initiation to account for parameters related to subsequent movement (e.g., response time; RT). In motor cortical dynamics, an external input could be considered mainly in two different ways; 1) an external input could affect the parameter of motor cortical dynamics, 2) an external input could be considered as an additive term that does not make any change in the parameter. A recent study has revealed that an external input, which is from the midbrain-thalamus pathway, is essential for movement initiation in ALM - without it, the state transition from movement preparation to execution is failed, followed by the omission of movement. Despite the importance, it has not been addressed if the external input could change the behavior of subsequent motor cortical dynamics. If motor cortical dynamics could change by the external input, it could result in behavioral differences such as RT. In this study, we aim to investigate whether the external input could be another factor in determining subsequent motor cortical dynamics. We analyzed the firing activity of the anterior lateral motor cortex (ALM) of mice during the delayed-response task (publicly available at CRCNS.org). Six mice were trained to perform the fixed delayed-response task (3.3 sessions per mouse on average). An auditory cue was presented at 3 or 12 kHz for 1.15s to inform water port location (right or left, respectively). The mice licked right or left according to the given auditory cue after a 2s delay. We decomposed firing rates into 3 different components: motor planning dynamics (D1), putative state transition dynamics evoked by the external input (D2), and movement execution dynamics (D3). We employed principal component analysis (PCA) to estimate a subspace emerged during D1, D2, and D3 respectively. We defined D1, D2, and D3 as firing rates which are reconstructed from PCs that explain 80% of the variance of the data during motor planning, dynamics state transition, and movement execution each. Reconstruction has been made with or without considering D2 dynamics to compare the effect of the firing rate related to the transition dynamics. How much neuronal activity is explained in the motor execution subspace was computed as an index of neuronal dynamics. We explored if the external input affects parameters by examining a relationship between neuronal dynamics and subsequent movement. The neuronal dynamics without considering D2 has positive correlation right before the movement onset. However, the D2 activities evoked during 0~RT (s) did not show any correlation with RT. We found out that the motor cortical dynamics is related to the response time when the firing rate related to the transition dynamics is excluded. Our result could provide an insight that external input may not be a factor in determining subsequent motor cortical dynamics.

1-G-57 Internal states as a source of subject-dependent movement variability and their representation by large-scale networks in the human brain

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Neuroscientists are faced with a challenge when studying humans because humans can dwell on the past which can affect the present and future behaviors. Variability is often observed across sequentially cued movements because past outcomes alter a subject's internal states (i.e., confidence, emotion, or motivation) which influence the way the subject moves. The effects of internal states on goal-directed behavior tend to be overlooked, as they are not directly measurable and, therefore, difficult to connect back to neural processes. In this study, we attempt to investigate these factors by utilizing state-space models to estimate the internal states from measured behavioral data, and then we map these states to neural activity. We exploit a unique experimental paradigm in which 10 human subjects, implanted with depth electrodes, performed a goal-directed center-out reaching task designed to induce changes in internal states with instructed speeds and random perturbations. For example, a subject attempting to reach a specific target at a specific speed may be forced to reevaluate their trajectory when faced with a perturbation, thus negatively affecting their performance and perhaps their confidence. Neural recordings were collected using StereoElectroEncephaloGraphy (SEEG) technique to obtain Local Field Potential (LFP) activity from nonmotor regions, including limbic and cognitive structures. This makes these data particularly useful as we believe it is here where internal states may be encoded, as opposed to the motor cortex. We were able to estimate internal states that (1) predicts variability in reaction time and speed and (2) are encoded in brain regions by large-scale brain networks. Specifically, we identified two state variables that accumulate past evidence on errors and perturbations and predict highly variable movement in all subjects. This demonstrates the utility of the state-space modeling framework to estimate latent factors that explain variability from measurable data. We then mapped the neural activity represented in the spectral domain to these two internal states. We found that the perturbation state is encoding in the default mode network (DMN), suggesting that a role of the DMN during goal-oriented movements is to track how uncertainty in environments (such as external random perturbations) affects movement. We also found that past motor error is encoded in the dorsal attention network (DAN), which is known for visuospatial attention modulation, specifically by working memory. Finally, we showed that strength and connectivity of these two large-scale networks modulated based on performance. The stronger the error state encoding and connectivity strength of the DAN, the better subjects were able to reach the instructed speeds, leading to better performance; and the weaker strength and connectivity of the DMN, the more subjects were affected by perturbations, leading to worse performance.

1-G-58 Effects of task conditions on human hand pose selection strategies in a bimanual fine manipulation task

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Many manipulations in human everyday activities rely on the collaboration of our two hands. Bimanual fine manipulation tasks are particularly demanding when precise coordination among fingers of both hands are required. Yet, despite the abundant degrees of freedom (DoFs) that need to be controlled, humans can perform such tasks nearly effortlessly. Ample evidence suggests that the central nervous system (CNS) predetermines hand poses that are compatible with task conditions prior to manipulation. However, the mechanism by which the CNS encodes task conditions and translates such information into appropriate motor commands is poorly understood. We conducted a comparative study to infer task conditions' effect on hand pose selection strategies. Twenty right-handed subjects (aged 24.2 /-6.0, 5 women) were tasked to a precise unscrewing task consisting of two steps: placing a screwdriver on a tiny (1.6mm) screw that was tightly mounted on a watchface, and unscrewing it without sliding off. Subjects were equally assigned to two groups and performed the same task in two conditions. In the free-base condition, the watchface was left free to move on the table; whereas in the fixed-base condition, it was fixed on the table. We hypothesised that subjects use both hands to manipulate watchface and screwdriver respectively in the free-base condition, while use one hand to manipulate only the screwdriver in the fixed-base condition. Subjects were instructed to perform the task with five repetitions as fast and as accurately as possible. We monitored hand poses employed by subjects and constructed a hand pose taxonomy, based on which we analysed properties of hand pose combinations across trials. Results showed that although subjects used similar hand poses across steps within the same experimental conditions, the hand poses differed significantly in the two conditions. In the free-base condition, subjects needed to stabilise the watch face on the table. The role distribution across hands was strongly influenced by hand dominance: the dominant hand manipulated the tool, whereas the nondominant hand controlled the additional degrees of freedom that might impair performance. In contrast, in the fixed-base condition, the watch face was stationary. Subjects used both hands even though a single hand would have been sufficient, contrary to our hypothesis. Importantly, hand poses decoupled the control of task-demanded force and torque across hands through virtual fingers that grouped multiple fingers into functional units. This preference for bimanual over unimanual control strategy could be an effort to reduce variability caused by mechanical couplings and to alleviate intrinsic sensorimotor processing burdens. To afford analysis of this variety of observations, a novel graphical matrix-based representation of the distribution of hand pose combinations was developed that integrated atypical hand poses that have not been documented in extant hand taxonomies.

1-G-59 The goalkeeper dilemma at the penalty kick

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We address the question of identifying the learning strategy of a player, trying to guess, in real time, successive symbols he/she is exposed to. This is done by discussing two issues related to the structural learning of a sequence of sensorimotor events. First, which structural features of a sequence of events generated by a stochastic chain make it more difficult to learn. Second, how to model the structure of temporal dependences that learners identify from the stimuli in order to make predictions. Behavioral data was collected using a videogame called the Goalkeeper game (https://game.numec.prp.usp.br/). Playing the role of a goalkeeper, participants were asked to predict, step by step, the successive directions (left, center or right) to which the 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. The dependence from the past is represented by the tree of contexts and the associated family of transition probabilities. We collected data from 122 participants divided in four groups. Each participant was exposed to one out of four different stochastic chains organized in pairs. For each pair, the chains were chosen so as to have the same context tree but different associated families of transition probabilities. Moreover, for each pair the entropy of the first chain was smaller than that of the second chain. Furthermore, for the second pair, the first chain (but not the second) can be described as a randomization of a basic ternary cell. This experimental protocol was approved by the local Ethics Committee (58047016.6.1001.5261). By analyzing the sequences of goalkeeper responses, we investigated (1) whether they correctly identify the context trees and associated transition probabilities governing the choices of the kicker and (2) which strategy they used to face the randomness of the kicker choices. We developed a novel statistical approach allowing identifying the context trees assigned by each participant to the sequences of kicker's choices. Finally, results for different participants facing the same kicker were summarized by a mode context tree. Our results point towards an increasing order of learning difficulty from the first to the fourth kicker's stochastic chain. Learning curves obtained per participant for each of the employed context tree models gave an empirical measure of each of the kickers' chains learning difficulty. Concerning the strategy employed to model the structure of temporal dependences, evidence shows that after identifying the kicker's context trees, the goalkeepers stop using their last predictions and start relying only on the kicker's past choices to guide their new predictions.

1-G-60 An integrated neurodynamic theory for action regulation predicts motor deficits in Parkinson's disease patients

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Surviving in an uncertain environment requires not only the ability to select accurately and rapidly the best action, but also the flexibility to withhold an action when the environmental conditions change and new opportunities become available. How actions are initiated and regulated is a fundamental neurobiological question that is of critical importance for understanding how the brain functions. A key component of action regulation is the suppression of actions, which when abnormal contributes to various neuropsychiatric disorders, including Parkinson's disease (PD), Tourette syndrome (TS), and obsessive-compulsive disorders (OCDs). Action suppression occurs in at least 3 ways: (a) action selection - selecting one action requires suppressing alternative motor plans (e.g., picking a glass of water with your right hand requires suppressing motor actions towards the glass with your left hand), (b) decision conflict - selecting one action in the presence of conflicting information requires suppressing alternative actions to buy more time to make a correct decision, and (c) outright stopping - suppressing a response when it is rendered inappropriate or no longer needed (e.g., you should cancel crossing a street intersection, when a bus bears down on you). Although extensive studies have attempted to decipher the mechanisms of these action regulation functions, the relationship between them is still elusive, and the related mechanism of action programming and reprogramming remains inconclusive. A critical gap impeding consensus is the lack of a computational theory that will integrate the action regulation mechanism into a unified framework. The current study aims to advance our understanding by developing a large scale neurodynamical computational framework that combines dynamic field theory with stochastic optimal control theory, simulates the mechanism of action regulation, and predicts how disruption of this mechanism can lead to motor deficits in PD patients. We evaluated our model predictions by studying the motor behavior of neurotypical individuals (n=15) and PD patients (n=32) in three behavioral tasks that involve motor decision between two opposed directions, action selection in the presence of conflicting information and abandon of an ongoing action when a stop signal is presented. To the best of our knowledge, our results revealed for the first time an integrated mechanism of action regulation that affects both planning of action initiation and inhibition. When this mechanism is disrupted (as in PD patients), motor behavior is affected leading to longer reaction times and higher error rates in decisions and actions. Overall, our findings provide significant insight on how the brain regulates actions that involve suppression, and open new avenues on improving the effectiveness of neuromodulation techniques for neurorestorative therapies.

1-G-61 Exploring Neural States in the Parietal Cortex during arm reaching movements with Hidden Markov Models

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During arm reaching movements, our brain needs to integrate the sensory representation of the external world and our body parts with the intrinsic states representing our experiences and willingness to act. These integrative processes take place in the parieto-frontal neural circuit, where several areas transform sensory information into movement intentions and then motor commands. Over the years these networks have been studied extensively using single cell approaches, although this has led to a better characterization of these areas, it is now necessary to move the exploration to the population level where more cognitive functions emerge. In particular, several studies focused on the population dynamics of the motor and premotor cortex, reported that neural activity during reaching movement, has been characterized by a stable sequence of neural patterns called 'neural states' related to the start and end of the movement, that are in line with the low dimensional representations of the motor cortices neural dynamics. Here, we explored whether the parietal cortex population activity formed from pooling together single neurons' spiking activity could be also reduced to a limited number of neural states or whether the sensory integration processes taking place in PPC could be traced in additional states. We used spiking activity recorded from two visuomotor parietal areas (V6A and Pec, 209, and 176 neurons) and from the somato-motor area PE (130 neurons) during a delayed reaching task towards targets placed at different directions and depths in darkness. To probe and characterize the different ensemble activity patterns, we applied an unsupervised machine learning method, the Hidden Markov Model. In all three parietal areas, exactly as found in motor and premotor cortex, we reliably detected three neural states that corresponded to the temporal evolution of the task: motor preparation, execution and holding the target period. Subsequently, using a decoding-based approach we were able to decode from these neural states combined spatial and temporal information. Training the algorithm with 200-ms bins of neural activity, the task epoch was decoded with high accuracy from

V6A (85.5%), and PEc (87%) and significantly lower accuracy in PE (62.5%). Regarding the target decoding, the accuracy was still high in V6A (82%) and PEc (69.5%), and quite low in PE (for vs 35%). These results highlight that while motor actions unfold the population activity dynamics are highly consistent across parieto-frontal areas and they reflect timing constraints. Furthermore, decoding approach reveals that these neural states encode both spatial and temporal information, thus shedding new light on how dynamic processing of multidimensional information to guide movement in parietal cortex occurs. This research was supported by: H2020-EIC-FETPROACT-2019-951910-MAIA and PRIN20172017KZNZLN

1-G-62 Rapid switching between learned controllers for different visuomotor maps

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In everyday life, we frequently need to switch between different skills. For instance, when picking up and using a tool, or when getting on a bike. Studies of cognitive flexibility have found that switching between different cognitive tasks entails a switch cost in the form of temporarily higher reaction times and being more error-prone. It's unclear whether analogous task switch costs exist in the context of switching between different motor skills, and what the nature of any switch costs may be. We examined participants ability to switch between different mappings to control an on-screen cursor. Previous work has found that people struggle to switch between two different external perturbations, such as a visuomotor rotation, that were learned through adaptation. However, for more extreme remappings of the relationship between hand and cursor movements, people do not learn through adaptation but instead engage a different "de novo" learning mechanism (Yang et al., eLife 2021). De novo learning is distinguished from adaptation by an absence of implicit aftereffects, suggesting that people should be more able to switch their behavior on the basis of explicit cues. We therefore examined whether participants could switch between a newly learned "de novo" controller and a pre-existing controller guided by a visual cue. In the first four days, healthy participants (N = 24) practiced a de novo mapping in which forward-backward movement of the left hand controlled left-right movement of the cursor, and left-right movement of the right hand controlled forward-backward movement of the cursor, showing gradual improvement in performance across days. On the fifth day, participants completed a task-switching assessment in which, on each trial, the cursor was controlled either by the newly learned de novo mapping, or by a baseline mapping in which the cursor appeared at the average location of the two hands. The background color of the screen indicated which mapping should be used and was available 500ms before the target location was presented. Using a Bayesian analysis, we found that, in both switch directions (de-novo-to-baseline, and baseline-to-de-novo), some participants were able to perfectly change their behavior on the very first trial after a switch in the mapping. Most participants had a slight impairment in performance on the first trial after the switch, which could not be wholly attributed to neglecting to notice the change of color cue, but successfully changed their behavior by the second post-switch trial. In summary, we found minimal switch costs when switching between two different motor controllers for different mappings. Our findings also further reinforce the qualitative difference between controllers learned "de novo" and those learned through adaptation.

1-G-63 Model of gait control in Parkinson's disease and prediction of robotic assistance

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Gait variability of healthy adults exhibits 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. Previous works have shown that this property is altered in patients with Parkinson's disease (PD), such that their gait pattern corresponds to a more random process. Here, we adapted a model of gait control to interpret the reduction in LRA that characterized PD patients in the framework of optimal control. Gait regulation was modeled as a Linear-Quadratic-Gaussian (LQG) control problem where the objective was to maintain a fixed velocity through the coordinated regulation of stride duration and length. This objective offers a degree of redundancy in the way the controller can maintain a given velocity, resulting in the emergence of LRA in simulated time series of stride parameters. To capture the behavior of PD patients, we reanalyzed a previously published dataset that included 20 patients, who were asked to walk overground for 10 minutes at a self-selected speed. The model was adapted to patients' data first by first increasing the noise in the process dynamics to reproduce the increase in variability observed in this population; then the decline in LRA was reproduced by increasing the regulation of stride duration and length around a fixed set of target values. As a consequence, the model suggested that PD patients exploited less the task redundancy, likely to mitigate the impact of noise, leading to the alteration of the correlation structure of stride series. Furthermore, we used this model to predict the potential benefit of an active orthosis on the gait pattern of PD patients. The orthosis was embedded in the model as a low-pass filter on the time series of stride parameters in agreement with previous work. We show in simulations that, with a suitable level of assistance, the orthosis could help patients recovering a gait pattern with LRA comparable to that of healthy controls. Under the assumption that the presence of LRA in a time series is a marker of healthy gait control, our study provides a rationale for developing gait assistance technology to reduce the risk of fall associated with PD.

1-G-64 Grasping decoder recalibration is facilitated by the alignment of neural manifolds throughout the frontoparietal network

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Limb neuroprostheses aim to drive limb movements by thought alone. The development of such systems would enable paralyzed patients to restore movement and, from an economical perspective, provide broad potential for numerous industries. Neuroprostheses use implanted arrays of electrodes in the brain to capture the spiking activity of many neurons in parallel that are used to decode intended movements. However, these devices require calibration, and classical approaches require extensive recalibration on a daily basis to account for neural drift, i.e., the inevitable loss of some neurons and the capture of new ones over time. Fortunately, recent research has leveraged latent low-dimensional structure, often termed "neural manifold" or "latent variables", which could be preserved across days, weeks, and even years and might provide an opportunity to reduce the amount of data needed per recalibration. To test this hypothesis in the primate hand grasping system, we evaluated multi-array recordings of spiking activity from primary motor (M1), premotor (F5), and posterior parietal (AIP) cortices while monkeys repeatedly performed a delayed grasping task to 48 objects of different size, shape, and orientation. In an offline analysis, we confirmed the existence of a stable neural manifold during this grasping context and found that the neural manifold is stable not just across time, but also across different recording sites both within and largely also across the cortical areas AIP, F5, and M1. The neural manifold approach therefore appears as a promising technique to reduce recalibration requirements in neuroprosthesis applications.

1-G-65 Goal-oriented correction during continuous sensori-motor action can be discriminantly identified with dynamic programming methods and uniquely modulates activity in human basal forebrain

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As humans realize action warranting corrections during continuous sensori-motor tasks, they require a computational system that can discern and correct for errors of goal-oriented value that are supraordinate to lower-order sensory and motor errors. For example, the simplest sensori-motor correction might not result in the greatest reward. However, the tight coupling between the sensori-motor magnitude of an error, and its implications for reward, complicates identification of brain networks contributing separately to each class of error. We accordingly designed a task where error across a performance epoch could be parsed into a continuous hierarchy; two forms of subordinate error (direct spatial traces and segmental spatial traces), and a supraordinate value-based error (segmental dynamic traces). Using modeling based on dynamic programming methods, flexure within each of these traces summarized epochs in terms of the magnitude of error-specific correction rather than error magnitude alone. We observe sites within the basal forebrain that uniquely track with value-based flexure (correction) relative to the two lower order traces. This finding is consistent with basal forebrain's known neuromodulatory function during learning, neuroplasticity, motivational salience and hierarchical prediction error.

1-G-66 Is co-contraction good or bad for movement control? A simulation study using a single model for various movements

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[INTRO] Co-contraction is a simultaneous activation of agonist-antagonist muscles, and in general believed to improve stability. Such co-contraction implies muscles contracting more than minimally needed to achieve the same motion and external forces. Therefore, higher level of co-contraction is often associated with increased metabolic cost, and thus seems to have a trade-off between its benefit and increased cost (Falisse A, et al. 2019). In contrast, some studies suggest that co-contraction may reduce metabolic cost when there is noise and delay in the system (Koelewijn AD, Van Den Bogert AJ, 2022). Previous studies often focused on the effect of the co-contraction level to a single type of a movement. Here, we simulated the effects of co-contraction and demonstrated its optimality during catching, balancing, and reaching tasks using a single model, by changing the cost functions, constraints, or types of disturbances it experiences during the simulation. We tested how the model incorporates co-contraction to achieve better precision, stability, or efficiency, and qualitatively compared it to observations of human movements in these tasks. [MODEL] Our simulation model consists of a one degree of freedom rotating rigid body, and two agonist-antagonist muscles that has identical muscle properties controlling the rigid body. We optimized muscle activation patterns and feedback gains of the controller, such that the resulting movement minimizes the cost function, which combines energetic cost and a task performance measure. Using the model, we reproduced experimental observations on the effect of co-contraction in various tasks. [SIMULATIONS] The catching tasks was formulated as a position control task in the presence of a sudden velocity and mass disturbance, and the simulation produced pre-activation and counter movement before the impact as observed in experiments. The reaching task was formulated as a control task where initial state and final state are specified. We tested the effect of a target size on the co-contraction level during reaching tasks by changing the error tolerance in the final position, and as observed in experiments, the simulation found a solution with more co-contraction for a smaller target. To model balancing tasks subject to unexpected disturbances, we ran the optimization algorithm multiple times with altered conditions and looked for a solution that performed overall the best. Our simulation model produced a solution with more co-contraction when there were more uncertainties, as seen in experimental observations. Moreover, when a large disturbance was applied, more co-contraction up to a certain level was more energetically efficient than not using co-contraction, as seen in some previous studies. [DISCUSSION] The framework here can help design new experiments to examine how nervous systems incorporate various objectives and constraints in control of movements in the presence of uncertainty.

1-G-67 A neural hashcode model of basal ganglia function

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The hypothesis that dopaminergic neurons in the ventral tegmentum and substantia nigra could encode predicted future reward has led computational neuroscientists to propose that the basal ganglia could be part of a network that implements Reinforcement Learning (RL). However, RL requires a network that represents the relationship between state, state change, and predicted future reward, and such networks have not been found. I propose a new model based on known basal ganglia anatomy that implements a form of RL related to Q-learning. Current state is mapped to action through direct and indirect pathways that place rewarded or non-rewarded state-action pairs into separate "buckets" with excitatory or inverting outputs. "Bucket Q-learning" provides a biologically plausible network structure without the need for explicit representation of future predicted reward. Efficient implementation is based on neural hash coding, a new learning algorithm that permits one-shot learning by using random representations of state to eliminate overlap between training examples. While this structure requires generalization to be implemented elsewhere (for example, in the input representation), in return it gives very rapid and reliable learning, reminiscent of human behavior in which a single rewarded or punished example is often sufficient to modify future action. Finally, in this model the output of basal ganglia modulates thalamo-cortical loops, thereby allowing basal ganglia to select state-dependent cortical dynamics for movement, accentuating or inhibiting dynamic components based on prior experience of reward. The model thus combines three elements: (1) bucket Q-learning, (2) neural hash codes, (3) modulation of dynamics. I show that not only does this provide stable rapid learning of dynamics from reward, but specific injuries can provide models for hypertonic dystonia, hyperkinetic dystonia, and chorea.

Poster Session 2

Wednesday July 27, 2022

A – Control of Eye & Head Movement

2-A-1 Body-state modulates head-body coordination in Drosophila courtship pursuit

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To successfully pursue a prey to eat or a conspecific to mate, animals need to coordinate the movements of their eyes, head and body to acquire spatial information about the target's position and guide the oriented movement of the body through space. Vision is a critical sensory information supporting these high-performance locomotive behaviors, yet how vision is integrated with movement across the body to guide goal-directed locomotion remains poorly understood. To address this question, we study the pursuit behavior of a male fruit fly (Drosophila melanogaster) towards a conspecific female during courtship. This goal-directed walking behavior depends on vision. During courtship pursuit, a male-female pair engages in tortuous walking paths; nevertheless, males keep the moving female directly in front of them with high precision. This suggests that a frontal region of the fly's eye has an important function on pursuit performance. By occluding different areas of the fly's eyes, we found a functionally specialized region in the retina that is critical for pursuit, without which males cannot follow females swiftly. We then examined how flies use their head to keep the female in this specific region. To monitor head movements in high detail, we established a virtual pursuit behavior in a tethered fly walking on a spherical treadmill. We took advantage of the genetic toolkit of Drosophila and induced a male courtship-state to promote the pursuit of a virtual, controlled fictive female. We found that tethered males follow the position of the fictive female with a combination of head and body rotations, with the head preceding body movements. Similar to what we found with real females, occluding the specialized retinal region degrades the following behavior for both the head and the body. Moreover, we found two distinct modes of head movements: a smooth movement that closely follows the position of the fictive female, and a rapid, saccadic-like head movement that anticipates the fictive female position. The display of these two distinctive head movements correlate with the walking speed of the fly, suggesting an interesting and previously overlooked interplay between the state of the body and head-body coordination. All together, our findings reveal that fruit flies' display analogous features to other species during an ethologically-relevant oriented behavior, in which the combination of the visual input from a specific retinal region and the relative angle from the head to the body are critical for the overall pursuit performance. Our results open up the opportunity to understand how brains integrate visual and motor information across the body to control oriented movements by systematically studying the neural implementation of this coordination in a compact and genetically tractable system.

2-A-2 Perception of time-varying envelopes begins at the single-neuron level in central vestibular pathways: Implications for perception and motor control

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The vestibular system encodes head motion during our daily activities giving rise to vital autonomous reflexes as well as self-motion perception. Recent studies have shown that self-motion experienced during everyday activities consists of a fast time-varying head velocity waveform (i.e., the carrier or 1st order) whose amplitude (i.e., the envelope or 2nd-order). While previous psychophysics studies have

shown that humans can perceive differences in the envelope as low as 2 deg/s, how neurons within ascending vestibular pathways encode these has not been investigated to date. Here we recorded from vestibular-only (VO) neurons within the vestibular nuclei that project to the thalamus as well as the spinal cord, thereby mediating self-motion perception as well as vital reflexes to control posture. Neuronal responses were recorded during rotational stimulation consisting of a noisy waveform whose envelope varied sinusoidally at lower frequencies within that seen under natural conditions (0.05 - 1 Hz). The envelope was furthermore varied such that the underlying stimulus waveform only elicited linearly related changes in firing rate for semicircular canal afferents. Overall, we found that VO neurons robustly encoded the time-varying envelope with a gain that decreased as a function of frequency. Interestingly, VO neural responses increasingly lagged the envelope stimulus as frequency increased consistent with a long stimulus-response latency of ~100 ms. Using a linear-nonlinear cascade model we determined that envelope responses in VO neurons could not be explained by static nonlinearities (i.e., cut-off and saturation). Rather, VO neuronal responses could be reproduced only by accounting for long experimentally-observed stimulus-response latency. Finally, to compare our single unit findings with results of prior psychophysical studies, we computed neural amplitude detection and discrimination thresholds. We found that neural detection and discrimination threshold values were an order of magnitude higher than those observed for human perception. Indeed, to account for perception, it was necessary to pool the activities of about 150 to 200 neurons - a value much greater than for thalamus neurons (~10 neurons, Carriot et al. 2021). Overall, our results show that, while encoding of time-varying envelopes begins at the level of the vestibular nuclei, perceptual performance is likely mediated by downstream neurons (e.g., cortex) that first extract the envelope signal and then send this signal upstream to VO neurons. As such, our results have critical implications for understanding how self-motion perception as well as critical reflexes mediating posture control are mediated by ascending vestibular pathways.

2-A-3 Eye-hand coordination at the frontier between discrete and continuous movements

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Although many studies have characterized eye-hand coordination during discrete (e.g. reaching) and continuous actions (e.g. pursuit tracking), how eye-hand coordination might be organized for actions lying at the frontier between discrete and continuous movements has not been explored yet. The main goal of this study was to investigate to what extent eye-hand coordination described for discrete and continuous actions might account for movements lying in between. To achieve this goal, participants (N=28) were asked to keep their gaze and/or a cursor (by means of a joystick) as close as possible from a visual target that followed a pseudo random trajectory. To manipulate the discrete/continuous aspect of the task, we varied the rate at which the new position of the target was updated. Eight refreshing rates were tested (1.5, 2, 2.5, 3, 3.5, 4, 8 and 240 Hz) allowing to examine actions ranging from discrete point-to-point actions (low refreshing rate) to continuous pursuit movements (high refreshing rate). For each refreshing rate, the task was performed under the following three conditions: with the eyes only (EO), with the hand only (HO, eyes being fixed), and with both the eyes and hand (EH). Preliminary analyses of the eye data suggest the following key observations. The transition from discrete to continuous hand movements is accompanied by a smooth transition in eye behavior leading to a tradeoff between eye fixations and smooth pursuit episodes. Moreover, for all refreshing rates, the comparison between EO and EH conditions reveals a decrease in the rate of catchup saccades. Regarding temporal coordination between eye and hand movements, positive correlations between cursor-target and eye-target delays are found at both high and low refreshing rates. Finally, we noticed that eye movements also influence hand movements. Indeed, at low refreshing rates the number of hand sub-movements is greater when eye movements are not restricted. Altogether these preliminary analyses confirm many earlier observations made in the context of discrete and continuous actions (Danion and Flanagan 2018; Gribble et al. 2002; Niehorster et al. 2015), but they also suggest that eye-hand coordination is flexible enough to smoothly accommodate movements lying at the frontier between discrete and continuous ones.

2-A-4 Programming and Triggering of Catch-up Saccades to Accelerating Targets

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Humans visually track moving objects by combining smooth pursuit and saccadic eye movements. Accelerating motion is common as humans interact with their surroundings, thus it is essential to accurately estimate and act on object acceleration. We know position and velocity errors are the primary sensory inputs for estimating the magnitude and timing of catch-up saccades. However, whether they also take retinal acceleration (RA) into account remains mostly unknown. The purpose of the current study is to investigate how humans coordinate pursuit and saccades to accelerating targets. We hypothesized that RA influences the timing and magnitude of catch-up saccades. Previous studies have used an abrupt change of target position and velocity during ongoing smooth pursuit to test the influence of position error (PE) and velocity error (retinal slip RS) on saccade amplitude and trigger times (de Brouwer et al., 2002). In our experimental design, we manipulated the position, velocity, and a novel acceleration component of visual targets to quantify their influence on the timing and magnitude of catch-up saccades during pursuit. 13 participants completed ~2500 trials each. After fixation, we presented a continuously accelerating (0deg/s initial velocity) or decelerating (40deg/s initial velocity) target. 750-1250 ms later, a position jump occurred intended to elicit a saccade. We recorded the latency and amplitude of the first saccade (750 deg/s^2 acceleration threshold) after the position jump and estimated retinal PE, RS, and RA during a 50ms window centered around 125ms (or earliest available for PE after step) before saccade start. We hypothesized that RA is estimated and used to control saccade amplitude. We used a multiple linear regression to investigate the contribution of RA in conjunction with RS and PE in estimating the resulting amplitude of catch-up saccades, finding that all variables significantly influenced the resulting saccade amplitude across participants: Saccade Amplitude = -0.3198+ 0.9478*PE + 0.1221*RS + 0.0012*RA This amounts to a prediction of RS-related (resp. acceleration-related) accumulation of PE 122ms (resp. 49ms) into the future. We also hypothesized that RA influences error accumulation used to determine whether a saccade is triggered. Nachmani et al. (2019) has shown that predicted position error (= PE + 150ms * RS) determines saccade latencies. We thus predicted that RA increases saccade latencies if acceleration decreases the absolute predicted position error (PEpred) and vice versa. We assessed the influence of estimated PEpred in catch-up saccade triggering using a rmANOVA across participants. Our analysis revealed a significant interaction between the effects of the sign of RA and size of PEpred. Thus, RA modulated saccade trigger times. Overall, our results indicate that the mechanisms that program and trigger catch-up saccades may be using RA in addition to velocity estimates as a predictor of future target position.

2-A-5 **Eye-head coordination during active head-unrestrained gaze shifts in mice**

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Reorienting the visual axis requires a combination of head and eye movements to generate a gaze shift. Gaze shift strategies vary across species, with some animals relying on head-driven and others eye-driven movements to rapidly shift the location of the eye's axis. The prevailing view is that animals lacking the high-acuity visual center known as the fovea (afoveates) perform head-directed gaze, while foveate animals (monkeys, for instance), use their eyes to redirect gaze, followed by compensatory head movement (Land and Nilsson, 2012). Mice are one of the prevailing afoveates in the study of vision, though little is known of the neural mechanism of their natural gaze shift strategy. One hypothesis is that voluntary (active) gaze shifts are largely generated by voluntary head movements such that eye movements are produced by involuntary reflex responses (i.e., a combination of vestibular slow and quick phases). Alternatively, it is possible that mice generate both voluntary eye and head movements to redirect their gaze. In this study, we assess the dynamics of mouse gaze during active and passive movements to define their natural gaze behaviors and distinguish between these two possibilities. To assess gaze during active movements, mice were trained to perform small (approx. ±10° from center) and large (approx. ±40° from center) horizontal head movements. Specifically, they actively generated goal-directed movements to orient between two waterspouts for water reward. A small camera system tracked horizontal and vertical pupil position during task performance and a high-resolution potentiometer measured head rotation. Gaze shifts were calculated by summing head position in space and eye position in orbit. Within 10-20 ms of active head motion, mice generated rapid saccade-like eye movements in the direction of the head motion, resulting in an enhanced gaze response. For comparison, we recorded eye movements evoked in response to comparable passive movements (ie., ±10° versus ±40° from center) that were generated by applying an external torque to the mouse's head. In contrast to actively generated head motion, the eye movements generated in response to passive head motion were characterized by a robust and sustained VOR response as evidenced by an equal and opposite eye and head position persisting for ~100ms, after which a corrective quick phase was generated. Further, during the large movements, subsequent compensatory and quick-phase VOR were generated until the head stabilized. Together, our results contrast with the prevailing view and suggest that mice generate both voluntary eye and head movements to redirect gaze. The onset of the saccade-like eye movements generated during active orienting head movements occurred an order of magnitude faster than VOR quick-phase eye movements generated during comparable passive head movements. We propose that although mice lack a fovea, they can reorient gaze using a combined eye-head strategy.

B – Fundamentals of Motor Control

2-B-6 **Long-term, stable 2D direct cursor control by neural manifold dynamics**

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In the last two decades, brain-machine interfaces (BMIs) have emerged as a solution for people with paralysis to regain some level of independence. The clinical efficacy of BMIs critically depends on the intuitiveness and temporal stability of the decoding strategy. Here, we present a novel BMI paradigm designed to achieve ease of learning and long-term robustness. To this end, we built on previous studies

([Sadtler, 2014, Nature]) showing that learning a new task is facilitated when the underlying neural activity pattern lies within a so-called neural manifold, i.e., an intrinsic neural ensemble that arises from constraints imposed by brain circuitry ([Gallego, 2017, Neuron]). We hypothesized that by directly linking the dynamics of intrinsic neural ensembles to the controlled variables, the user could quickly learn to master a BMI task and adapt the neuromodulation strategy to long-term recording changes. Thus, we extended the approach of direct control based on single-neuron activity, which has been validated in the past ([Moritz, 2008, Nature]), to the use of manifold dynamics. We tested our manifold-based direct control paradigm in a macaque monkey implanted with an intracortical array in the hand area of the primary motor cortex. We computed one time, at the onset of the protocol, a 2D manifold capturing a significant portion of the animal's neural activity variance while performing a reach-to-grasp task. Next, we linearly coupled the cortical activity along the manifold axes to the 2D movement of a cursor. Finally, we tested this BMI paradigm in a delayed point-to-point task over a 16-week incremental training protocol. The monkey showed rapid learning of new tasks and a stable success rate of ~90% until the end of the protocol, without recalibration of the control space. We found that the animal could adjust the tuning of neural ensembles, also depending on the experimental conditions, to overcome neural recording instabilities and maintain high performance over the long term. This effortless adaptation was likely due to the inherence of neural manifolds and the intuitiveness of direct control links. These results provide evidence that manifold-based direct control holds promise for clinical applications of BMIs.

2-B-7 Age-related differences in finger kinematics during daily-life hand movements

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Fine motor skills of the fingers are crucial in many daily activities, and their deterioration leads to limitations in the quality of life. It is well known that hand function diminishes during healthy aging, but the expression in terms of finger kinematics is fairly unknown. For instance, the pattern of finger interdependence, i.e. the involuntary co-movement of fingers not intended to move, is known to vary across the life span, influencing the stability of prehensile tasks. However, the magnitude and direction of this effect across ages are ambiguous across studies and tasks. In addition, most of the previous literature has focused on restricted, force-producing finger movements, not facilitating the understanding of finger kinematics during daily activities. Here, we investigated six different patterns of finger movements inspired by daily-life activities (e.g. opening a jar) across two age groups. We tested seventeen younger (mean age 27 years) and seventeen older adults (mean age 72 years) performing movements with their right dominant hand. We focused on changes in finger interdependence across ages using standard statistical analyses and machine-learning approaches. Our results showed that age-effects on finger interdependence are not only finger-combination- but also task-specific, and follow a clear pattern across groups in most of the daily-life movements. Specifically, fingertip touching, i.e. the rhythmical tapping of fingers against the thumb, showed higher interdependence indices (more co-movement) in older compared to younger adults. Fingertip touching is most similar to the movement tasks used in previous studies, and therefore in agreement with the idea that older participants have larger co-movement when performing finger movements. Interestingly, this pattern was reversed in the other five movements, which in contrast required the manipulation of an object with a finger grip. Here, young adults showed stronger co-movement compared to older adults for all combinations of instructed (the finger requested to perform the movement) and adjacent non-instructed fingers. Only the combination of instructed ring and non-instructed little finger showed opposite age effects, with higher interdependence in older adults. Beyond statistical analysis, we additionally demonstrated, using machine learning, that finger kinematic data reflect age-related differences in finger interdependence patterns, making it possible to predict the age group from a single movement trial. Taken together, in our study we show that finger kinematics are task-specific and change with age. We illustrate that previous results on finger interdependence are not easily comparable, even if they follow clear patterns under specific conditions. Hence, age-related differences in finger kinematics have to be taken into account when it comes to the development of diagnostic gloves, automated rehabilitation support, and other clinical applications using finger kinematic data.

2-B-8 Sensorimotor Integration and Motor Learning During a Novel Visuomotor Task in Young Adults with Attention-Deficit/Hyperactivity Disorder

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Background: Attention-Deficit/Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder with unique neurological and behavioural characteristics [1, 2]. ADHD has been shown to alter motor performance and coordination [3, 4], potentially affecting learning processes involved in the acquisition of motor skills. Additionally, there are alterations in somatosensory processing [5] and the integration of multisensory stimuli [6]. It is currently unknown whether motor learning and performance may be altered, and whether there are neural markers relevant to these potential differences in adults with ADHD. This work will provide insight into the role of altered neural processing and sensorimotor integration (SMI) while learning a novel visuomotor task. Methods: This work compared adults with ADHD ($n = 12$) to neurotypical controls ($n = 15$), utilizing a novel visuomotor tracing task, where participants used their right-thumb to trace a sinusoidal waveform that varied in both frequency and amplitude. This learning paradigm was completed in pre, acquisition, and post blocks, where participants additionally returned and completed a retention and transfer test 24 hours later. Right median nerve somatosensory-evoked potentials (SEPs) were collected pre and post motor acquisition. SEPs are named based on their polarity and latency and are reflective of specific neural processes and structures. SEPs were stimulated at two frequencies, 2.47Hz and 4.98Hz, and were recorded using 64-electrode electroencephalography (EEG) at 2048Hz. Each SEP peak was normalized to each participant's baseline values. Preliminary Results: Behavioural: There was a main effect of time for both the normalized ($p < 0.001$) and absolute ($p < 0.001$) performance scores. Neurophysiological: N18: showed a main effect of group ($p < 0.05$) and a time by group interaction ($p < 0.05$), where the ADHD N18 increased post motor learning (1.26 ± 0.65) and controls decreased (0.83 ± 0.37). N20: showed a main effect of time ($p < 0.01$), where N20 increased for both groups post motor learning (ADHD: 1.11 ± 0.14; Control: 1.05 ± 0.12). P25: showed a main effect of time ($p < 0.001$), with P25 increasing for both groups post motor learning (ADHD: 1.09 ± 0.08; Control: 1.09 ± 0.13). N24: showed a main effect of time ($p < 0.05$), where N24 increased for both groups post motor learning (ADHD: 1.10 ± 0.16; Control: 1.13 ± 0.28). Discussion: This is the first work to utilize SEPs as a neurophysiological marker in conjunction with a visuomotor learning paradigm to assess processes involved in motor learning in adults with ADHD. These findings, particularly those related to the N18, suggest that there may be differences in cerebellar-cortical [7] processing in response to this novel motor task in those with ADHD. Future work should further investigate the potential role of cerebellar function in response to motor learning in this population.

2-B-9 New technology for high-resolution muscle recording during skilled behavior in rodents, songbirds, and primates

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Neurons coordinate their activity to produce an astonishing variety of behaviors. Our present understanding of this coordination has grown rapidly thanks to new methods for recording and analyzing populations of many individual neurons over time. In contrast, current methods for recording the brain's actual motor output - the spiking activity of "motor units," the muscle fibers innervated by a single motor neuron - lag far behind neural recording technology. Current electromyographic (EMG) methods using intramuscular wires or skin-surface arrays typically measure only bulk muscle activity, can only resolve the activity of individual motor units in highly restricted settings such as isometric tasks, and cannot resolve single motor unit activity in small muscles, including those of many widely used animal models of motor control. Here we present a novel class of electrode devices that record muscle activity at cellular resolution across a wide range of muscles and species. Thin polymer "threads" are embedded with up to 32 electrode contacts and equipped with micron-scale structural features that allow them to be inserted into muscles as small as 3mm in length. Together with our collaborators, we have created variations on this basic design to record single motor unit activity across muscles groups (forelimb, trunk/axial, orofacial, respiratory, and vocal muscles) and species (mice, rats, songbirds, and nonhuman primates). Moreover, the flexibility and tensile strength of the devices, along with the mechanical properties and low impedance of the electrode contacts, allows single-unit and bulk EMG recordings to be collected over a timescale of months following the implantation of a single device. This technology allows investigations of motor unit activity at unprecedented resolution during complex behaviors. I will present results from three projects that use our electrodes. First, we collected long-term (thousands of breathing cycles) from respiratory muscles of songbirds to understand how populations of motor units coordinate their activity to shape respiration. We found that the activity of individual motor units is coordinated on timescales ranging from milliseconds to hours, including both precise co-timing of action potentials as well as long-timescale changes in the population of motor units driving the behavior. Second, bilateral recordings from mice during unconstrained locomotion reveal the complex patterns of motor unit recruitment within and across multiple forelimb muscles. Third, recordings from upper limb muscles of nonhuman primates performing target-directed reaching tasks show how the activity of individual spinal motor neurons is influenced by the mechanical demands of the task and the statistics of the sensorimotor environment. These findings establish the flexibility and scientific impact of our recording methods. Finally, I will present data from in-progress studies combining these EMG methods with neural recordings.

2-B-10 Motor sequence learning: different effectors, similar processes

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Introduction. Sequential actions are needed in everyday life. Sequential finger tapping task (SFFT) is the most widely used task in motor sequence learning (MSL) paradigms (Kuriyama et al., 2004). Grosser MSL of sequential hand movements (Gudberg et al., 2015) and whole body movements (Freitas

et al., 2020) have also been studied, but rarely been directly compared to fine MSL. Therefore, this study aimed at comparing MSL processes (acquisition and consolidation) of sequential movements involving different body parts. Methods. Twenty healthy and young participants (8 women; 22.6 ± 3.5 years) randomly performed four tasks: unimanual with four fingers of the right hand, bimanual with both forefingers, bimanual with both hands, bipodal with both feet and whole body. All participants performed one task a day with a morning training session followed by a retest at least 6 hours after the initial training. During training, the participants had to repeat an 8-items sequence as fast and accurately as possible during 12 blocks of 30s, interspaced by 15s of rest. Before and after training, as well as during retention, they repeated the sequence during 2 blocks of 30s. The number of correct responses was the dependent variable. Results. The participants i) improved performance in the four sequential tasks, during the acquisition phase, with no differences for manual tasks and a greater increase in the bimanual task with both forefingers compared to the bipodal task ii) stabilized performance during the retention test, i.e. the consolidation phase, with no task difference. Conclusion. Despite differences among sequential tasks (bimanual vs. unimanual coordination, fine vs. gross movements), these skills involved similar MSL processes, thus highlighting that MSL processes with SFTT are also observed during more ecological tasks. References. Freitas et al., (2020) Scand J Med Sci Sports; Gudberg et al., (2015) Neurobiol Aging; Kuriyama et al., (2004) Learn Mem

2-B-11 A novel force-constrained non-negative matrix factorization algorithm reveals that muscle synergies are effective in the task space

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According to the muscle synergy hypothesis, the motor system recruits and combines a small number of synergies in a task-dependent manner. Dimensionality reduction algorithms can be used to extract synergies from electromyographic (EMG) signals. Yet, little is known about the extent to which the combination of those muscle synergies encodes task-relevant variations of muscle activity. We have previously demonstrated that human subjects are able to use muscle synergies identified by non-negative matrix factorization (NMF) to control a cursor during an isometric reaching task in a virtual environment using a linear EMG-to-force mapping (Berger & d'Avella, 2014). The accuracy of trajectories in synergy-control, where forces are estimated by projecting the recorded EMGs into the synergy space, was the same as in EMG-control, where forces are estimated according to the individual muscles. However, when reconstructing the forces executed in EMG-control using muscle synergies (Synergy Reconstruction, SR) the accuracy was significantly lower. In the present work, we wondered whether SR fails in some cases because the extracted synergies do not accurately encode the task-relevant variations of the muscle activity and whether performance would increase if the effectiveness of synergies in the task space in addition to their capability to reconstruct muscle patterns are considered. To address these questions, we developed a synergy extraction algorithm that takes the task space into account by adding a term penalizing force reconstruction error in the cost function optimized by gradient descent. We compared the synergies extracted by the standard NMF algorithm and a novel force-constrained NMF (FCNMF) algorithm using simulated noisy muscle patterns generating multidirectional forces and EMG-control experimental data. We found the failure of SR with the synergies extracted by the NMF algorithm to be highly dependent on the characteristics of the noise added to the simulated data. In case of zero-mean isotropic Gaussian noise, the NMF algorithm has a high SR quality even for high noise levels. However, adding small amounts of noise along the directions in muscle space generating force in the task space has a dramatic effect on the NMF synergies. This is not the case for synergies extracted by the FCNMF algorithm. Specifically, SR with FCNMF synergies recover the simulated trajectories adequately, even with amounts of noise that leads the standard NMF algorithm to fail. Finally, we used the FCNMF algorithm to extract muscle synergies from the dataset where the SR using NMF synergies failed to accurately reconstruct the trajectories. Indeed, synergies extracted with FCNMF accurately reconstruct the trajectories for all participants. These findings show the effectiveness of synergies that also account for the task space, possibly thanks to its robustness to non-isotropic noise present in muscle data and thus provide an effective strategy for motor coordination.

2-B-12 Cerebellar thalamocortical interactions during motor preparation

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Cerebellar drive to primary motor cortex (M1) by way of motor thalamus is predicted to subserve motor preparation, yet this has not been studied in the non-human primate. We combine simultaneous population recordings, deep brain structure electrical stimulation identification, and modern statistical methods to distinguish the M1 projecting, cerebellar-recipient motor thalamus (VLp) and evaluate the trial-by-trial relationship in single-unit activity between VLp and M1. Here we present evidence that interactions between populations of neurons in VLp and M1 are a signature of motor preparation in the non-human primate.

2-B-13 A geometric approach to distinguish feedforward planning from feedback control

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Planning is a critical aspect of movement production. Previous studies have suggested that the planning happens at the endpoint with stereotypic mean straight-line trajectories and bell-shaped velocity profiles, while the joints explore a range of possible solutions during the movement due to redundancy (Bernshteĭn 1967; Morasso 1981; Todorov and Jordan 2002). In this context, prior work has focussed on inter-trial variability where it is not possible to track a single trial across time. In this study we looked at the intra-trial variability of 1) Cyclic flexion-extension movements with one active finger (Chakrabhavi and Skm 2019) and 2) Horizontal centre out reaching movements with dominant and non-dominant arms of 24 subjects. We assigned an ordinal value (z-score) to trajectories across trials and performed canonical correlation analysis (CCA) of joints (shoulder, elbow, and wrist angles) and endpoint (x and y trajectories) and a Pearson's correlation for each joint, endpoint, and finger trajectories between the initial and any subsequent time point. For finger movements, we found that the active finger had the least R value as compared to passive fingers indicating that an active intervention led to a disordered arrangement of the trajectories. We then used a similar approach to analyse horizontal reaching movements, and observed that joint angles were correlated across time, while the correlations of the endpoint decreased significantly. We propose from this analysis that the joints rely on a feedforward plan while the end point is controlled by active feedback intervention (similar to the active finger). When we analysed for skill, we found that the endpoint correlation for the dominant arm was significantly lower than the non-dominant arm and that the decrease in R value was significantly correlated with an increased endpoint accuracy. Interestingly, the skilled arm relied on a proximal to distal strategy of recruitment of joints while it was not the case for the non-dominant arm. To investigate whether intra trial correlations were sensitive to the presence of feedback control, we performed CCA for joints and end point between successive time points. We found an initial drop in the R value associated with the decreased reliance on the feedforward plan and a phase of increase in R value indicating an active feedback intervention. Further, the average decrease in R value was significantly greater at the endpoint as compared to joints. Also, the average decrease in R value of the endpoint was significantly greater in the dominant arm suggesting a higher utilization of feedback control. Taken together, we observed distinct signatures of temporal correlations between joints and endpoint and suggest that the joints rely on a feedforward plan, while the endpoint is controlled by active feedback intervention. We also found that this active intervention was higher in the dominant arm which is a key aspect of acquired skill.

2-B-14 Tactile suppression stems from specific sensorimotor predictions

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The ability to sample sensory information with our hands is crucial for smooth and efficient interactions with the world. Despite this important role of touch, tactile sensations on a moving hand are perceived weaker than when presented on the same but stationary hand. This phenomenon of tactile suppression has been explained by predictive mechanisms, such as internal forward models, that estimate future sensory states of the body on the basis of the motor command and suppress the associated predicted sensory feedback. The origins of tactile suppression have sparked a lot of debate, with contemporary accounts claiming that suppression is independent of sensorimotor predictions and is instead due to an unspecific mechanism. Here, we target this debate and provide evidence for specific tactile suppression due to precise sensorimotor predictions. Participants stroked with their finger over textured objects that caused predictable vibrotactile feedback signals on that finger. Shortly before touching the texture, we probed tactile suppression by applying external vibrotactile probes on the moving finger that either matched or mismatched the frequency generated by the stroking movement along the texture. We found stronger suppression of the probes that matched the predicted sensory feedback. These results show that tactile suppression is specifically tuned to the predicted sensory states of a movement.

2-B-15 A Simplified Framework of Motor Control

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Control of movement is commonly examined and assumed to be either cortical, spinal, or purely biomechanical in nature [1,2]. When investigating a particular level, it tends to be separated from the rest and studied in isolation. Interactions with other levels are generally either ignored or explored poorly. This restriction misrepresents how movements occur in realistic scenarios. We propose a framework for motor control which conceptually and mathematically accommodates the entire motor process, from cortex to the endpoint. We suggest that motor control starts with a simple representation of endpoint coordinates at the cortical level. This is then transformed, mainly at the subcortical level, into specific movements at each involved end-effector. This transformation is proposed as a composition of stages, where each stage involves a selection from a range of possibilities that are appropriate for the task (eg. the goal of the task, the appropriate muscles to use). The components of these transformations (sensory influences, variability) are designed in line with experimental data. Our approach accounts for sensory effects and muscle properties, along with the variability of the process (across trials and individuals). It can provide a clearer understanding of the functional deficits that occur from ALS, stroke, or sensory neuropathy introduced by the absence of components in this representation. It allows otherwise purely cortical, spinal, or biomechanical findings to be described in terms of the entire motor control system, and hence provide insights into motor control in both dynamic and passive scenarios without the need to eliminate sources of variations. [1] Song, Y., Hirashima, M., & Takei, T. (2022). Neural network models for spinal implementation of muscle synergies. Frontiers in Systems Neuroscience, 16. [2] De Santis, D. (2021). A Framework for Optimizing Co-adaptation in Body-Machine Interfaces. Frontiers in Neurorobotics, 15, 40.

2-B-16 Motor cortical activity in a control space predicts muscle state-dependent cortical influence during naturalistic behavior

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The motor cortex plays an important role in the production of complex and agile movements that cannot be driven by the brainstem or spinal cord alone. Yet long-standing questions concerning how and when the motor cortex steers limb movements remain unresolved. Traditional approaches have lacked the precision required to study cortical influence on the timescale at which movement unfolds. In addition, behavioral paradigms typically emphasize simplified movements that become increasingly stereotyped through training. Recent studies, however, suggest that these behaviors may engage motor circuits differently than those used to negotiate the unpredictable sensory stimuli inherent to real world environments. We have therefore developed a naturalistic climbing paradigm to examine how motor cortical firing dynamics vary in a behavior that involves a wide range of non-stereotyped forelimb movements and is central to a mouse's natural movement repertoire. Using this paradigm, we first examined how motor cortical output drives muscle activity in real time. As they climbed, we randomly and sporadically inactivated the caudal forelimb area (CFA; mouse M1) of transgenic mice expressing channelrhodopsin2 in inhibitory interneurons, and simultaneously recorded forelimb muscle activity using electromyography (EMG). To achieve sufficient statistical power in measuring inactivation effects, we defined trials using 50 ms segments of EMG preceding CFA inactivation and equivalent epochs when CFA was not inactivated (controls). Dimensionality reduction on these segments yields a 2D map where trials at similar muscle activity states are clustered. We then defined a grid across this map, and at each grid point computed trial-averaged EMG with trials weighted by their distance from the grid point. For each muscle, the effect of inactivation was then quantified by taking the difference between the changes in inactivation and control trial averages at each grid point. The resulting inactivation effect maps reveal that CFA's direct influence on motor output is specific to certain muscle activity patterns during climbing, and this pattern-specificity itself varies across muscles. To determine how the motor cortex exerts this state-specific influence, we used acutely implanted neuropixels to record activity from the CFA of mice for which inactivation maps had been computed. We embedded segments of EMG collected during these neural recording sessions onto the inactivation maps, and similarly calculated trial-averaged neural activity for each grid point. Linear regression showed that CFA activity precisely predicts inactivation effects for each recorded limb muscle. Using partial least squares and canonical correlation analysis, we find that the activity predicting CFA influence across all muscle activity patterns during climbing exists in a low-dimensional activity subspace (control space).

2-B-17 Neural integration of movement order and timing occurs during motor sequence execution, but not planning

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Movement sequences are an integral part of everyday skill production such as writing, typing, and sports. Depending on context, sequence production requires flexibility regarding the order and timing of constituent movements, which are transferable sequence features and separable in premotor and parietal areas during execution. Whilst sequences can be decoded from the planning period in those areas, it is unknown how sequence order and timing integration unfolds from planning to execution. In a pre-registered study (osf.io/g64hv) we used multivariate pattern analysis of surface-reconstructed fMRI data to investigate the integration of order and timing in healthy participants during planning and execution, focusing on pre-defined regions of interest (ROIs) on the premotor to parietal axis. 24 participants produced four 5-element finger sequences comprised of two finger orders and two temporal interval orders (timings) from memory with their right hand on a force-transducer keyboard following two days of training. Sequences began with the same finger and were matched in target speed. In each trial, the sequence to be produced was cued by a unique abstract image. FMRI activity related to planning was sampled from 'no-go' trials where sequences were cued but not produced, and execution-related activity was sampled from 'go' trials, where sequences were cued and then produced. A linear discriminant analysis was used to identify information related to order, timing, and their non-linear integration, independently across planning and execution. Above-chance decoding accuracy in contralateral premotor to parietal ROIs was probed. During preparation, only order decoding was found in posterior superior parietal lobule (p=.036). During production, above-chance decoding accuracy was widespread, primarily driven by the integration of the two sequence features in dorsal premotor (p=.018), primary sensorimotor(p=.003), and anterior and posterior superior parietal regions (p<.001; p=.012), alongside the emergence of timing-related patterns in ventral premotor (p=.018), supplementary motor (p=.036), and anterior superior parietal regions (p=.042). No significant decoding of sequence features was found in the primary motor cortex in line with recent findings. A 3-way ANOVA between phase, classifier, and region showed a significant main effect of phase (F(1,23)=9.49, p=.005) and a significant interaction of phase by classifier (F(2,46)=10.34, p=.044) which was driven by an increase in integration during the execution period (p=.003), suggesting an overall shift towards integration from planning to execution. Our results show a generalised dependency on trial phase, with a widespread state switch within the same cortical regions from a separation of order and timing control during planning, to holistic integration during execution, indicative of a shift from high-level to low-level hierarchical control.

2-B-18 Reorganization of distinct low-frequency and beta networks of neurons underlies different behavioral states and conditions in monkey fronto-parietal cortex

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An essential function of the brain is to transform perceived information into the generation of movements to interact with the environment. This process requires the selection of relevant perceptual information, which needs to be flexibly transformed into movement related activity according to the behavioral demands. Rhythmic co-activation of neurons, referred to as oscillatory synchrony, has been proposed as a mechanism for selective behavior-dependent information processing. Yet, several fundamental questions remain elusive about how changes in the oscillatory network of neurons relate to flexible transformation processes. During behavior-dependent processes, it is unknown whether the same population of neurons synchronizes in different oscillatory frequencies or whether distinct subpopulations of neurons exist that only synchronize in one frequency band. Moreover, it is not known whether the oscillatory dynamics in different frequency bands are lawfully related to different behavioral states and if so, how. Finally, it is unclear whether fine-scale reconfigurations of the oscillatory network structure are present at the neuron-level for different task conditions (e.g., different sensory inputs, movement plans or movement executions). The latter two questions are of particular importance, because state and condition dependent changes of the oscillatory network structure are a prerequisite for flexible information processing by oscillatory synchrony. To address this gap, we simultaneously recorded large populations of neurons and LFPs form the fronto-parietal grasping network (F5 and AIP), while monkeys performed a flexible sensory-motor grasping task. Behavior-dependent changes in the oscillatory network structure were estimated by calculating pairwise phase consistency between all neuron-LFP pairs over the time course of the task and across conditions. Neurons of the fronto-parietal grasping network were predominantly synchronized in either the low frequency band (3-6 Hz) or beta band (17-35 Hz), suggesting separate frequency-specific subnetworks. Over the time course of the task, neural oscillatory dynamics were tightly coupled to steady (passive fixation and movement preparation) and active states (visual observation and movement execution). However, the two frequency bands showed opposing temporal dynamics with strong beta synchrony during steady states and strong low frequency synchrony during active states. Furthermore, both low frequency and beta neurons showed strong changes in oscillatory synchrony for different context and grip type conditions. These changes were strongly diminished at any larger scale then neurons such as LFPs, suggesting that the total amount of condition dependent changes in oscillatory synchrony can only be detected at the neuron-level. This first insight into the spatiotemporal network structure of oscillatory synchrony at the neuron-level may provide a new basis for flexible information processing.

2-B-19 Wide-field Voltage Imaging of Fast Cortical Dynamics during Reaching in Mice

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Population imaging of cortex-wide activities has shed light on the cortical dynamics and functional networks of motor control (Quarta et al., 2022; West et al., 2021). To date, the majority of wide-field imaging studies utilize calcium indicators. The relatively slow kinetics of calcium sensors have left the investigation of fast cortex-wide dynamics at the time scale of limb kinematics an uncharted area. In order to better understand cortical activities of motor control with higher temporal resolution, we performed wide-field voltage imaging at 200Hz with a novel and improved voltage sensor, JEDI-1P. First, we demonstrated that JEDI reliably follows responses of air-puff stimulation of up to 60Hz in somatosensory cortex. Given that this finding establishes fast-frequency following of JEDI in vivo, we then imaged mice performing a reaching task cued for either right or left forelimb reach. The imaging data showed rich and fast temporal signals in the caudal forelimb area (CFA) orchestrating this decision motor behavior task. Even within CFA, we found variability between small regions of interest with distinct relations to motor execution. Pending detailed analysis of this rich dataset on fast cortical dynamics with voltage imaging is expected to provide further insights on how sensorimotor information is processed for generating dexterous movement. Quarta, E., Scaglione, A., Lucchesi, J., Sacconi, L., Allegra Mascaro, A.L. & Pavone, F.S. (2022) Distributed and Localized Dynamics Emerge in the Mouse

Neocortex during Reach-to-Grasp Behavior. J Neurosci, 42, 777-788. West, S.L., Aronson, J.D., Popa, L.S., Feller, K.D., Carter, R.E., Chiesl, W.M., Gerhart, M.L., Shekhar, A.C., Ghanbari, L., Kodandaramaiah, S.B. & Ebner, T.J. (2021) Wide-Field Calcium Imaging of Dynamic Cortical Networks during Locomotion. Cereb Cortex.

2-B-20 Distinct control processing of finger flexion and extension during dexterous behavior

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Finger dexterity, fundamental in our daily lives, is manifested by generation of multi-finger multi-directional patterns of muscle activity during various motor tasks. Although most everyday hand movements involve coordination of flexor muscles for both gross and fine activities (e.g., grasping, typing), the role that extensor muscles play in these types of movements is unclear. Here, we investigated two aspects of digit independence during flexion and extension in a single and multi-finger isometric force task: individuation - the degree to which all uninstructed digits remain still during instructed movement of a particular digit, and stationarity - the degree to which a particular uninstructed digit remains still during movements of all instructed digits. In Exp. 1, healthy participants (n=13) used a hand robot (Tyromotion's Amadeo®) and produced finger forces, each time with a different single finger, to maintain one of four levels (20,40,60, and 80% of the maximal voluntary contraction) in both the extension and flexion directions. Participants then performed multi-digit chords (2-digit, 3-digit, and 4-digit) in each direction. We found that during single-digit tasks, individuation and stationarity were significantly lower for extension (RM-ANOVA, p<0.0001). Interestingly, we found dissimilar involvement of the opposite muscle direction for uninstructed digits when comparing extension and flexion. While exertion of single-digit extensor forces revealed that in the uninstructed fingers, extensor muscles were primarily involved, single-digit flexor forces involved flexors of the adjacent uninstructed digits and extensors of the non-adjacent uninstructed digits. In the multi-digit task, accuracy was reduced for fingers during exertion of force in the extension direction (RM-ANOVA, p<0.0001), and chords with 2 or 3 digits were less accurate for both flexion and extension compared to chords with 1 or 4 digits. In Exp. 2, we tested whether mechanical coupling between digits contributed to movement of uninstructed fingers and thereby limited the ability to individuate finger extension. A single digit of each participant (n=20) was moved passively by the robot in each direction while measuring isometric forces of the unmoved fingers. Our data ruled out the possibility that mechanical coupling of the digit extensors explains the reduced individuation in the extension direction, suggesting a neural origin underlying the dissimilar control. Overall, our data indicates that control of single and multi-digit dexterous patterns is different between flexion and extension movements, supporting the hypothesis that neural control circuits for producing finger flexion and extension might be distinct.

2-B-21 Stimulus-locked muscle responses to visual disturbances are impacted by urgency and certainty to move

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The human brain is capable of producing rapid motor responses in less than 100ms when responding to a visual stimulus. These Stimulus-Locked Responses (SLR) can be difficult to elicit in all individuals and appear to be more prevalent under predictable conditions. Further, it was recently shown that reaching to a moving target is more successful in generating SLRs compared to previously used tasks of normal reaching or "target jump". Here, we used a fast feedback interception task (FFIT) in which the subjects' hand was represented with a paddle and they had to hit a ball moving towards them. In some trials, the ball was randomly jumped to the left or right and we systematically varied the time of the jump in order to vary the speed of the required motor correction (level of urgency). Electromyographic activity was recorded from shoulder and elbow muscles while two cohorts of participants were performing two experiments. In the first experiment, there were different numbers of trials in which the ball did not jump (no-jump trials), making participants uncertain about whether they needed to move or not (level of certainty). Different levels of certainty were tested for different urgencies in separate blocks (%0, %20, %40 and %60 no-jump trials and 250, 350 and 450ms time to reach), so that the effect of urgency and certainty could be investigated separately. For the same level of certainty, SLRs occurred slightly earlier, with bigger magnitudes for trials with greater urgency. In trials with the same level of urgency, being more certain about the need to move (less no-jump trials) led to greater prevalence and larger SLRs. In the second experiment, jumps with different urgencies were combined in the same blocks with two different levels of certainty (%0 - %40 no-jump trials). When the subjects were sure that they needed to move (%0 no-jump trials), they were able to modulate their response based on the urgency, showing stronger and faster SLRs for more urgent jumps. Notably, a common strategy when expecting a jump was to co-contract agonist and antagonist muscles during the trial. However, increased uncertainty when there were 40% no-jump trials reduced co-contraction. Overall, our results highlight SLRs are more prevalent when there is a high certainty and urgency to respond to attain behavioral goals.

C – Posture and Gait

2-C-22 Predicting vertical ground reaction forces from 3D accelerometery using reservoir computers leads to accurate gait event detection

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Accelerometers are low-cost measurement devices that can readily be used outside the lab to record large amounts of data. However, determining isolated gait events from accelerometer signals, especially foot-off events during running, can be a challenge and typically involves peak detection based and pre-selection of epochs of interest. We present a proof-of-concept two-step approach where machine learning serves to predict the shape of vertical ground reaction forces (vGRFs) from accelerometer signals, followed by force-based event detection for walking and running data. Shank accelerometer data were obtained from five young adults (mean ± SD, 24.2 ± 2.5 years) during comfortable walking and running on an instrumented treadmill to simultaneously record ground reaction forces. A reservoir computer was trained to predict vGRF waveforms based on shank accelerometer data along the direction of maximum variance (the leading principal component of the 3D accelerometer signals) and the derived velocity and position. For each trial, 25% of the continuous data were selected for testing and validation, respectively. The remaining 50% were segmented into strides and pooled across trials and mode of locomotion and used for training. This was repeated 100 times with a random draw each time. We also verified the machine learner's capacity to predict separate trials using a leave-M-out cross-validation with M = 5. The reservoir computer performed exceedingly well at predicting continuous vGRF waveforms after training on segmented data $R^2 = 0.97 \pm 0.001$, $\varepsilon = 5.2 \pm 0.4\%$ (mean ± SD). Foot contact (foot off) was equally high with an accuracy (mean absolute error) of 9.8 ± 0.7 ms (9.8 ± 0.8 ms). The sampling frequency of the accelerometers was 2000/14 Hz and thus, the best possible performance has 7 ms (1 frame) accuracy. Results of the leave-M-out cross validation did not match those of pooling the strides across participants, but it still performed very well ($R^2 > 0.88$). A single accelerometer placed on the shank combined with a reservoir computer proved to be highly accurate in predicting vGRF waveforms and step events during locomotion. By just training a small number of strides, the machine learner can accurately predict continuous data which is particularly beneficial for use outside the lab. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no 715945 Learn2Walk) and from the Dutch Organisation for Scientific Research (NWO) VIDI grant (016.156.346 FirSTeps).

2-C-23 Postural sway characteristics of professional dance couples - partnering effects

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Ballroom dance tournaments are very sophisticated competitions, where male and female partners as couples maintain a hand hold position and move in harmony through the dance floor. The scientific literature contains many studies on the balance of professional dancers, although these analyses usually concern dancers as individuals. Considering the fact of the utmost importance of the unison in the dance between the couple we believe that this is especially interesting to assess dancers as a couple, rather than as a solo partner. In addition, it is important to use such measures of equilibrium that will reflect different neurophysiological and mechanical factors. The aim of the study was to identify differences in the mechanism of postural control in competitive ballroom dancers when standing solo and with a partner during specific swing position. Seven competitive dance couples participated in the study. Force plate was used for balance assessment. The experimental procedure comprised 4 dance position characteristic of swing dances: standard, preparatory , chasse and contra check position. These positons were staged twice: solo and with a dance partner. The assumption of the assessed position was precedented by dance phase after which the participants were instructed to freeze on the force plate and hold the position for 30 seconds. The dependent variables analyzed in this investigation were velocity of COP (v-COP) and the ratio of velocity of rambling to the COP (RM/COP) and trembling to COP (TR/COP). Standard measures of COP showed no significant difference in velocity of COP between standing solo both for the male and female dancer, and standing with a dance partner during standard, starting and chase position $p > 0.05$. However, during contra check position the female dancer obtained significant higher values of velocity of COP compared to the male dancer and to the couple ($p > 0.05$). Rambling and trembling COP decomposition showed a significant main effect of partnering (female-solo, male-solo, couple) on ratio velocity RM/COP and ratio velocity TR/COP during four dance position. During standard and stating position female and male dancers were characterized by higher values of the velocity RM/COP ratio and lower values of the velocity TR/COP ratio compared to standing with a partner. During chasee and contra check position female dancers presented significantly lower values of the velocity TR/COP ratio compared to standing with a partner. Partnering has a huge impact on the changes in the effect postural control of the dance couple. Interestingly, it is visible, that the rambling components of the velocity decreases when dance partners are standing together and at the same time trembling components of velocity increases. According to the theory standing behind the rambling and trembling decomposition, an increase in trembling components could indicate a higher reliance on spinal reflex, which would suggest grater automaticity.

2-C-24 Cerebellar population recordings during mouse locomotion

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The cerebellum is critical for locomotor coordination, but it is still not well understood how locomotor signals are represented within the cerebellum, or how cerebellar circuit computations enable coordination across the body. Recent work from our lab (Marques, Ramirez et al., NCM 2022) suggests that single Purkinje cells (P-cells) are modulated by multiple limbs during locomotion, and that this could facilitate cerebellar control of interlimb coordination in dynamic environments. That work raises important questions about how this nonlinear mixed selectivity is constructed from afferent inputs, and how this information can be used for real-time control. To address these questions, we are recording cerebellar population activity during locomotion in head-fixed mice with Neuropixels probes. We use spike waveforms, spiking statistics, and probe location and depth to identify recordings from putative Purkinje cells, mossy fibers, granule cells, interneurons, and deep nucleus neurons. Consistent with previous work, we find that most units show clear modulation to the locomotor stride cycle. Moreover, we also observe prominent responses associated with specific locomotor events such as paw swing and stance onsets, in agreement with recent findings. Moreover, different putative cell types show differential responses to locomotor events, as well as modulation such as burstiness or long pause periods. These responses hint at distinct functional roles throughout the cerebellar circuit. Preliminary analyses suggest that locomotor kinematics are readily decoded from cerebellar population activity, showing that paw movements are faithfully represented in the cerebellum. Yet this success could be driven mostly by strong correlations in paw kinematics arising from intrinsically low-dimensional behavior. To test this, we first performed dimensionality reduction of paw positions and confirmed that gait kinematics can be summarized in a low-dimensional space; a direct consequence of phase-locked locomotor patterns. Next we asked whether the same was true for neural data, in light of neocortex findings showing low-dimensional manifolds related to behavior. Critically and contrastingly, our results suggest that neural activity in the cerebellum during locomotion seems to be characterized by high-dimensionality. Such high-dimensional population activity may help ensure robust and flexible motor control in variable contexts.

2-C-25 The influence of anxiety on feedforward locomotor (de)adaptation

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Background and Aim: Humans quickly learn to adapt their movements in response to sensorimotor perturbations. This is a process known as motor adaptation and allows the performer to adjust their movements in a predictive, 'feedforward' manner, rather than relying on sensory feedback to correct movement after the perturbation has occurred. However, if deployed inappropriately, feedforward control can disrupt motor performance. It is therefore important that feedforward motor patterns can be quickly updated in situations where they are no longer appropriate. We investigated how anxiety affects such process. Methods: Young adults (n=28) performed a locomotor adaptation task in which they learned how to safely step onto a moving surface whilst in a virtual environment. Participants learned the task whilst immersed in either an anxiety-inducing (raised 25-m above ground; 'Anxiety Learning' group, n=14) or control virtual reality environment (ground level; 'Control' group, n=14). After the learning phase, participants then performed a de-adaptation phase, in which they stepped onto the surface which was now stationary (rather than moving). Both groups performed the de-adaptation trials

in the control (ground level) environment, and participants were unequivocally reassured that the surface would not move during these de-adaptation trials. Results: Participants in both groups displayed a pronounced 'locomotor after effect' in the first de-adaptation (stationary platform) trial. This was characterised by participants initiating - in a feedforward manner - the postural and neuromuscular responses required to step safely onto the moving surface in the previous trials; followed by a stumble-like response following foot contact onto the now-stationary surface. However, participants in the 'Anxiety Learning' group displayed a persistence of these inappropriate feedforward locomotor behaviours into subsequent de-adaptation trials, whilst Control subjects were able to de-adapt after a single stationary trial. Conclusion: These findings highlight that anxiety can disrupt locomotor (de)adaptation, leading to the persistence of inappropriate feedforward behaviour. We propose that these findings may account for the persistent inappropriate feedforward locomotor behaviours observed in clinical populations who are anxious about falling, e.g., patients with functional gait disorders and overly cautious gait in fearful older adults.

2-C-26 Humans optimize energy and time for point-to-point walking movements

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Humans often perform voluntary movements such as walking at self-selected speed and duration. The speed trajectories of some point-to-point tasks, such as upper extremity reaching and visual saccades, are thought to minimize objectives such as accuracy or smoothness. Such objectives do not, however, explain point-to-point walking bouts. Steady walking appears to minimize energy expenditure per distance traveled, but there is no governing principle for the speed trajectories of point-to-point walking bouts, nor for how those speeds are influenced by task urgency or movement vigor. We propose an optimization principle for walking that resolves both speed trajectories and durations, by combining energy and time. The energy cost is the total energy expenditure over the whole walking bout, and the time cost is a penalty linear in task duration, with an individual-specific coefficient. This energy-time cost can predict an entire speed trajectory over a given distance, including acceleration, deceleration, and overall duration. Both energy and time appear important for walking, and could influence arm and eye movements as well. We predicted speed profiles with a computational, dynamic walking model. The minimization objective is expressed as the energy needed for (ankle) push-off each step, plus a cost proportional to task duration, with a coefficient for an individual's valuation of time. The optimal trajectory is dictated by walking dynamics, where the swing leg behaves like a pendulum and the stance leg like an inverted pendulum, and push-off work is needed to power walking and modulate speed. The model predicts a somewhat rounded speed profile, with a gradual acceleration and deceleration, and a peak about halfway through the walk. Steady walking speed emerges as an optimum for longer walks. The objective's coefficient for duration increases or decreases the overall speed, but does not affect the speed profile's shape; it may be considered a time valuation for the energy one is willing to spend to save a unit of time. We tested model predictions with an experiment (N=10) where healthy adults were instructed to walk prescribed short distances (2 - 20 steps). Walking speed for each step was measured using inertial measurement units attached to the feet, and the resulting speed trajectories compared to model. There was good agreement in the overall shape of the speed profiles, as well as the relationships between peak speed and distance ($R^2 = 0.8620$), and walking duration and distance ($R^2 = 0.9835$). Individuals differed in walking duration, but their trajectories were consistent with an individual-specific valuation of time. This objective can predict walking speed trajectories, and can potentially apply to reaching and saccade movements as well. Both energy and time could be important for general, goal-directed movements.

2-C-27 Biomimetic stimuli from a vestibular prosthesis improve postural control in a nonhuman primate

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Dynamic balance requires rapid and precise integration of vestibular, somatosensory, and visual inputs. Patients experiencing bilateral vestibular loss (BVL) frequently complain of postural imbalance and remain at high risk of falls even following rehabilitation. An innovative solution to replace vestibular function is the vestibular prosthesis, which bypasses damaged neuroepithelial tissue in the vestibular periphery to stimulate vestibular afferents directly. In clinical trials, vestibular prostheses improve posture, gait, and quality of life. However, they do not yet effectively restore natural function. We hypothesize that the utility of the prosthesis may be enhanced by applying mapping functions between head motion and pulsatile stimulation rate that better mimic the response of endogenous vestibular afferents. Thus, here we investigated the effects of applying naturalistic prosthesis mapping functions in a primate model of posture during transient support surface perturbations. We first established that rhesus monkey postural responses to support surface motion resemble those of humans. Motion of the monkey's head was measured using a wearable IMU, ground reaction forces measured by a force plate, and joint positions were estimated using video-based markerless motion tracking (DeepLabCut). The monkey's responses were consistent with those observed in other animals, tilting against the direction of support surface tilt to regain an earth-vertical head and body orientation. To determine the contribution of vestibular signals to dynamic postural responses, we then applied these support surface perturbations to a monkey with BVL. The BVL monkey exhibited misdirected upper body and head movements, reacting in the opposite direction to the normal monkey. Both head movements and torque were also greater in magnitude for the BVL monkey than normal. Finally, we repeated the perturbations while delivering vestibular stimulation to the BVL monkey via vestibular prosthesis using mapping functions derived from the natural responses of regular and irregular vestibular afferents. We also compared these mappings with a static mapping like those used for clinical trial participants. The animal began exhibiting consistent responses to support surface perturbations within 30 trials after starting the stimulation. When vestibular stimulus profiles were generated using irregular afferent mapping, the misdirection of postural responses was corrected, and the animal began responding in the same direction as a normal animal. In contrast, both regular afferent mapping and static mapping reduced the magnitude of postural responses but did not reverse their direction. This result is congruent with prior results which indicate that irregular afferents are the primary contributors to vestibulo-spinal reflex pathways. Thus, leveraging knowledge of the vestibular system's endogenous dynamics improves behavioral outcomes in a clinically-relevant model of vestibular loss.

2-C-28 Optogenetic perturbation of distinct cerebellar nuclei differentially affects coordinated locomotion in mice

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Smooth and efficient walking requires the coordination of movement across different parts of the body. The cerebellum plays an essential role in this process. Previous work suggests a medial-to-lateral

functional organization of cerebellar output, based in part on the afferent and efferent projections of the individual deep cerebellar nuclei (DCN). We previously developed LocoMouse, a quantitative framework for mouse locomotor coordination, and used it to identify specific, cerebellum-dependent features of this complex, whole-body behavior in mutant mice (Machado, Darmohray, et al., eLife 2015; Machado, et al., eLife 2020). Here, we combine this approach with optogenetics to ask how different output regions of the cerebellum differentially contribute to locomotor coordination. We expressed ChR2 selectively in cerebellar Purkinje cells and stimulated their terminals in the medial, interposed, or lateral cerebellar nuclei of freely walking mice. Electrophysiological recordings showed similar effects on DCN activity across the different cerebellar nuclei in response to optogenetic stimulation. The behavioral effects of this perturbation, however, varied systematically across the different nuclei. Overall, acute stimulation of Purkinje cell terminals in the medial and interposed nuclei dramatically perturbed ongoing locomotion, while optogenetic manipulation in the lateral nuclei had no discernable effect. Beyond this, we found that optogenetic perturbation of the medial cerebellar nucleus drastically reduced ongoing locomotion during the entire stimulation period, while in the interposed, behavioral disruption was transient and limited to stimulation onset. 3D paw trajectories across all paws during the stimulation and non-stimulation periods revealed differential behavioral outputs depending on the phase of the locomotor cycle within which the stimulation began. The pronounced and differential behavioral effects we observe upon optogenetic stimulation of Purkinje cell projections to the DCN are consistent with a medial-to-lateral functional organization of cerebellar output. They also underscore the challenges associated with interpreting the behavioral consequences of acute optogenetic stimulation within highly recurrent neural circuits during dynamic, whole-body behaviors.

D - Integrative Control of Movement

2-D-29 Ocular eccentricity affects subjective visual vertical perception in health and disease

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Body coordination is critical when interacting with our environment, requiring appropriate integration and reweighting of visual, vestibular and somatosensory cues. One's subjective perception of gravity relies on such integration along with prior knowledge about head orientation in space. It is a crucial aspect of space representation and important for static and dynamic postural control. Age-related vestibular deficits affect mobility and contribute to increased visual dependence for postural control. These changes may be exacerbated by eccentric viewing, leading to higher fall risk for older adults with central vision loss (e.g., due to age-related macular degeneration, AMD) who often adopt eccentric eye positions to exploit their peripheral retina. Visual information is transformed, from retino-centric to head- and body-centered coordinates according to task demand. In addition to vestibular signals, the eye-in-orbit position is a reference for egocentric perception. Thus, an incomplete re-referencing of eye/retinal positions with respect to the body in AMD may affect individuals' interaction with their environment. To determine the effect of eye eccentricity alone, we first tested young adults performing subjective visual vertical (SVV) tasks using central and eccentric eye position. Next, we investigated the effect of central field loss (CFL) due to AMD, while controlling for aging and disease progression, by testing individuals with monocular CFL. We compared SVV judgements during binocular (analogous to central viewing in young adults, since foveal fixation is used with the healthy eye) and monocular viewing with their affected eye - as they adopt an eccentric fixation due to CFL. Participants judged the orientation of a briefly flashed rod, tilted with respect to gravity, with and without a misleading visual context. Depending on the viewing condition, young adults fixated a target centrally or eccentrically, to the right. Eye-tracking was used to monitor fixation. The target appeared centrally in both viewing conditions for those with CFL. Responses were analyzed to determine bias in participants' SVV. In young adults, we found a significant effect of eccentricity, with the bias shifting in the direction opposite fixation and of visual context, with the bias shifting in the direction of the visual context. In participants with monocular CFL, there was an influence of monocular versus binocular viewing and of the visual context, with bias shifts of up to 7°. These data suggest that eccentric viewing affects SVV in both healthy younger adults and older adults with CFL. Our data also show that despite visual impairment, those with CFL are still reliant on visual orienting cues. The interaction of eye position and visual dependence will be important to consider further in the design of rehabilitation tools for individuals with AMD who have eccentric fixation and may have increased visual dependence.

2-D-30 Adaptive Eye-Hand Coordination when Manipulating and Monitoring the Environment in Parallel

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Research on eye-hand coordination has focused on action tasks performed in isolation. However, real world actions are often performed at the same time as perceptual tasks that compete for gaze. Here we examined how eye and hand movements are adapted when an action task is performed in parallel with a visual detection task. Participants repeatedly grasped a ball located at the base of a tube, inserted it into a slot in the tube, and then returned their hand to the start position before repeating this action sequence. While performing this ball-drop task, participants simultaneously monitored a display to detect letter changes that occurred, probabilistically, every 1.5 to 6 seconds. Participants were rewarded for each ball insertion and penalized for each missed letter change. To vary visuomotor demands, participants performed the ball-drop task with either their fingertips or a grasped tool (i.e., tweezers). We hypothesized that participants would adapt their eye and hand movements in two ways. First, we predicted that participants would allocate gaze to prioritized key control points, representing subgoals of the action task. Second, we predicted that participants would learn the statistics of the letter changes and exploit this knowledge when timing their hand and eye movements. We found support for both hypotheses. First, we found that frequent gaze shifts away from the display to either the ball or the slot were linked to the action task subgoals. Specifically, the onsets of ball and slot fixations were temporally coupled to ball grasp and slot entry. The frequency of ball and slot fixations depended on visuomotor demands. When using a hand-held tool, gaze was almost always directed to both the ball and slot whereas, when using fingertips, gaze was often directed to the slot but seldom to the ball. Second, we observed that participants modulated the timing of their reaching movement, at the start of each repetition of the ball-drop task, such that the probability that a letter change would occur at the time of ball grasp was reduced. In addition, we found that participants were more likely to allocate gaze to the action task during the 1.5 second 'silent period' between successive letter changes (during which a letter change could not occur). Previous work on eye-hand coordination has identified several functions served by gaze when performing manual tasks, including locating targets, directing and guiding the hand (or object in hand), and checking action outcomes. We show that, in our task, guiding and to some extent checking are the prioritized functions. Previous work on visual perception has shown that people can learn the temporal regularities of externally determined perceptual events to optimize performance

in detection tasks. Here we show that, in addition, people can actively modulate their hand and eye movements to take advantage of these learned regularities when acting and perceiving in synchrony.

2-D-31 Anterolateral motor cortex involvement and cortical network processing in a cued left/right lick motor task in mice

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Previous studies have established causally impactful participation of a thalamo-cortical loop involving anterolateral motor cortex (ALM) and ventromedial thalamus (VM) in the execution of lick decision making tasks with a delay period in mice. In our current studies we are expanding our knowledge of how this task is processed in mouse cortex both at the scale of dendritic dynamics in ALM through optogenetic manipulations, 2-photon (2p) imaging, and modeling, as well as network processing in cortex-wide networks with wide-field voltage imaging. A particular interest in understanding VM input to layer 1 (L1) in ALM depends on the relative balance between direct activation of apical tufts of pyramidal cell dendrites and L1 inhibitory interneurons. Since previous work has specifically implicated GABA-B receptors in the suppression of apical dendritic calcium spikes we used the GABA-B blocker Baclofen applied locally to the surface of ALM during lick decision task execution to study the behavioral relevance of this mechanism. We found that this GABA-B block leads to an increased error rate of the mouse licking at the wrong side, which appears in a clustered manner, indicating perseveration. In different experiments, GCamp8m was sparsely expressed in L5 pyramidal neurons for 2p imaging during the task. Dendritic activation shows a side specific ramping prior to lick execution, indicating dendritic involvement in task processing. Preliminary modeling work using a modified version of an established NEURON model of a L5b pyramidal neuron demonstrates that different basal and apical input contingencies for lick task related input patterns can induce a rich repertoire of apical dendritic calcium activity. Overall, a picture begins to emerge that apical dendritic processing is critical for the processing of VM input to ALM in the framework of lick decision making in mice. To determine cortical network integration of lick task execution we used the novel genetically expressed voltage sensor JEDI for brain-wide imaging. We find that lick task processing is widely distributed across many cortical areas, and includes distinct spatial and temporal patterns of sensory responses as well as ramp components prior to lick initiation. These results indicate cortex-wide participation in lick task processing.

2-D-32 Motor control beyond reach ? How humans hit a target with a whip

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Humans are strikingly adept at manipulating complex objects, from tying shoelaces to cracking a bullwhip. These motor skills exhibit highly nonlinear interactive dynamics at extremely fast speed that defy reduction into simpler 'parts". Yet, despite advances in data recording and processing, research in motor neuroscience still prioritizes experimental reduction over realistic complexity. This study embraced the fully unconstrained behavior of manipulating a 1.6m bullwhip to hit a target at a 2.2m distance. We examined both hand and whip dynamics to understand how humans handle this prodigiously complex object to hit a target accurately. The overall hypothesis was that humans simplify these complex dynamics to render the high-dimensional nonlinear object controllable and predictable. 16 participants with widely ranging experience performed 5 blocks of about 30 trials each in two task variants: hitting the target with a single discrete movement, and in a continuous rhythmic sequence keeping the whip in the air. Kinematics of the subjects' dominant arm and the whip were measured with 3D motion capture; 10 customized markers enabled recording of the high-speed motions of the whip. Unsurprisingly, given the highly redundant hand-arm system, significant inter-individual differences appeared. However, for almost all participants performance in the discrete style was more accurate, while rhythmic performance showed some improvements over blocks. Rhythmicity of the action exhibited a surprisingly low variability that decreased across blocks, similar to synchronizing movements to a metronome, suggesting an emerging dynamic attractor that simplified the complex hand-whip interaction. Further analyses adopted the object-centered task-dynamic approach from our previous work and focused on the whip's initial configuration (extension and orientation) at peak speed and its unfolding towards the target. Specific hypotheses were: a) extension and orientation of the whip at the beginning of the throw correlate with hitting error, and b) regular kinematic patterns emerge during the whip throw. Despite widely differing whip speed profiles, whip extension and orientation at peak hand speed predicted performance error, suggesting that humans accomplished the task by setting initial conditions. Both discrete and rhythmic styles featured a cascade-like unfolding of the whip, consistent with energy propagated along the whip. These results suggest that subjects indeed strove to simplify this prodigiously complex dynamic object, probably because smooth evolution of the whip made the infinite-dimensional object predictable and therefore manageable. These first steps into highly complex interactive behavior may stimulate and inform further studies on human control of realistic behaviors.

2-D-33 Neural signatures in the fronto-parietal reach network for planning subsequent reaches in a sequential action selection task

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Performing everyday tasks often require a sequence of actions. Knowing which movements will follow, allows us to prepare for an upcoming action before the first action has been executed. Here we ask in how far areas of the fronto-parietal reach network show proactive movement planning activity during ongoing actions in preparation of a consecutive movement. We trained rhesus macaques to perform a memory-guided sequential action selection task on a touchscreen. Animals were instructed to subsequently reach to two cued targets in a defined sequence. For each target four possible locations were arranged in a horizontal line. In each trial two possible target locations for each reach were shown in different colours, one serving as the target the other serving as a distractor. Colour cues indicated the correct reach target and disappeared with the go cue. The correct target colour for both reaches was known from trial start. During proactive trials, both targets and distractors were shown in colour from the beginning. In sequential trials, the target and distractor for the second reach were shown in grey until the end of the first reach. Behaviorally, proactive compared to sequential trials resulted in shorter reaction time towards the second reach (pro: 283±69ms (m±sd), seq: 469±116ms), suggesting that the animals proactively prepared the second movement if possible. We recorded neural activity in the primary motor cortex (M1), parietal reach region (PRR) and dorsal premotor cortex (PMd) and analysed their spatial selectivity with respect to the horizontal direction of the upcoming reaches. As a result, spatial selectivity for the second reach target was already expressed during the reach to the first target in proactive trials, while it could only be observed after the first reach was completed in sequential trials. We used a SVM to decode the spatial position of the second reach target in time bins aligned to the touch of the first target separately in the three different brain regions and the two trial conditions. In sequential trials the spatial position of the second reach target could only be decoded after the first target had been touched, as only then the information on the target position was known to the animal. In contrast, during proactive trials, the decoding performance already increases from chance level roughly 150ms before touching the first target from signals in PRR and PMd. In contrast, the decoding performance from signals in M1 are similar for proactive and sequential trials, meaning that the spatial position can only be decoded after the first reach has been completed. Our results suggest that reaches are planned in a proactive manner, making use of the information about following movements in an action sequence before the ongoing action has been completed, and that this information is available with comparable lead-time in parietal and premotor areas.

2-D-34 Context coding in the mouse nucleus accumbens modulates motivationally relevant information

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The nucleus accumbens (NAc) is an important contributor to the motivational control of behavior, acting directly through output pathways involving brainstem motor nuclei ("limbic-motor interface") and indirectly through return projections within cortico-striatal loops. Accordingly, neural activity in the NAc is thought to track fundamentally value-centric quantities linked to reward and effort. However, lesions or inactivations of the NAc lead to deficits that are not straightforward to explain from a purely value-centric perspective. In addition, prominent corticolimbic inputs suggest that the NAc has access to non-value signals that would be expected to not only inform its function but help shape its neural activity. This raises the question of if, and how, non-value signals are encoded in NAc, and if found, how such a signal relates to classical value correlates. To address this issue, we trained 4 mice to perform a biconditional discrimination task using odor cues, in which two different "context" cues determine whether a subsequent "target" cue will be rewarded. Thus, in context O1, O3 but not O4 is rewarded, whereas in context O2, O4 but not O3 is rewarded. We recorded ensembles of NAc neurons and tested whether there is coding of the (reward-independent) context cues at the single cell and population level. We found coding for context cues in 26% of all recorded units, that could not be attributed to differences in the perceived values of the cues. Next, we sought to determine the relationship between this context signal and classical value coding, using population analysis tools to test if context coding can be used to inform subsequent value-related processing of target cues. We found that the population level context signal occupied a neural subspace orthogonal to classic value representations, suggesting that both can be read out without interfering with each other. Despite this independence, the context signal could explain a significant proportion of variance in the subsequent value signal in response to a given target cue. Together, the finding of clear non-value correlates suggests a revision of the value-centric account of NAc neural activity, encouraging future work to explore the precise computational role of these signals. Furthermore, the functional link at the population level between the context signal and value signal supports a circuit-level gating model for how the NAc contributes to behavioral flexibility and provides a novel population level perspective from which to view NAc computations.

2-D-35 Inferring function from information transfer during coordinated eye and arm movements

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The function of a module embedded within a circuit can be described by the relationship between its output and input, observed across a sufficiently broad range of circumstances. When studying the brain, this sort of information can be difficult to measure and characterize. An alternative approach is to deduce function based on the flow of information between modules. Input and output of a module are difficult to measure but we can infer information flow by looking at shared information across modules. In this study, we apply this approach to the Lateral Intraparietal area (LIP) and the Parietal Reach Region (PRR) to better understand their relative roles in planning coordinated eye and arm movements. We simultaneously recorded spikes and local field potentials (LFPs) from LIP and PRR while rhesus macaques planned and executed different types of coordinated eye and arm movements. We assayed communication between these two areas using time-lagged spike-LFP coherence and LFP-LFP spectral Granger causality. Somewhat surprisingly, we find that PRR transmits more task-specific information to LIP than vice versa, particularly during movements involving a reach. This is true when transmission is assayed using either coherence or Granger causality. It is true in the period immediately following a movement instruction as well as during a prolonged delay interval while the movement is being planned. This suggests that PRR plays a commanding role in determining the spatial goals of coordinated eye and arm movements, instructing LIP of those goals rather than vice versa. This is consistent with LIP playing an oculomotor-specific role rather than a more sweeping role in target selection. More generally, we argue that using either time-lagged spike-LFP coherence or LFP-LFP Granger causality can be informative of the pattern of information flow between brain areas, and that the direction and magnitude of this flow across multiple task types can in turn be informative of the roles that these brain areas play in those tasks.

E – Disorders of Motor Control

2-E-36 Postural instability in DYT-TOR1A dystonia dynamically dependent on sensory feedback

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There is significant evidence that there are components of the neural control of moving and holding that are segregated anatomically and functionally within the nervous system. Dystonia is a movement disorder in which disordered postural control dominates the clinical picture. In this study we explored the influence of sensory feedback within a prolonged hold state. We studied the symptomatic arm of patients with DYT-TOR1A related dystonia. Such patients are rare but can be used a pure model for dystonia as the isolated dystonia is due to a homogenous genetic mutation. Ten patients with DYT-TOR1A dystonia and 30 controls held the handle of a planar robotic arm to make 80 point-to-point reaching movements with their symptomatic right arm. Reaches were made from a central start box to eccentric targets (15°, 135°, 225° or 315°). Position was then held within the target box for 10s. Visual feedback during the hold state was pseudo-randomized (present/not present). During the hold phase, in the dystonia group, increased fluctuations (movements associated with a defined velocity peak) consistently interrupted postural stability. By the end of the hold phase a performance segregation across feedback conditions occurred in the dystonia group; with visual feedback there was high accuracy, low variability; with no visual feedback there was low accuracy and high variability. Postural fluctuations did not appear to be a result of accumulated positional error / drift. With vision patients could compensate such instability to keep accuracy in line with performance of controls however without vision a significant deterioration in postural accuracy was seen. Our results (re)open the interesting debate on whether the primary deficit in dystonia reflects a central instability in the neural control of hold and/or disordered afferent feedback. By shifting our experimental emphasis onto holding, rather than moving, the hope is that we are closer to defining biomarkers related to the symptomatic phenotype and shed light on mechanistic axes that can better inform our therapeutic interventions.

2-E-37 Deep brain stimulation frequency affects evoked potential delay, amplitude, and frequency components

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Deep brain stimulation (DBS) is an emerging treatment for movement disorders, including dystonia. While DBS has proven effective, not much is known about the mechanisms of action of the treatment method, nor of dystonia itself, which makes it difficult to provide the ideal treatment for each patient. Hence, this study aimed to shed light on these areas by investigating the effect of DBS frequency on evoked potentials (EPs) recorded in deep brain structures of dystonic patients. Externalized DBS leads were implanted bilaterally in 10 pediatric patients with dystonia selected for DBS treatment. Up to 6 leads per hemisphere were placed in target areas including the thalamus (ventral intermediate, VIM; ventral posterolateral, VPL; ventral anterior, VA; and ventral oralis, VO) and basal ganglia (globus pallidus interna, GPi; and subthalamic nucleus, STN), based on prior studies of clinical efficacy in patients with movement disorders when lesioned or electrically stimulated. Stimulations consisting of 3-V, 90-us pulses ranging between 9 and 250 Hz were delivered through conventional low-impedance macro-contacts. Neural data were simultaneously gathered through high-impedance micro-contacts, allowing us to record high-frequency neural components in the kHz range. Each recording was investigated for the existence of an EP, which, if found, was characterized by its amplitude, delay, and frequency components. These characteristics were then compared between stimulation frequencies. Preliminary results alluded to a clear effect of stimulation frequency on EP delay, amplitude, and frequency components. Stimulation frequency was found to be negatively correlated with EP amplitude, and positively correlated with EP delay - i.e., higher stimulation frequencies typically evoked smaller and more delayed neural responses. Moreover, as the stimulation frequency was increased, any high-frequency components of EPs seemed to reduce, inferring a possible cerebral low-pass filtering effect at higher stimulation frequencies. These trends of decreased amplitude, increased delay, and "low-pass filtering" of EPs at higher DBS frequencies may be related to refractory periods and oversaturation of neural receptors when stimulations are delivered at shorter intervals. Qualitative and/or computational models will be developed with the aim to explain the neural mechanisms behind this frequency dependency. Future work also involves confirming preliminary results through group analyses, including multivariate regression, which will allow us to determine whether these trends are more prominent e.g. in particular stimulation and/or recording regions, in anti- or orthodromic connections, or in certain subjects. These findings will help shed light on the dystonic brain's frequency-dependent response to DBS and provide insight into how we can use stimulation frequency to generate wanted neural response patterns to elicit the most effective clinical response to DBS treatment.

2-E-39 Pallidal beta activity correlates with stimulation-induced bradykinesia in dystonia patients

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Bradykinesia is a side-effect of chronic pallidal deep brain stimulation (DBS) in dystonia patients that is reversible upon cessation of DBS. In Parkinson's disease, bradykinesia has been linked to subcortical oscillations in the low beta band (Lbeta, 13-20 Hz) of basal ganglia structures. A neurophysiological correlate of stimulation-induced bradykinesia has not been described yet, but we hypothesize that Lbeta oscillations represent a symptom-specific signature and should thus be present in stimulation-induced bradykinesia of dystonia patients as well. Pallidal activity was recorded in 6 dystonia patients with pallidal DBS through sensing-enabled Activa PC+S pulse generators, at 5 timepoints within 5 hours following cessation of DBS. Before each recording, finger tapping was videotaped and extracted by markerless pose estimation using DeepLabCut. Averaged movement velocity was correlated with pallidal Lbeta activity using a mixed-effects linear model. After cessation of pallidal DBS, movement velocity significantly increased over time ($P<.01$). Pallidal Lbeta activity significantly predicted velocity ($P=.01$) within a linear mixed-effects model and explained 77% of the variance in velocity within and across subjects ($r = 0.88$, $P < .001$). This effect was frequency-specific for the Lbeta band. These findings suggest that pallidal Lbeta activity might be a biomarker for stimulation-induced bradykinesia in dystonia. Our results strengthen the hypothesis that subcortical Lbeta activity is a symptom- rather than disease-specific oscillatory pattern.

2-E-40 Unilateral and bilateral subthalamic nucleus deep brain stimulation improves motor function while impairing cognitive function during memory-guided reaching

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In people with Parkinson?s disease (PD), subthalamic nucleus deep brain stimulation (STNDBS) greatly improves motor function; however, it can impair cognitive function, especially when neural resources are greatly taxed. Memory-guided reaching provides a way to study motor and cognitive function. Reaching amplitude and velocity represent motor outcomes while error and reaction time (RT) represent cognitive outcomes. The spatial load, the number of targets one must memorize, or the temporal load, the delay duration for holding the memorized locations, can tax neural resources. Previously, we showed that unilateral, and to a greater extent bilateral STNDBS improved motor function but impaired cognitive function during spatially loaded memory-guided reaching. Here, we manipulated the temporal load to tax neural resources. We studied the effects of stimulation condition (DBS-OFF, DBS-LEFT, DBS-RIGHT, DBS-BL) and delay (500 and 5000ms) on memory-guided reaching amplitude, peak velocity, error, and RT. Participants with PD underwent bilateral STNDBS (n=11) and performed the task on average 8.3 months post-surgery. In complete darkness, using peripheral-vision, participants held in memory the location of a target for either 500 or 5000ms. When cued, they reached their right hand to the memorized location as quickly and accurately as possible. They performed the task over 4 days while off medication on 1 of the 4 stimulation conditions. The order of stimulation conditions and delay was random. Linear mixed models evaluated the effect of stimulation condition, delay, and their interactions. There was no significant interaction between stimulation condition and delay for any outcome; thus, only main effects of stimulation condition and delay are reported. Velocity was statistically adjusted for amplitude and error was adjusted for velocity. Stimulation Condition:

Relative to DBS-OFF, we found DBS-LEFT, and to a greater extent DBS-BL, increased amplitude and velocity. We also found that DBS-LEFT, and to a greater extent DBS-BL increased error relative to DBS-OFF. Stimulation condition had no effect on RT. Delay: Relative to the 5000ms delay, the 500ms delay increased amplitude and velocity, yet reduced error and prolonged RT. These findings confirm that unilateral, and more so bilateral STNDBS, improve motor function while impairing cognitive function during memory-guided movements with varying encoding delays. The novel finding of this study is related to a double dissociation effect of delay. Shorter delays tax working memory resources less and result in minimal decay of the signal that maintains the spatial information of the memorized target. This explains why reaches with shorter delays had lower error, and possibly why these reaches were longer and faster. Simultaneously, short delays tax attentional resources, resulting in a slower release of inhibition, thus prolonging RT.

2-E-41 The effect of age, sex, sport experience, and multiple concussion history on visuomotor performance.

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Sustaining a concussion can affect many aspects of daily life, including basic and complex motor performance. While long-term effects of any concussion are increasingly documented, less is known about the effect of multiple concussions on skilled motor behavior, and factors that may moderate the impact of these injuries. Our previous work in humans has consistently shown a decline in rule-based visuomotor performance (i.e., cognitive-motor integration) in those with a history of concussion (vs. no history), those with less sport experience, and older individuals. We have not specifically examined the effects of more than one concussion on behaviour. Here we characterize the cognitive-motor integration (CMI) performance of individuals as a function of all these factors. We hypothesized that those with multiple concussions would experience significantly greater neuropathological effects on the brain networks required for rule-based visuomotor performance, relative to those with one concussion. We predicted that variance in cognitive-motor integration performance (reflecting brain network function) would be accounted for by concussion group (one versus more than one), after accounting for age and experience. The effect of sex as a factor was exploratory. Methods: We analyzed a dataset of 223 asymptomatic individuals ages 9-53 years old (29.2% female, mean 18.9±7.0) with a history of 1-10 concussions (mean 1.7±1.4). To assess CMI performance, participants were tested on 2 visuomotor tasks where reach and gaze were spatially dissociated using two linked touchscreens: 1) a standard condition requiring direct interaction with visual targets, and 2) a dissociated non-standard condition requiring CMI (visual feedback reversal and motion). We performed a linear regression of our four factors on 6 kinematic CMI outcome variables. In contrast to our hypothesis, we found that only a significant percentage of the variance was explained by age and sport experience ($p<0.05$). That is, in individuals with any number of concussions, their level of skilled performance was mainly explained by developmental age and sport experience. In our younger, mainly select-level athletes. We suggest that motor developmental stage and skill experience provide brain network resilience that can compensate for concussion-related performance declines. These data further emphasize the clinical importance of accounting for developmental age and sport experience when assessing the effects of multiple concussion on complex visuomotor skill. Future work will look at older and retired athletes.

2-E-42 **Mechanisms of increased motor output following stimulation of the motor thalamus**

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Severe and permanent motor deficits caused by brain injury, like stroke, are the most common source of disability in the United States. Despite the large population size of affected individuals, intense physical therapy remains the only significant intervention, with limited impact on moderate to severe paresis. Neurostimulation, like deep brain stimulation (DBS), is a promising approach that may extend recovery beyond physical therapy. Indeed, stimulation of the motor thalamus, specifically ventro-oralis posterior (VOP) nucleus, has been utilized to successfully reduce motor symptoms in patients with essential tremor and Parkinson's Disease. The VOP is a thalamic relay for incoming cerebellar projections and outgoing connectivity to the premotor and motor cortex. Here, we sought to leverage stimulation of VOP as a potential target for DBS to treat post-stroke motor symptoms. We hypothesize that stimulation of VOP can potentiate postsynaptic potentials over the motor cortex (M1) and thus increase motor output. Using an acute setup in macaque fascicularis (N=3), we implanted a stereoelectroencephalography (SEEG) electrode into the arm and face areas of VOP, a stimulating probe within the arm region of the corticospinal tract in the internal capsule (IC), and a bipolar cuff on the radial nerve. We then recorded from multielectrode arrays in the primary motor and sensory cortices, linear probes in the cervical spinal cord, and intra-muscle EMG needles in the arm and face. Our group has found that IC stimulation elicits EMG activity consistent with voluntary motor control, enabling us to assess motor responses in anesthetized studies. When stimulating VOP alone, we observed increases in peak-to-peak local field potentials and peri-stimulus spike counts in the cortex, implying an increase in excitatory postsynaptic potentials. These volleys of evoked potentials were significantly stronger in motor cortex than in sensory cortex. We also observed antidromic volleys in the spinal cord approximately 1.5 ms after VOP stimulation, suggesting a potential antidromic recruitment of spino-thalamic axons. Despite the presence of this antidromic activation in the spinal cord, we did not see motor evoked responses in the upper-limb or facial muscles. It was only when we simultaneously stimulated VOP and IC that we observed an increase in motor responses. These observed kinematics and motor evoked potentials were greater than those elicited from IC stimulation alone. Furthermore, the potentiated motor output exhibited a frequency consistent with the IC stimulation, demonstrating that VOP was only indirectly driving the excitation of activity and not directly through the spinal cord. These results are consistent with our hypothesis that VOP stimulation increases M1 excitability and motor outputs from M1, leading to potentiated movement. This study is a promising validation that we might restore motor functionality after brain injury through targeted VOP stimulation.

F – Adaptation & Plasticity in Motor Control

2-F-43 **Can you imagine? Measures of motor imagery ability are related to the magnitude of corticospinal adaptation following motor imagery training**

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Motor imagery (MI) is a motor-cognitive process that involves the mental simulation of movement in the absence of real, physical movement. Although there is evidence that MI training can elicit behavioural and neurophysiological changes, inter-individual variability exists both in the ability to imagine movements, and in the performance benefits gained from MI training. That is, there are varying

degrees to which people can vividly and accurately imagine themselves moving and there is variability in the amount gained or learned from practice with MI. The current project examined the relationship between behavioural measures of MI ability and: 1) the magnitude of corticospinal adaptation as a function MI training; and, 2) the magnitude of corticospinal activation during MI. To measure MI ability, participants completed a questionnaire (Movement Imagery Questionnaire-3), a mental chronometry task, and a hand laterality judgment task. To measure corticospinal adaptation, single-pulse transcranial magnetic stimulation (TMS) was administered to evoke involuntary thumb movements before and after MI training. Electromyography was recorded from the flexor policis brevis (FPB). Prior to training, participants imagined themselves flexing and extending their thumb. The change in the amplitude of motor-evoked potentials (MEPs) in the FPB from rest to imagination of flexion provided a measure of corticospinal activation during instances of MI. During training, participants imagined themselves moving their thumb in the opposite direction to the dominant direction of the TMS-evoked movements prior to training. The changes in the direction and velocity of the TMS-evoked thumb movements before and after the MI training session indicated the magnitude of adaptation as a function of MI training. All measures were submitted to a series of Pearson correlations to assess the strength and direction of any relationships between the behavioural/questionnaire measures of imagery ability, the changes in corticospinal excitability during MI, and the magnitude of corticospinal adaptation following training. The results showed a positive relationship between the MIQ-3 and the pre/post-training changes in the direction of TMS-evoked thumb movements. Further, a negative relationship was found between the mental chronometry measure and the pre/post changes in the direction and velocity of TMS-evoked thumb movements. Finally, no significant relationships were found between the behavioural measures of MI ability and the amplitude of MEPs during imagination. These findings suggest that ease of imagery and timing of imagery could predict the magnitude of corticospinal adaptation following MI training, but not the level of corticospinal activation during MI. Based on these findings, both measures of MI ability may be considered when assessing imagery ability and determining who might benefit from MI interventions.

2-F-44 Predictive feedback facilitates learning of novel sensorimotor transformations

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Learning a novel sensorimotor transformation often entails the development of an internal model of the transformation. A crucial determinant of this process is feedback, which can be as manifold as the sensorimotor transformations themselves. Among the many different aspects that characterise feedback, its timing has been shown to be of great importance in the context of reinforcement learning. When feedback is temporally delayed, the phenomenon of temporal discounting can occur, a subjective devaluation of reward that potentially impairs the development of a forward model and thus learning (e.g. Kobayashi and Schultz, 2008). The aim of the present study was to investigate whether the predictive presentation of outcome feedback (i.e., before feedback becomes naturally available) in a task with an inherent feedback delay modulates learning. Learning is thereby assessed on both the behavioral and neurophysiological levels and we assumed predictive feedback to facilitate learning in terms of throwing performance and internal predictive error monitoring compared to delayed feedback. In an EEG experiment, naive, right-handed participants practiced a goal-directed semi-virtual throwing task on two days. Participants were randomly divided into two groups that differed with respect to the timing of an additional auditory feedback signal indicating whether the respective movement hit or missed the target. The predictive feedback group (pFB) received this auditory feedback immediately after ball release and thus prior to the naturally available outcome feedback. In contrast, the normal feedback group (nFB) received the auditory feedback at the time when the minimum distance between ball and target had been reached, i.e. when outcome feedback became naturally available in the task. On the second day, additional auditory feedback was withdrawn in both groups. Preliminary analyses show faster learning in terms of improvement in hit rates in the initial phase of practice for the pFB as compared to the nFB group, but no group differences towards the end of day 1. In the absence of additional auditory feedback on the second day, both groups exhibited similar levels of throwing accuracy indicating neither negative nor positive effects of predictive feedback on final learning. On the neurophysiological level, both groups showed a clear frontocentral negativity elicited by the additional auditory outcome feedback indicating a miss. On the second day, ERN- and FRN-like components can be found in the EEG in both groups, respectively. The absolute amplitude of the ERN is significantly larger for the pFB group than for the nFB group. Thus, both groups appear to have developed a forward model for the sensorimotor transformation allowing to predictively perceive upcoming errors in their throwing performance. However, compared to the nFB group, the pFB group seems to have developed a stronger forward model or, alternatively, to make greater use of its internal predictions

2-F-45 Adaptation and plasticity in motor control

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Motor Adaptation is the process by which our learned, goal-directed movements are updated in response to sensory perturbations to remain accurate throughout the lifespan. However, several studies have suggested that both the initial learning and consolidation of motor adaptation are impaired in Parkinson's disease. Savings, or the systematic reduction in error across adaptation blocks may also be impaired. These changes have been attributed to deficient dopaminergic signalling, resulting in a failure to reward a correctly executed motor plan, or a disruption in learning consolidation. Others have suggested that leaning driven by sensory prediction error may be compromised in patients with Parkinson's disease. To investigate the ability of patients with moderate Parkinson's disease to perform prism adaptation, 19 patients and 13 aged-matched controls were recruited. To evaluate savings in Parkinson's disease, participants completed the prism task a total of eight times, half of which with their dominant arm and half with their non-dominant. Several models were built to describe participants' performance, assessed using the corrected Akaike Information Criterion. Results indicated that Parkinson's patients displayed slower rates of initial adaptation and aftereffects of a reduced magnitude, when compared with aged-matched controls. Contrary to expectation, however, patients displayed evidence of savings upon repeated exposure to the perturbation, albeit with distinct differences when compared to controls. Finally, both groups displayed aftereffects of a greater magnitude when performing the task with their dominant hand than with their non-dominant, potentially due to the effects of the dynamic dominance hypothesis. These results suggest that patients with moderate Parkinson's disease retain the ability to adapt to sensory perturbations and demonstrate learning across adaptation episodes. They appear to do so, however, at a slower rate and with less efficiency than aged-matched controls. Interestingly, whilst the short-term retention of adapted motor plans appeared intact in the Parkinson's group, their performance highlighted potential impairments in motor learning driven by both sensory prediction error and reinforcement learning.

2-F-46 Differential Changes in Early and middle-latency Somatosensory Evoked Potentials and Motor Performance: Pursuit Movement Task versus Force Matching Task

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BACKGROUND AND AIM: Neck dysfunction impairs proprioceptive awareness, upper limb motor control and motor acquisition. Accurate proprioception is integral to force production and modulation. Changes in cortico-cerebellar connectivity and cortico-motor excitability occur following a single session of force matching. This study compared changes in early somatosensory evoked potential (SEP) peak amplitudes and motor performance following a force matching task (FMT) to a pursuit motor tracing task (MTT) known to result in SEP amplitude changes. METHODS: 30 (18 females) right-handed, healthy participants aged 21.4 ± 2.76, had electrical stimulation at 2.47 Hz and 4.98Hz delivered over the right-median nerve, to elicit short and middle-latency SEP peaks. 1000 sweeps were averaged and recorded via a 64 channel EEG cap, pre and post motor acquisition of either a novel MTT or FMT, using their right abductor pollicis brevis muscle. Task performance was measured 24 hours later to assess retention. Repeated measures ANOVAs compared: SEP peak amplitudes, normalized to baseline (2x2 ANOVA); and performance accuracy (2x3 ANOVA). Log transformations were applied for datasets that violated tests of normality. RESULTS: Significant time by group interactions occurred for the N20 SEP: decreased by 6.3% post FMT and increased by 5.1% post MTT ($F(1, 29) = 7.004$, $p = 0.013$, np2 = 0.200). P25 SEP: decreased by 4.0 % post FMT and increased by 10.3% post MTT ($F(1, 29) = 8.680$, $p = 0.006$, np2 = 0.237). N18 SEP: increased by 113.4 % post FMT and decreased by 4.4 % post MTT ($F(1, 29) = 9.046$, $p = 0.006$, np2 = 0.244). The N18 also showed a significant effect of time ($F(1, 29) = 322.264$, $p < 0.001$, np2 = 0.920), as did the N30 SEP peak ($F(1, 29) = 2322.167$, $p < 0.001$, np2 = 0.988). Motor Performance Data: Relative to baseline performance, significant interaction effects were seen post-acquisition, where FMT improved by 15.3% while MTT improved by 24.3% ($F(1, 29) = 4.986$, $p = 0.025$, np2 = 0.166), and at retention, where FMT improved by 17.4 % and MTT improved by 30.1% ($F(1, 29) = 9.810$, $p = 0.004$, np2 = 0.259). There was also a main effect of time post-acquisition ($F(1, 29) = 108.007$, $p < 0.001$, np2 = 0.794) and at retention ($F(1, 29) = 137.262$, $p < 0.001$, np2 = 0.831), when compared to pre-acquisition performance. CONCLUSIONS: Task-dependant changes in SEP peaks associated with cortical somatosensory processing (N20 and P25) and cerebellar input (N18) were seen as well as similar changes in sensorimotor integration (N30) following motor acquisition. Improvements in motor performance, which persisted at retention, indicates that motor learning has occurred following the acquisition of both tasks, with greater improvements post-MTT. This suggests that processing of proprioceptive input through the unconscious relay pathways impacts neural correlates important for feedforward control. The FMT shows potential as a means to investigate altered sensorimotor integration.

2-F-47 Repetitive Somatosensory Stimulation of a finger affects some metric aspects of its mental representation

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The ability to represent our body relies on mental body representations (MBR), which are thought to be nourished -and continuously updated- from early stages of tactile input processing in the primary somatosensory cortex (S1). Yet, little is known about MBR susceptibility to changes in S1 plasticity affecting tactile perception. A few studies reported that some interventions, such as local anesthesia, or repetitive transcranial magnetic stimulation, may alter MBR through an induction of plasticity in S1. These interventions are nevertheless either interrupting or interfering with somatosensory processing, thus hardly revealing ecological processing. In contrast, Repetitive Somatosensory Stimulation (RSS) is a passive mechanical stimulation that, when applied to the index fingertip, changes tactile acuity along with the S1 representation of the stimulated region. This intervention increases the amount of tactile stimuli, thus boosting the system while maintaining its integrity. As such, RSS is more ecological and more likely to reveal physiological processing than the interventions mentioned above. In our study, we tested whether RSS, beyond affecting tactile perception at relatively low level (spatial discrimination), also alters MBR. To this aim, we ran a double-blind sham-controlled study in thirty-three healthy volunteers performing, before and after 3 hours of RSS on the right index fingertip, three tasks assessing finger size matching, tactile distance judgement and localization abilities on the stimulated finger. Tactile acuity was additionally assessed using the 2-point discrimination task (2PDT) to control for RSS efficacy. After confirming RSS efficacy through a decreased discrimination threshold in the 2PDT, we found that the perceived size of the stimulated finger in the template matching task was significantly reduced after RSS only. Moreover, no differences between the Sham and RSS conditions were observed neither on the tactile distance judgement nor on the localization abilities. Our results suggest that the perceived finger size is affected by RSS, while other metric aspects of MBR appear immune to RSS. The thorough investigation will be presented, deepening our understanding of the building of MBR and enriching its theoretical framework.

2-F-48 Unique and Interacting Roles of Reinforcement-Based and Error-Based Processes on Exploratory Motor Behaviour

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Exploration is critical for sensorimotor adaptation, from a toddler beginning to walk to relearning functional motor skills following a neurological disorder. Converging neuroanatomical evidence by Strick and colleagues (2018) shows bidirectional connections between error-based (cerebellar) and reinforcement-based (basal ganglia) neural circuitries, with both having neural pathways to motor planning areas. We currently know little on how error-based and reinforcement-based processes in isolation and in concert influence exploratory motor behaviour. Here we test the idea that error-based and reinforcement-based processes uniquely impact and interact to influence motor exploration. Building on the elegant work of van Beers (2009; 2013), we designed a series of five experiments and a model to investigate the unique and interacting roles of reinforcement feedback and error feedback on motor exploration. The model uses movement variability to explore the task-redundant solution space and predicts that: i) isolated reinforcement-based processes and error-based processes respectively boost and suppress exploration, and ii) both processes interact to produce moderate levels of exploration. Participants grasped the handle of a robotic manipulandum and made targeted reaching movements without vision of their hand. They received either reinforcement feedback (pleasant sound, small monetary gain for successful trials) and or error feedback (small cursor) at the end of their reach. We computed trial-by-trial statistical random walks (lag-1 autocorrelations) to quantify exploration. In

Experiment 1, participants received reinforcement feedback when reaching towards a short-rectangular or long-rectangular (task-redundant) target. Aligned with model predictions, participants showed greater exploration along the task-redundant dimension ($p = 0.001$). We replicated the finding that reinforcement feedback drives exploratory random walk behaviour along the task-redundant dimension when controlling for visual target size (Experiment 2, $p = 0.001$) and when manipulating the probability of reinforcement feedback (Experiment 3, $p = 0.002$). In Experiment 4, we found greater exploratory behaviour along the task-redundant dimension when participants received reinforcement feedback compared to error feedback ($p < 0.001$). In Experiment 5, we then tested the interplay between reinforcement and error feedback. Current results show that receiving both forms of feedback leads to moderate levels of exploration, which is greater than isolated error feedback ($p = 0.047$) and less than isolated reinforcement feedback ($p = 0.002$). Taken together, our results and model suggest that isolated reinforcement-based and error-based processes respectively boost and suppress exploration, while in concert these processes mutually oppose one another to result in moderate exploratory motor behaviour.

2-F-49 Modeling user-decoder learning dynamics in co-adaptive myoelectric interfaces

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INTRODUCTION. Neural interfaces provide novel opportunities for rehabilitation and human-machine interactions, but widespread adoption of neural interfaces has been limited by variable performance across users and a lack of intuitive control (Zhang et al, 2020). Designing neural interfaces that adapt to individual users while also guiding how the user learns to control the interface can potentially improve usability. However, these co-adaptive interfaces present a new challenge: both the user and the decoder are adapting in a closed-loop system, creating a two-learner problem. We recently proposed a game-theoretic framework for closed-loop, co-adaptive neural interfaces to improve the design of two-learner systems (Madduri et al, 2021). We consider the user and decoder as two agents in a dynamic game (Basar and Olser, 1999). Both the user and decoder adapt according to their own individual cost function. Our game-theoretic simulations of co-adaptive user-decoder dynamics showed that convergence to stable performance and equilibria is influenced by the decoder cost function and learning rate. Here, we test our simulated predictions by modeling the user-decoder learning dynamics of a co-adaptive myoelectric interface experiment. Our experiment varied 3 adaptive decoding parameters: learning rate, decoder initialization and decoder cost weights. We aim to model and analyze the experimental data to identify convergence to and stability of user-decoder stationary points. We further explore whether game theoretic adaptive decoding can be used to shape user learning in a neural interface. METHODS. We experimentally tested our game framework in a 2D-continuous control myoelectric interface. We used a velocity-based Wiener filter decoder. The decoder is updated by minimizing a combination of two costs: task error and decoder effort, the decoder-specific contribution. Users started with random decoder initialization and no calibration. ANALYSIS. We developed a model of the user as a dynamical system to mirror the decoder. The user's neural activity will be split into task-relevant and task-irrelevant (or null) spaces. Convergence of the user and decoder learning will be determined by stable task performance and the element-wise change in Frobenius norm of the user and decoder representations in the task-relevant space. EXPECTED RESULTS. Our experimental results show that user performance improved across all decoder conditions and that learning rate was the only condition that significantly impacted performance. Given these results, we expect to see user learning within and across trials and convergence to an equilibrium in the task-relevant spaces for the user and decoder. We also expect to see a trade-off between user effort and decoder effort; decoder cost weights are expected to influence user learning and effort. This analysis and modeling of myoelectric interface experimental results can provide insights to user-decoder co-adaptive dynamics.

2-F-50 Humans can quickly and optimally adapt to non-Earth gravity fields locally induced by a robotic exoskeleton

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Earth's gravity has pervasive effects on human neuromechanics and motor control. Several studies have suggested that our central nervous system has an internal representation of gravity, spread over different brain areas, which may allow to optimize movement planning and control with respect to the ambient gravity field. The most direct evidence of such a gravity exploitation came from studies conducted with astronauts in - or returning from - missions and during parabolic flights. Indeed, the adaptation of motor patterns to new gravity fields was found to comply with the predictions of optimal control models minimizing effort. However, this theory would benefit from further investigation with arbitrary gravity fields. Indeed, classical parabolic flights only allow to test specific hypo- and hyper-gravity fields and usually lack statistical power because of the difficulty to include many participants and trials. Moreover, while very relevant to space exploration, immersing participants in a novel gravity field is not pertinent to other applications, such as rehabilitation. During weight support, the neuromechanical system is only locally impacted, mostly through somatosensory information. Theoretically, this information could be sufficient to trigger optimal motor adaptation to such an artificial gravity field, but it is also possible that congruent information from the vestibular system is required to update the internal representation of gravity. Therefore, analyzing if and how humans adapt their motor patterns to a variety of local gravity fields could shed new light on how gravity is internally represented and exploited by the central nervous system. In the present study, we used an active upper limb exoskeleton to induce different local gravity fields. A total of 71 participants were asked to perform vertical elbow flexions in a mechanical context ranging from normal gravity (1g), to microgravity (0g), and then reversed gravity (-1g, which pushes upward). A gradual change of gravity with a 0.2m/s2 step from 1g to -1g was also tested (which includes Mars-like gravity). Our results showed a fast adaptation to the different gravity fields applied by the exoskeleton. The temporal structure of hand trajectories varied significantly with the applied gravity field. In -1g, an interesting reallocation of the antigravity vs gravity roles of the main muscle groups was observed. Movements were initiated with deactivation of the triceps to take advantage of the inverted gravity. When gradually changing gravity, a continuous evolution of the temporal structure of velocity and acceleration profiles was observed. These experimental observations agreed well with the predictions of an optimal control model minimizing effort. These findings show that humans can adapt quickly and optimally to novel gravity fields locally induced by an exoskeleton, which suggests that somatosensory information is sufficient to update the internal gravity model.

2-F-51 Imaging Purkinje cell complex spikes during locomotor adaptation

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Motor adaptation is an essential part of behavior that involves, through practice, the refinement of movements in response to external perturbations. Motor adaptation has been studied in a variety of model systems, from reflex adaptation to whole-body behaviors like locomotion. Previous work has shown that this form of supervised sensorimotor learning depends on the cerebellum, where sensory and motor inputs converge at the level of Purkinje cells in the cerebellar cortex. Instructive signals for motor adaptation are thought to be carried to the cerebellum by climbing fiber axons of neurons located in the inferior olive. Climbing fibers elicit powerful complex spikes in Purkinje cells that are thought to drive neural plasticity that supports learning. For many forms of cerebellum-dependent learning, climbing fibers convey sensorimotor errors that are crucial for adapting motor output. The role of climbing fibers in controlling and adapting locomotor behavior is poorly understood. Locomotor adaptation has been demonstrated following walking on a split-belt treadmill, in which each side of the body is exposed to different treadmill belt speeds. Our research group has shown that mouse locomotor adaptation, as in humans, reflects changes in spatial and temporal components of interlimb coordination and is cerebellum-dependent (Darmohray et al., 2019). However, the nature of error signals for locomotion and locomotor learning, and how they are represented in the cerebellum, is entirely unknown. To investigate this, we are performing calcium imaging from Purkinje cell dendrites in unrestrained mice walking on a motorized, split-belt treadmill. Custom microendoscopes are head-mounted above the dorsomedial/intermediate cerebellum of mice expressing the fluorescent calcium indicator GCaMP6f selectively in Purkinje cells. This approach allows us to image and measure putative complex spikes simultaneously from populations of Purkinje cells, while animals are walking in both tied- and split-belt conditions. We combine this approach with high-speed video tracking of the four limbs, tail and nose. We observe widespread correlated activity along parasagittal axes within the miniscope field-of-view. This organization of complex spike activity is consistent with the existence of cerebellar microzones that result from anatomical connections between climbing fibers and Purkinje cells and from electrical coupling in the inferior olive. Preliminary results further reveal activity in Purkinje cell dendrites that is modulated by locomotor speed and stride cycle. Ongoing work aims to understand the nature of the locomotor signals represented by this activity, and how it evolves during the course of locomotor learning.

2-F-52 Predictive steering: integration of artificial motor signals in self-motion estimation

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Perception of self-motion depends on the integration of vestibular and visual signals and, when the motion is self-generated, also relies on motor efference copies. The brain's computations for both active and passive self-motion estimation can be unified with a single model that optimally combines vestibular and visual signals with sensory predictions based on motor efference copies (Cullen, 2019; Laurens & Angelaki, 2017). However, it is unknown whether this theoretical framework also applies to the integration of sensory signals with indirect motor feedback, like the motor signals that occur when driving a car. Here, we examined if training humans to control a self-motion platform would lead to the construction of an accurate internal model of the mapping between the steering movement and the vestibular reafference. Participants (n = 15), seated on a linear motion platform, manually steered a wheel to control the platform's velocity in order to translate their body midline sideways to align with a memorized visual target. Thus, in this self-motion condition, there was not only sensory (vestibular) feedback about the motion available, but also an internal motor signal, i.e., a cognitively mediated signal of efferent nature. A second group (n = 15) remained stationary and handled the steering wheel to translate a line from their body midline to the remembered target location. Only the final location of the translated line was shown to the participants. Participants were not informed about the gain between the steering wheel angle and the displacement of the platform or line (cm/s per degree). This gain changed twice during the experiment (high gain - low gain - high gain). For both the self-motion and stationary condition, participants only received visual feedback about their error after the movement had ended. Results show that gain changes are virtually undetectable in the displacement error during the vestibular whole-body steering condition. This suggests that in this condition, with the indirect motor signals, the vestibular signals are continuously monitored to correct for unexpected changes in the control dynamics of the platform and to update the internal prediction of self-motion within a single trial. In contrast, when participants did not receive any sensory feedback during the movement, gain changes resulted in considerable displacement errors that only reduced across a number of trials. This suggests that participants adjusted their steering movement only between trials based on the displacement error feedback. Overall, our results suggest that the brain integrates and anticipates the sensory consequences of an indirect motor signal to accurately estimate self-motion.

2-F-53 Sensory adaptation to visuomotor errors limits motor adaptation

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Humans learn to adjust their movement to novel environments based on the error they make (i.e. motor adaptation). Previous studies have mainly focused on how the error is used to correct the next movement, implicitly assuming that the motor system has direct access to the unbiased error information. In contrast to this view, here, we show that error information can be biased upstream to its usage and disrupt motor learning. Neurons in fronto-parietal areas code visuomotor errors in a spatial feature dependent manner. Therefore, we hypothesised that repeated exposure to certain error direction can lead to an adaptation of the set of error direction tuned neurons and bias the error estimation, a similar mechanism to sensory adaptation. Participants performed a right-hand reaching movement and moved a visual cursor to a target on the screen. Online visual feedback was prevented during the movement, but after each trial, the location where the cursor has passed was shown in a form of clouded dots. A rotation between the hand movement path and the cursor movement was gradually introduced (visuomotor (VM) rotation). The rotation angle increased linearly up to 32 degrees over the course of 208 trials, enabling the participants to be exposed to a biased error distribution during rotation angle increase. To examine participants' error direction estimate, after each trial, they were asked to judge whether the visual error (i.e. visual cloud) was on the left or on the right with respect to the target. Participants continuously made errors towards the direction of VM rotation, leading to a shift in the movement error distribution. Importantly, the error distribution remained biased even after the visuomotor rotation had plateaued. Participants' estimate of the error shifted towards the centre of the biased error distribution, showing that participants adapted and became less sensitive to the repeatedly exposed error direction. Further experiments revealed that adaptation to visual error (target-cursor displacement) can occur without motor execution but with lesser amount. Finally, by using fMRI, we showed that the posterior parietal cortex activity reflects the error adaptation effect as an attenuated fMRI response to the repeatedly exposed error size. Our results demonstrate that the error representation can be adapted, bias the error estimation and disrupt motor learning. Such error adaptation during motor adaptation may partly explain why in some cases, humans cannot fully compensate for visuomotor perturbations even after extensive practice.

2-F-54 Evidence for automatization of temporal sequences through motor training

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Automatizing a practiced skill is omnipresent in everyday life, from mundane tasks to expert performance in music and sports. An automatized skill is thought to rely less on deliberate cognitive effort, thus freeing up cognitive resources to engage in parallel tasks. Dual-tasking paradigms have provided abundant evidence that motor skills can be automatized, including the order of sequential movements. However, besides order, movement sequences often follow a specific temporal pattern, which is encoded partly independently from order. Can movement timing be automatized, too? Although evidence exists for a disadvantage of complex vs. simpler rhythms and longer vs. shorter temporal intervals when dual-tasking, the emergence of automaticity of motor timing after training has not been adequately addressed. We recruited 30 non-musician young adults, trained them for five consecutive days to produce single-finger movements from memory in a specific rhythm (interval ratios of 2:5:3:1:4 where 1 = 183 ms), and tested them in a dual-task condition at the end of the first and the last day. The secondary task was a visual working memory task. Only the encoding stage of the visual task coincided with sequence production to avoid motoric interference between the tasks. The load of the visual task was adjusted to each participant using a Bayesian adaptive staircase procedure, i.e., QUEST. Participants were instructed to put equal emphasis on both tasks when dual-tasking. While dual-task costs for the temporal motor sequence remained unchanged after training, we observed a strong reduction in dual-task costs for the visual task after training. Together, this implies that cognitive resources were indeed liberated through motor training, and available for a secondary task, hence pointing to emerging automaticity of the motor sequence. The persistence of dual-task costs for the motor task may be due to the non-metrical, non-beat-based nature of the chosen temporal sequence, and to the length of the training, with five days deemed not enough for this type of rhythmically complex sequences. Together with a previous pilot study we conducted, we identified pitfalls in designing the paradigm, such as the role of categorical perception of rhythms which necessitates a constant reminder of the rhythmically complex sequence to restrict participants from drifting away to idiosyncratic or regularized versions of the sequence, the need to match the difficulty level of the secondary task across participants, and the role of fatigue. In conclusion, our findings suggest that temporal sequences can indeed be automatized, although details of the experimental paradigm are of paramount importance.

2-F-55 The effects of immersive visual cues on adaptation to internal and external errors

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When performing motor tasks, we improve performance by modifying future movements to correct for observed errors. The assigned source of the errors can affect many aspects of adaptation including its generalizability and the updating of internal models. Adaptation to errors assigned to internal sources (e.g., our arm) is often specific to the arm and is poorly generalized when acting with a different effector. Adaptation to errors assigned to external sources (e.g., the environment) on the other hand, is agnostic to the effector being used but may be specific to the environment. Since the cause of an error is often ambiguous, sensory cues can be used to estimate the likely source of the error. We developed a task in which motor errors could be assigned to internal or external sources. Participants made arm movements to roll a ball toward targets in a head-mounted virtual reality environment. We induced errors by either modifying the mapping between the arm movement and the initial movement of the ball, or by applying a change in the ball path only after the release of the ball. Additionally, we used informative visual cues to signal changes in the environment to increase external error attribution. We show visual cues can facilitate the assignment of errors to external sources. The visual cues can be the dynamics of the ball movement or global environmental changes. External error attribution can in turn allow for rapid switching between motor memories.

G – Theoretical & Computational Motor Control

2-G-56 Movement Primitives of the Shoulder-Arm in Activities of Daily Living

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Introduction Humans control complex motions with little effort. Movement primitives (MPs), pre-computed motions often used for controlling robotic systems, may provide a way to better understand how the human central nervous system plans and drives motion. Moreover, identifying MPs in human motion could be useful for improving the design of assistive systems for amputees and tetraplegic patients. For example, modern anthropomorphic robot hands are controlled with primitives derived from human hand movements [1]. Problem statement The shoulder-arm system requires a high range of motion and operational space when performing Activities of Daily Living (ADLs) compared to the hand. This suggests that the complexity of motor planning and execution is also higher for the shoulder-arm as compared to the hand. Objective This work aims to identify lower-dimensional spaces with which multi-degree-of-freedom (multi-DoF) shoulder-arm motions may be described. These lower-dimensional spaces should not only be able to 1) explain the nonlinear temporal dynamics of ADLs, but also to 2) provide a mathematical formulation for transitions between different activities. Findings Using Nonlinear Principal Component Analysis [2] on a database of 30 ADL motions performed by six healthy subjects [3], we were able to identify MPs that can be explained by a one-dimensional variable. Conclusion These results suggest that a one-dimensional control variable could be used to drive the movement of multi-DoF movements of the shoulder-arm. This may be visualized using a musculoskeletal model. Perspective and Outlook We plan to explore the hypothesis that MPs representation can be found in the brain by analyzing 1) neural manifolds of intracortical activity and 2) brain connectivity extracted from electroencephalography. Furthermore, we will employ the one-dimensional control space of the shoulder-arm for Brain-Machine Interface applications and human-inspired control of assistive mechatronic devices. Acknowledgment We gratefully acknowledge the funding of the Lighthouse Initiative Geriatronics by StMWi Bayern (Project X, grant no. IUK-1807-0007// IUK582/001), and the Project AI.D by BMBF. References: [1] Catalano, M. G., Grioli, G., Farnioli, E., Serio, A., Piazza, C., & Bicchi, A. (2014). Adaptive synergies for the design and control of the Pisa/IIT SoftHand. The International Journal of Robotics Research, 33(5), 768-782. [2] Scholz, M., Fraunholz, M., & Selbig, J. (2008). Nonlinear principal component analysis: neural network models and applications. In Principal manifolds for data visualization and dimension reduction (pp. 44-67). Springer, Berlin, Heidelberg. [3] Hu, T., Kuehn, J., & Haddadin, S. (2018). Identification of human shoulder-arm kinematic and muscular synergies during daily-life manipulation tasks. In 2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob) (pp. 1011-1018).

2-G-57 Where is the target of our movement?

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When modelling the neural control of movement, one generally focusses on how to generate motor commands that bring the hand to the target. In such models, the location of the target is often taken for granted. However, our brain must rely on sensory information to estimate target location. Sensory information has a limited precision, which could lead to imprecise movements, so it might be worthwhile improving sensory judgments by averaging over time. However, if the location is changing because the object moves, averaging will introduce a bias. Do we rely on the latest location information at each instant, or do we integrate information over time to compensate for the limited precision of instantaneous visual judgments? What if the target moves, so the present location is not where we want our movement to end? What information do we use for the extrapolation? To assess when and how visual information is used, we investigated how participants tapped on objects that were stationary, moving at a constant velocity or accelerating. We added some jitter to the trajectories and studied how the movements were influenced by this jitter. We also varied the regularities between subsequent trials. We show that participants continuously control their movements on the basis of the latest available information about the target's location with a delay of 100ms. The gain of this control increases during the movement, the largest gain being found for the jitter 150 ms before the tap. The same control is used when the target is moving. In that situation, participants combine this instantaneous target location with an extrapolation of the location over the remaining time to reach it. This extrapolation is based on the target's velocity during the last several hundred milliseconds, without considering that the target's velocity may be changing within that period. If the target is accelerating, participants do not take this acceleration into account, so they make predictable systematic errors. By adjusting their movements to compensate for errors made in previous trials, they make accurate goal-directed movements whenever the acceleration is constant across trials. Such heuristics can also deal with misalignment between the senses Our finding that participants only use the instantaneous estimate of target location for controlling their movements might suggest that their movements have to be imprecise. However, at every instant a new noisy estimate is obtained. The characteristics of the muscles introduce the low-pass filtering required to ultimately achieve a precise movement. In conclusion, when making a goal-directed movement, humans build an estimate of the location of the target by using instantaneous information on location that is extrapolated using accumulated velocity information and combine this with a heuristic based on performance feedback.

2-G-58 Predicting full-body proprioceptive cortical anatomy and neural coding with topographic autoencoders

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Proprioception is one of the least understood senses yet is fundamental for the control of movement, its loss producing profound motor deficits. Even basic questions of how pose and movement are represented, as well as how these representations are arranged across the somatosensory cortex, are unclear. To this end, we adopt a task-driven modelling approach, using a variational autoencoder with Poisson distributed latent variables to approximate a population of cortical neurons. We optimize the model to encode natural movement stimuli derived from recordings of human kinematics and impose biological constraints which we hypothesise to be important for reproducing characteristics of proprioceptive neural coding, namely, enforcing a sparse code and implementing lateral effects between neighbouring neurons in the model to produce topographical structure in neural tuning. To evaluate the effectiveness of these coding principles at reproducing empirical observations in neural data (without any direct fitting to recorded firing rates), we task our model with encoding movement kinematics during a centre-out reaching task and compare activity in the cortical grid of the model to recordings from multi-electrode arrays in area 2 of monkeys performing the same centre-out reaching task. The model is able to reproduce several key observations from the empirical data, including the shape and velocity dependence of proprioceptive receptive fields in hand-centred coordinates despite the model having no knowledge of arm kinematics or hand coordinate systems, the distribution of neuronal preferred directions (PDs), and the topographical arrangement of neural tuning across the cortical surface. Furthermore, we are able to demonstrate the importance in training such models on data that reflects the true distribution of natural behaviour, with the model failing to reproduce key properties of the empirical data when trained on data from stereotyped reaching behaviour only. We then highlight two testable predictions made by the model: 1. The distribution of PDs across the cortex has a blob-and-pinwheel-type geometry. 2. Few neurons encode just a single joint. Lastly, we task the model to encode full-body movement statistics to generate further predictions on the somatotopic organisation proprioceptive stimuli. In summary, the topographic VAE (Topo-VAE, Blum et al, 2021) provides a principled basis for understanding the sensorimotor representations and theoretical basis of neural manifolds using deep generative modelling. These basic scientific principles may have application to the restoration of sensory feedback in brain-computer interfaces (Weber et al, 2012) and the control of humanoid robots.

2-G-59 Characterization of head orientation and heading during everyday activity: Implications for modeling.

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Estimation of head orientation relative to gravity and the direction of linear self-motion (i.e. heading) is necessary for postural control, locomotion, and perception of spatial orientation. While it is accepted that estimation is constrained by natural stimulus distributions, empirical data describing natural distributions of human head orientation and heading is lacking. Here, we measure 6DOF head position, velocity and acceleration over dozens of hours of unprescribed natural activity. The resulting distributions fill an important gap in the literature and are further used in a Bayesian framework to model known biases in perception of both head orientation and heading. Approximately 50 total hours of unprescribed natural activity was recorded across 10 subjects using an Intel Realsense T265 tracking camera that estimates position at 200 Hz via a proprietary visual-inertial fusion algorithm. Accuracy of the T265 has been evaluated previously (Hausamann et al 2021). Subjects completed calibration movements (head nod and shake) every half hour to facilitate transformation of data into a head-centered reference frame. Across-subject distributions of head orientation relative to gravity were non-normal. Roll was symmetrical and leptokurtic; pitch was asymmetrical, with an over-representation of downward head pitch and higher variance than roll. Across-subject distributions of heading azimuth and elevation were non-normal. Heading azimuth was multimodal, with modes at 0 and ± 90 deg. Heading elevation was unimodal with fat tails and high variance. To explore how natural distributions might shape perception, orientation and heading distributions were used as priors in Bayesian models that aim to explain perceptual biases. Free parameters of the models were constant and signal-dependent noise on orientation and heading estimates, which determined the variability on the Bayesian likelihood for each orientation and heading direction. Variability was modeled to increase linearly or sinusoidally with eccentricity from straight ahead (for heading) or from vertical (for head orientation). Models were fit by minimizing the residual standard error (RSE) between biases observed in previous psychophysical studies and modeled biases. Qualitatively good model fits were obtained for previously observed biases in perception of pitch (Cohen & Larson, 1974), roll (De Vrijer et al., 2009), visually-perceived eye level (VPEL) (Hudson et al., 2000), heading azimuth (Cuturi and MacNeilage, 2013), and heading elevation (Crane 2014). Generally, predicted biases increased with eccentricity, like observed biases. In addition, predicted biases were asymmetrical where the natural distributions were asymmetrical, e.g. for head pitch, and asymmetry was reflected in previously reported psychophysical data. Goodness of fit was quantified using RSE: these values were 8.346° for roll, 4.847° for pitch, 1.475° for VPEL, 2.775° for heading azimuth, and 8.476° for heading elevation.

2-G-60 An integrated model of muscle dynamics, motor unit recruitment, and energetic cost of movement

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Muscles are critical to the control, mechanics, and energetics of human movement. Most prevalent to date are "Hill-type" muscle models, which phenomenologically describe muscle's force-length-velocity behaviour, and may be augmented with phenomenological descriptions of energetics. But these models have limited utility for optimal control predictions of movement, because they lack important mechanisms such as cross-bridge cycling and active calcium transport. These two mechanisms are thought to determine muscle work efficiency and the cost for rapid force production respectively, of which in particular the latter is not well predicted by current Hill-type models [e.g., 1]. Although quantitative models of muscle cross-bridge cycling and active calcium transport have been developed that account for work efficiency [e.g., 2], these models also cannot account for the energetic cost of rapid force production. We propose that this may be due to the absence of motor unit recruitment in these models. Here we present a new model that integrates a previous, "Distribution Moment" model of crossbridge and calcium dynamics [2] with a simple model of motor unit recruitment, and mechanistically explains the energetics of both muscle work and rapid force production. The model predicts that (1) calcium release is required during rapid force production owing to rate-limiting contraction dynamics, (2) calcium transport is especially costly for the first in a train of action potentials, which makes it more economical to produce greater muscle force by increasing firing rate considerably before recruiting additional motor units. This model can help explain the smoothness and energetics of arm reaching [3] and locomotion [4] via optimal control. The proposed model's crossbridge-cycling dynamics and calcium-pumping dynamics are derived from the previously formulated Distribution Moment model [2]. Motor units are recruited in an orderly manner based on empirical observations [5], where both firing rate and recruitment increase with overall muscle force. We used optimal control to find the neural drive for cyclic work and force production at a range of frequencies and amplitudes, and found the predicted energy cost to agree well with empirical human measurements (data from [1]). Model simulations suggest that the cost of active calcium transport can exceed 50% of the total energy cost during rapid force production. This preliminary model is very approximate, but can accommodate new data and observations within a mechanistic framework, whereas phenomenological models can only accept improved curve fits. 1. van der Zee, T.J. & Kuo, A.D. (2021). J. Exp. Biol. 224, jeb233965. 2.

Zahalak, G.I. & Ma, S-P. (1990). J. Biomech. Eng. 112, 52-62. 3. Wong, J.D. et al. (2021). eLife, 10, e68013. 4. Rebula, J.R. & Kuo, A.D. (2015). Plos One, 10, e0117384. 5. Monster, A.W. & Chan, H. (1977). J. Neurophysiol. 40, 1432-43.

2-G-61 Inferring position and velocity control strategies of monkeys and humans in a virtual balancing task

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Redundancies in our motor system and in the many tasks that we perform in daily life allow for myriad ways in which we interact with the world. Consider balancing a tray of dinner plates: there are many ways in which we can hold and move the tray. Successful accomplishment of this and similar tasks requires both prediction and sensory feedback about the position and velocity of the tray, which in turn helps to drive the many possible hand and arm movements that keep the tray balanced. The strategies employed to balance the tray may change, within a single trial or over time and repetitions. Is it possible to infer the control strategy adopted by individuals from their observed behavior for such a balancing task? To address this question, we used a virtual balancing task, called the "Critical Stability Task" (CST) [Quick et al., 2018], that was developed to examine sensory-driven motor control in monkeys and humans. The task affords sufficient complexity while preserving analytic tractability. In the CST, subjects view a horizontally moving cursor on a computer screen and make corrective hand movements to keep the cursor from drifting off-screen to the left or right. The rate of drift, and hence task difficulty, is determined by a single parameter set at the start of each trial. The system is inherently unstable and without appropriate hand movements, the cursor will drift off-screen. Successful performance of the task can be achieved through at least two different control policies: subjects might intend to keep the cursor at the center of the screen for the duration of the trial ("position control"). Alternatively, subjects might attempt to keep the cursor as still as possible, regardless of its position on the screen ("velocity control"). Owing to the unstable nature of the task coupled with natural variability in hand position, each trial is unique, making trial-averaged analyses unsuitable to identify possible control strategies. To address this challenge, we adopted a generative model approach, which implemented an optimal control model to perform the CST under different control objectives. The model successfully emulated the overall performance of both human subjects and non-human primates. Moreover, the behavioral attributes of different control strategies of the model served to identify the different control policies in the data. This approach was adopted to characterize control strategies in both human and monkeys. These results provide a step towards improved understanding of the neural activity associated with highly interactive sensorimotor behavior, and how these different control priorities might be represented in the neural activities in the motor system.

2-G-62 The parietofrontal cortical grasping network does not differentiate distinct grips during action observation

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Cortical areas which control movement are also active during the mere observation of others' movements. This observation-related activity is thought to reflect the presence of shared computations across movement execution and observation contexts. The nature of such computations remains unclear, in part because a consensus description of observation-related activity and its relationship to execution-related activity remains lacking. To address this, we used multielectrode arrays to record populations of single units simultaneously from the anterior intraparietal area (AIP), the rostroventral premotor cortex (F5), and the primary motor cortex (M1) while animals either performed a delayed grasping task (execution context) or observed a human partner doing the same (observation context) across dozens of different objects. We found that neurons span a continuum of relative preferences for the execution and observation contexts, with no clear separation of neurons into classical "mirror" and "nonmirror" subtypes. However, at the population level, a common subspace clearly emerges in AIP and F5 that captures shared patterns of activation across the two contexts, even after accounting for the confounding visual representations of object shape. Nonetheless, different grips are only weakly differentiated from one another during the observation context. The computations supported by observation-related activity remain unclear, but they do not seem to involve a replication of the action specificity of neural activity seen when executing movements.

2-G-63 Temporal structure of descending activations and their interplay with spinal reflexes in producing arm movements

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Sensory feedback interacts with brain descending activations at different levels of the motor hierarchy. While transcortical feedback is instruction-dependent and contributes to muscle activities at relatively longer latencies (>50ms in arm muscles), spinal feedback continuously interacts with descending activations and contributes to the muscle activity with short delay (<25ms). Teasing apart the role of descending activations from spinal reflexes helps the understanding of higher-level motor control. Here we aim to reconstruct the temporal profile of descending activations by inverting a neuromuscular model with spinal reflexes, based on peripheral measurements of arm movements (kinematics and EMG). The reconstructed descending patterns differed qualitatively from muscle activation patterns, suggesting a significant role of spinal-level modulation on muscle activations. With increased movement speed, the temporal profile of descending activations became more complex. This indicates the need for descending control to consider peripheral dynamics. We also found that introducing additional co-facilitation during fast movements reduced the complexity of estimated descending patterns. Our study provides an analytical tool for probing descending control and emphasizes that motor control theory should incorporate spinal-level mechanisms.

2-G-64 Context-dependent Sensorimotor Learning by Variational Inference

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Goal-directed movements occur in a variety of different contexts, e.g. while holding different objects. Our brain therefore needs to learn both the specific sensorimotor transformations of each context and which context (including possible novel contexts) is relevant at any given time[1,2]. As the exact solution is intractable, our brain has to rely on approximations. We propose a model that utilizes a variational approximation, whereby human learners pursue the computational goal of minimizing free energy[3]. When constrained by a generative model of how contexts occur in the environment and are observed by

the learner, minimizing free energy approximates a solution to the context learning problem. Our model simulates a learner who, on each trial, experiences a noisy observation of a sensorimotor perturbation context (e.g. a visuomotor rotation via motor prediction error) and tries to infer the size of the perturbation and assign responsibility. This hypothetical learner assumes a generative model by which the perturbation observed is either the same as on the previous trial ("sticky" case) or is drawn from a large pool of possible perturbations ("non-sticky" case) that can also be previously unobserved. The perturbation is then observed with Gaussian sensory/motor noise. Our algorithm minimizes free energy under this generative model, with the additional approximation that it only begins to represent a potential novel context in memory if this reduces the free energy for the current observation, thus accounting for limited memory. This model is able to qualitatively capture canonical phenomena, such as savings, spontaneous and evoked recovery, and slower decay after learning smaller perturbations, under a single set of hyperparameters. It does so via inferred context rather than memory updating, in line with recent findings[1,2]. Recently, it has been suggested that the brain may solve the contextual inference problem through a sampling-based algorithm (COIN model[2]). However, sampling tends to be computationally intensive or, if done overtly would not produce the relatively consistent moment-to-moment motor output typically observed in humans. Our model obviates the need for sampling and its computational demands. Variational or free energy approximations can in principle be realized in neural networks by predictive processing, rendering our algorithm a plausible starting point for eventually modelling implementation in biological hardware. [1] Oh & Schweighofer. J Neurosci. 2019 [2] Heald, Lengyel, & Wolpert. Nature. 2021 [3] Friston. Nat Rev Neurosci. 2010

2-G-65 Partner representation, action selection and learning in joint coordination: experimental results and computational model

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Previous studies using sensorimotor games have suggested that human dyads develop coordination strategies which can be interpreted as Nash equilibria. We previously argued that if players are uncertain about what their partner is doing, they develop a coordination strategy which is less sensitive to the actual partner actions. This suggested that humans maintain an explicit representation of what the partner is doing - a partner model - possibly also accounting for their degree of confidence about it. Here we focus on a joint coordination task in which two humans are mechanically coupled through a virtual spring and are instructed to perform reaching movements with the same start and end point, but different via-points. Each subject knows their own via-point, but not their partner's. We varied the amount of information about the partner (haptic, visual). We also varied the via-point locations: symmetric (located on the axis of the start-end segment); or asymmetric, (respectively, shifted to the left or to the right with respect to the axis). We reasoned that the available sensory information affects the reliability of partner representations. The task admits two Nash equilibria, which are cost-equivalent in the symmetric condition but not in the asymmetric one. Hence in the symmetric condition each subject must choose among two strategies.   We modelled the joint task as a quadratic game and accounted for uncertainty at perceptual and action selection level. We assumed that each player predicts their partner's next move (partner model) by optimally combining predictions and sensory observations. Players selects their actions through a stochastic optimization of its expected cost, given the partner model. The symmetric version of the task implies that not only the selection of an action - a trajectory - but also a strategy choice (whether to cross VPs earlier or later in the movement) must be made at each trial. We used the model to simulate the development of a coordination strategy. We also derived a maximum-likelihood identification procedure for model parameters from the experimental results. The experimental results indicate that reducing the uncertainty about the partner leads to faster and more stable coordination which closely resembles Nash equilibria. In the symmetric via-point condition, achieving a stable coordination is harder as dyads tend to oscillate between cost-equivalent trajectories, but this effect is reduced when sensory information is more reliable. The model qualitatively reproduces these observations and model parameters can be reliably estimated from the experimental data. Overall, these findings are consistent with the notion that learning a joint coordination through repeated trials relies on a simple strategy (fictitious play) based on optimal estimation of partner actions and stochastic action selection under the assumption of stationary partner behavior.

2-G-66 Trajectories in speech production: can optimal control markedly shape the intrinsic biomechanical dynamics?

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From the previous work of one of us, we know that the biomechanics of the articulators have a decisive influence on the shape of speech trajectories. Recently, we examined whether, on top of that, an optimality principle can be useful to account for trajectories from schwa to vowel production. Here we wish to push further our analysis and study how it can affect trajectory formation in longer phoneme sequences. In order to achieve that, we implemented an optimal control model for speech production. The planner, which assumes that the central nervous system is stocking association between values of the control variables corresponding to goal positions and the corresponding formant frequencies, and the plant to be controlled, which is a biomechanical model of the tongue in our case, were taken from the GEPPETO model of speech motor control. In the optimal control model, trajectories were determined by the selection of motor command that jointly minimized the motor effort and the motor error (bias in production). The internal model used for that optimization was a LSTM trained from the biomechanics of GEPPETO. Thus trajectories reflected both a representation of biomechanics and a higher-order effort constraint. In contrast, in the GEPPETO model, trajectories emerged from the actual biomechanical properties of the articulators and the only specification of sensory targets. We contrasted the two models in [VV] and [VCV] sequences and compared the results obtained in either the acoustic, kinematic, or motor domain.

2-G-67 Neural representations of motor decision-making found to vary across planning strategy subgroups

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The human brain must constantly integrate its decision-making, motor planning, and action execution systems in order to seamlessly navigate through the world. How these system interactions are encoded in the brain in preparation for the execution of complex action sequences has not been explored. Furthermore, differences in motor planning strategies across individuals are not often considered. We designed a 360-trial fMRI task where each trial requires a decision (the "Choice Stage"). Given a map of a starting point and end goal, participants may choose one of two cursors to navigate from the start to the goal and optimize reward returns. The two cursors vary in both route planning constraints and navigation difficulty (more vs. less difficult), and each trial has one optimal cursor choice. The trial-by-trial variations in start/end goal positions create "Conflict" trials (optimal cursor choice is less obvious) and "Confident" trials (optimal cursor choice is more obvious). Drift diffusion models were fitted to Choice Stage reaction time (RT) to determine if participant RT was modulated by Conflict vs. Confident trials. Participants were then classified as either "Route Planners" (RT modulated by potential trial reward gained by either cursor; N=13), "Heuristic Planners" (RT modulated by start-goal offset angle; N=10), or "Non-Planners" (RT exhibited no significant modulation; N=10). Local maxima of Choice Stage fMRI BOLD activations (cluster corrected at $t>5$, $p<0.05$) were used to create 41 region-of-interest (ROI) masks (5mm sphere; 81 voxels each). Bayesian variational representational similarity analyses assessed whether Choice Stage (just before cursor selection) ROI activation patterns were sensitive to whether participants picked the more vs. less difficult cursor for each trial. Across all participants, 17 ROIs were found to credibly exhibit pattern covariance changes sensitive to cursor choice (Bayes Factor ≥ 3), consisting mainly of visual occipital and motor cingulate areas. These effects appear to be mainly driven by the Heuristic Planners, signaling that the system responsible for encoding motor decision-making may differ based on individual planning strategy.

Poster Session 3

Thursday July 28, 2022

A – Control of Eye & Head Movement

3-A-1 **Sensory tuning in neuronal movement commands**

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Movement control is critical for successful interaction with our environment. However, movement does not occur in complete isolation of sensation, and this is particularly true of eye movements. Here, the superior colliculus (SC) plays a fundamental role, issuing saccade motor commands in the form of strong peri-movement bursts that are widely believed to specify both saccade metrics (encoded spatially) and kinematics (encoded temporally). However, practically all models of saccade control by the SC rely on observations with small light spots as saccade targets. Instead, we asked monkeys to "look" at images, akin to more natural behavior. For each recorded SC neuron, we presented different images centered on the hotspot location of the neuron's movement field, and we ensured that the saccade vectors and kinematics were matched across images. We tested gratings of different contrasts, spatial frequencies, and orientations; images of animate and inanimate objects (as well as their non-object scrambled versions); and black versus white stimuli. Despite matched saccades across trials within a given image manipulation, the SC motor bursts were strongly different for different images; that is, they were sensory-tuned, preferring some visual features as the saccade targets over others. Surprisingly, such sensory tuning in the neuronal movement commands could be even sharper than that in passive visual responses: the difference in movement burst strength between the most and least preferred image features (for the same saccade vector) was often larger than that in the visual bursts at stimulus onset during fixation; this is consistent with known pre-saccadic perceptual enhancement. Most intriguingly, even purely motor neurons (without significant visual sensitivity during fixation) exhibited strong sensory tuning in their motor bursts. Sensory tuning was also present in peri-saccadic local field potential modulations. Since SC motor bursts are relayed virtually unchanged to cortex (Sommer & Wurtz, 2004), one implication of our results is that the visual system is primed (via ascending pathways from the SC) not only about the vectors of upcoming saccades, as is traditionally believed, but also about the movement targets' visual sensory properties. Consistent with this, in further human psychophysical experiments, we additionally found that the visual features of a given saccade target significantly modulate the strength of two classic peri-saccadic perceptual phenomena: suppression and mislocalization. Our results provide novel insights about the functional role of SC motor bursts: beyond representing saccade target locations via a spatial code, SC motor bursts also carry information about the saccade target visual features in their temporal profiles. These observations motivate extending theoretical accounts of saccade-related corollary discharge beyond just spatial movement-related reference frames and into the realm of visual feature representations.

3-A-2 Coding strategies for representing natural self-motion strongly differ from those used to represent artificial self-motion across ascending vestibular pathways.

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Understanding the neural mechanisms by which sensory input gives rise to behavior requires knowledge of how the sensory representations of this input evolve between successive brain areas. Here we investigated how natural self-motion stimuli are represented in ascending vestibular pathways ranging from more peripheral to central cortical areas contributing to both vital reflexes as well as spatial perception. Recordings were made from neurons within the vestibular nuclei (VN), vestibular thalamic neurons within the ventral posterior lateral (VPL) Thalamus and neurons within the parieto-insular vestibular cortex (PIVC) during both artificial and naturalistic self-motion. Our results show that neurons within ascending vestibular pathways gradually become more optimized to natural stimuli. Further, our results demonstrate radical changes in neural coding strategy of self-motion across successive brain areas. Specifically, while VN neurons transmit information through a combination of changes in firing rate and precise spike timing, VPL neurons instead represent self-motion exclusively through changes in firing rate and PIVC neurons use a burst firing pattern. In contrast to postural reflex pathways, we found that VPL and PIVC neurons encodes naturalistic head velocity differently from artificial ones. Precisely, while VPL responses to artificial stimuli are ambiguous they faithfully encode naturalistic head motion. Moreover, PIVC neurons fire bursts of action potentials that reliably detect recurring features during naturalistic but not artificial stimulation. In contrast, overall neurons in all three brain areas encode artificial stimulation in a relatively similar manner via changes in firing rate. Taken together, our results show that VPL and PIVC neurons respond in a fundamentally different manner to naturalistic as opposed to artificial self-motion stimuli. In particular, our results showing that PIVC neurons detect recurring features of naturalistic self-motion, while instead encoding the detailed timecourse of artificial self-motion have important implications as they suggest that our perception of natural self-motion stimuli differs fundamentally from that of artificial self-motion stimuli that have been used to date.

3-A-3 Co-contraction of extraocular muscles during blinks causes eyeball lifting, retraction and compression. A high-speed MRI study.

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Blinks are accompanied by a unique but elusive eye movement. Unlike most eye movement which consists of purely rotational motion, the eyeball as a whole is being retracted into the socket during a blink arguably by some form of co-contraction of extraocular muscles. Reports on the translational component of this blink-related eye movement are often anecdotal and the little data available stems from forcibly holding the eye open and filming the eye in side view. Our lab has recently developed MREyeTrack, a method to track eye movements based on high-speed single-slice MRI video footage. This allows measurements even when the eye is closed, and visualises displacements & deformations of the whole eyeball. We used this technique to measure the translational eye motion trajectory for blinks of varying duration from 11 human participants. We found that the eye lifts up more than it retracts and can move by a much larger amount than expected. Averaged across participants we observed eyeball retraction of 0.79 mm (SD = 0.16 mm) and lifting of 1.35 mm (SD = 0.67 mm) with considerable variability across individual blinks. For some participants eyeball lifting could reach up to 3 mm, far exceeding the amount of translation previously reported to occur during natural eye movements. We also established the existence of a holding state with regard to eyeball translation that was reached for prolonged periods of lid closure for all participants. Co-contraction of extraocular muscles also produced slight eyeball compression of 0.59 mm (SD = 0.21 mm) along the anterior-posterior axis. It was previously suggested that co-contraction of only the two rectus muscles would be sufficient to explain eyeball retraction, but our novel finding of eyeball lifting implicates that other extraocular muscles are probably involved as well. We believe that our findings are best explained by an activation of the superior oblique, because its tendon is guided through the superiorly located trochlea before innervating the eyeball. Dynamic MRI helped to uncover the surprising complexity of ocular motility during blinks and given how frequent blinks occur in everyday life, eyeball translations should be considered a fundamental part of oculomotor control. The anatomical video footage we obtained might also interest clinical researchers because of potential consequences of the force exerted on the eye during blinks and similarities with certain types of strabismus which also exhibit eyeball translation.

3-A-4 Prosthesis-evoked eye and head movements are linear beyond the maximum afferent firing rate: implications for vestibular prosthesis dynamic range

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Bilateral vestibulopathy can lead to debilitating visual and postural instability in addition to constant dizziness. One approach to improve the quality of life in this patient population is a vestibular prosthesis that senses head rotation and transforms it into vestibular afferent stimulation, substituting for the damaged periphery. Early results from clinical trials, while encouraging, have shown only partial functional improvements. Specifically, the evoked vestibulo-ocular reflex (VOR) fails to fully stabilize the gaze (i.e., gain < 1). Current strategies to improve the VOR gain have notable downsides; increasing stimulation current level can lead to non-specific activation, while modulating the stimulation rate more strongly for a given head velocity can lead to earlier saturation and narrower dynamic range. One key parameter that remains uninvestigated, however, is the maximum stimulation rate. This is typically set at the maximum endogenous afferent firing rate (~350 Hz) based on the assumption that each stimulation pulse will reliably evoke a spike in the afferents. Accordingly, here we investigated the linearity of prosthesis-evoked eye and head movements across a large stimulation frequency range. We recorded eye and head movements, in addition to neck EMG activity, in one monkey during acute afferent stimulation up to 1500 Hz. Eye movement data showed linear response up to ~600-800 Hz before starting to plateau. Head movement and neck EMG exhibited sooner saturations with linear response up to ~400 Hz. These results contradict the common assumption that each stimulation pulse will reliably evoke an action potential in the afferents (i.e., 100% stimulation efficacy). Thus, finally, we examined this efficacy assumption using a model of the VOR pathway to predict eye velocity based on stimulation rate. The model yielded accurate predictions only when stimulation efficacy was reduced to 28%, a value similar to that from afferent recordings during stimulation previously published by our group. Due to the <100% efficacy, by setting the maximum stimulation rate equal to the maximum afferent firing rate, the conventional approach artificially limits the dynamic range of the prosthesis. Taken together, our results suggest that, by accounting for the actual physiological efficacy of afferents responses, the vestibular prosthesis can better utilize the range of afferent firing rates. We suggest a complementary approach combining eye movement recording and modeling can be used to optimize the prosthesis gain and dynamic range for prosthesis users in the clinic.

B – Fundamentals of Motor Control

3-B-5 Repetition effects in extrinsic and intrinsic coordinates reveal shared representations of movement sequences across the two hands

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Most daily activities involve the production of movement sequences. Recent evidence suggests that, while the primary motor cortex is mainly concerned with the control of individual movements, the brain maintains representations of longer action sequences in premotor and parietal areas. The exact nature of these representations, however, is unknown. For example, when planning to type the PIN at an ATM machine, the brain may maintain a representation of 1) the numbers (visual or symbolic representation), 2) a spatial plan of the sequence of movements on the keyboard (extrinsic representation), and/or 3) a plan of the sequence in muscle or joint coordinates (intrinsic representation). Here we disambiguated these different representations by studying the behavioral phenomenon of repetition effects: when a participant repeats the same sequence, they move faster than when they have just executed a different sequence. In our paradigm, sequences could either repeat within the same hand or from one hand to the other. This allowed us to determine whether the representations underlying the repetition effects were effector-specific or effector-independent. Furthermore, the repetition across hands could occur either in extrinsic (same numbers, different fingers) or intrinsic (different numbers, mirror-symmetric fingers) coordinate frames. Human volunteers (N=40) performed short sequences (5 elements) of finger movements on a custom keyboard with either hand. On each trial, they received a visual cue for which fingers to press (numbers from 1 to 5) and which hand to use (color of the numbers). Participants had enough time to analyze the stimuli and prepare the sequence of movements. After a go-signal, they were then instructed to execute the sequence as fast as possible. We replicated the previously reported within-hand repetition benefits, with faster reaction times and execution times for repeated sequences. We also found significant between-hand repetition effects: reaction times were faster when the cued numbers were repeated. Additionally, participants could execute sequences faster when they had just produced the same sequence with the other hand. This was not only the case for extrinsic repetitions, but also for intrinsic repetitions for which the participants had no explicit awareness. These results demonstrate the existence of effector-independent sequence representations in both extrinsic and intrinsic coordinates. Importantly, the sum of the intrinsic and extrinsic between-hand effects added approximately to the size of the within-hand effect, suggesting that repetition effects arise at the level of effector-independent, rather than effector-specific, sequence representations.

3-B-6 Distinct cortical areas for planning sequences before and during movement

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From buttoning one's shirt to texting with a smartphone, many everyday actions depend on the brain's ability to plan and execute sequentially coordinated finger movements. For a single movement, motor planning is thought to put the brain in an optimal readiness state, thus setting the stage for correct movement execution. But how does the brain coordinate the execution of rapid sequences of multiple finger movements? Previous work has shown that while the first few elements of a sequence can be pre-planned, longer action sequences are planned online throughout sequence production. This raises the key question of whether motor planning processes occurring during sequence production (online planning) rely on the same brain areas as those related to preparation (pre-planning) or recruit distinct neural substrates. Here we hypothesized that pre- and online planning may in fact be one and the same (1-process hypothesis). Alternatively, the brain might treat online planning while executing as a qualitatively different problem from pre-planning while at rest (2-processes hypothesis). To test these hypotheses, we designed a high-field (7T) functional neuroimaging (fMRI) study in which participants (N=22, 13 female) produced series of right-hand finger movements on a custom MR-compatible keyboard in response to numbers (1=thumb, 3=middle, 5=little). We directly compared three single-finger (e.g., 111111) and three multi-finger (e.g., 135315) sequences in a delayed movement paradigm with no-go trials. This design allowed us to isolate planning during sequence preparation (pre-planning) from planning during sequence production (online planning). We predicted that, if pre- and online planning are the same process, the contrast of multi- and single-finger sequences should reveal the same brain activity across the preparation and production phases. During sequence preparation, we observed significantly higher activation for planning of multi- than single-finger movements in contralateral premotor (PMd, PMv, SMA) and parietal areas (aSPL, pSPL), while primary sensorimotor (M1, S1) areas were significantly deactivated for both sequence types. During sequence production, the difference in brain activation between multi- and single-finger sequences was largest in the same areas that responded to multi-finger planning, seemingly favoring the 1-process hypothesis. Although activity patterns for the contrast of multi- and single-finger sequences were highly correlated across preparation and production (r=0.7), this correlation was significantly lower than 1 (even after accounting for measurement noise) due to systematic differences in the distribution of activations across brain regions, with PMd, M1, S1, and aSPL regions more active during online planning, and SMA, PMv, and pSPL more active during pre-planning. Together, our results support the 2-processes hypothesis: pre-planning and online planning of movement sequences elicit distinct brain responses.

3-B-7 Planning multiple future actions in sequential reaching

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Whether articulating sentences, preparing a cup of tea, or typing on a computer keyboard, naturalistic actions are usually composed of a sequence of temporally overlapping movements. Longer sequences cannot be pre-planned in their entirety, so the brain must be able to prepare the next actions while previous parts of the sequence are being executed. However, it is unclear how these different preparatory processes interact with each other. In this behavioral study, right-handed volunteers (N=10, 4 female) performed sequences of 14 reaches in a robotic exoskeleton (KINARM). To complete a sequence, participants were instructed to serially move their right hand to 14 circular targets (1 cm radius). The targets composing each sequence were randomly generated from a set of potential targets located on the vertices of a hexagonal grid with an edge length of 4 cm. To explore how the simultaneous preparation of future movements impacted ongoing behavior, we manipulated how many future targets participants could see while executing the current reach (horizon) and how long they had to stay in the target to capture it (dwell time). For all dwell times, we found that seeing one future target (horizon = 1) significantly reduced the average reach time. When information about multiple future targets was available (horizon > 1), we observed no further reduction in movement times. Although this suggests that participants only benefited from seeing one movement into the future, using an additional key manipulation, we could show the motor system actually plans further ahead: at the beginning of the reach to the 1 target, we displaced the next 2 target in the condition that participants could see two future targets (Horizon = 2). After the jump, we observed an uninterrupted reach to the 1 target, followed by a brief reach toward the original position of the 2 target. This indicates that planning of the 2 target had already started before the initiation of the movement to the 1 target. We also found that the preparations of multiple future movements interact with each other. First, we observed that the availability of a 2 target changes the curvature of the movement to the 1 target in a way that is biomechanically advantageous for the transition between movement segments. Second, in case of displacing the 1 target, the availability of the 2 target also slowed down the re-planning of the reach to the new 1 target suggesting that the two planning processes may compete for the same resources.

3-B-8 Co-contraction and force generation are driven by separate synaptic inputs

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The musculoskeletal system, owing to its redundancy, may produce the same joint trajectory or torque profile with a multitude of combinations of muscle activation patterns. What differentiates these patterns is the presence of co-contraction, which does not contribute to endpoint force but allows to modulate stiffness. Despite the generally acknowledged role in stiffness control, how the CNS regulates co-contraction is still unclear and two main hypotheses have been debated. According to one hypothesis, during a co-contraction task, muscles are independently recruited to control force and stiffness, and therefore the same synaptic inputs that drive motoneurons (MNs) to generate force also modulate stiffness. In contrast, according to the second hypothesis, co-contraction is regulated through a separate synaptic input shared by the MN pools of antagonist muscles and therefore independent from the inputs underlying force generation. In this study we used a recently developed approach that allows the independent control of the displacement and the stiffness of a virtual end-effector by simultaneous exertion of isometric force at the hand and modulation of co-contraction of several upper limb muscles. The exertion of force along multiple directions with different levels of co-contraction allowed to modulate independently the components of neural input to MNs responsible for force generation and those involved in stiffening the limb. We identified trains of action potentials of MNs by decomposing High-Density surface electromyograms recorded from two antagonist muscles, i.e. the Biceps Brachii and the Triceps Brachii muscles. As it is well established that the common synaptic input within a given MN pool can be identified using coherence analysis on the trains of action potentials of pairs of MNs, we used the same approach to assess the synchronous modulation of the neural drive to

MNs across muscles and to unveil synaptic inputs shared across muscles. We identified a common drive to MNs of the two antagonist muscles through a cross-muscle coherence analysis. We found a significant coherence peak in the beta band during the co-activation of the two muscles for stiffening modulation but not for force generation without co-contraction, thus demonstrating the existence of an independent synaptic input specific for modulating co-contraction. Moreover, a within-muscle analysis allowed to identify two subsets of MNs that were selectively recruited either to generate force or to modulate co-contraction. Based on our results, we propose that the generation of endpoint force and the active modulation of stiffness require two separate pools of MNs driven by separate neural pathways. This study is the first to directly investigate the extent of shared versus independent control of antagonist muscles at the motor neuron level in a task involving concurrent force generation and modulation of co-contraction.

3-B-9 Anticipatory force control for skilled manipulation of objects at variable contact points depend on visual feedback at grasp contact

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BACKGROUND AND AIM: Anticipatory force control is key for dexterous hand-object interactions. Visual feedback of an object's physical properties and sensorimotor memories from prior interactions form internal representations that enable anticipatory force control and subsequent dexterous manipulation. Most studies on which this prevalent theory is based used designs that constrain the grasp contact points, which fails to explain a fundamental aspect of dexterous manipulation: our ability to grasp an object at various contact points and adjusting our forces accordingly. This presents a major paradigm shift in that force planning relies not only on sensorimotor memories and visual cues of object properties, but also on where the object is grasped. In this study, we determine how sensory information of the hand from reach onset to grasp contact is integrated online and contributes to force coordination for subsequent dexterous manipulation. METHODS: Right-handed participants lifted a symmetrically shaped object with an asymmetric center of mass (CM) at unconstrained contact points. Sensorimotor learning rates were quantified based on minimizing roll of an object with a left or right CM, with the given CM switching after every block of 8 trials (total blocks: 8). Four between-subjects conditions manipulated the availability of visual feedback at reach onset (OFF-ON), grasp contact (ON-OFF), or both (OFF-OFF; ON-ON). RESULTS: The difference in object roll between the first and last post-rotation trial in each block of trials became smaller with subsequent blocks in all groups, indicating learning to generalize generating a compensatory torque of appropriate magnitude and direction for manipulating an object with a switching CM. Learning was faster and most notable in ON-ON and ON-OFF than OFF-ON and OFF-OFF groups. CONCLUSIONS: Our results suggest that visual feedback at movement onset, but not grasp contact, is used to modulate forces in responses to digit position during sensorimotor learning of dexterous object manipulation. The timing of sensory feedback contributing to successfully manipulating objects is highly relevant to work on brain-computer interfaces and other technologies aiming to restore skilled grasp in patients with a loss of hand function.

3-B-10 Restoring optimal motor sequence learning using brain stimulation

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The execution of a sequential motor task is often characterized by the emergence of hierarchical structures, commonly referred to as motor chunks, which facilitate the accurate execution of sequences at increasing speeds. Comparing motor skill acquisition in more than 150 healthy adults (Maceira-Elvira et al., 2021), we found that optimal motor skill acquisition relies on prioritizing the optimization of the accuracy over the speed, which allows for a more efficient mechanical execution, manifested as distinct chunking patterns. Finding this process to be diminished in older adults, we applied noninvasive brain stimulation in an attempt to support the aging brain to compensate for these deficits. Our results showed that anodal direct current stimulation applied over the motor cortex restored the mechanisms involved in the consolidation of spatial features, without directly affecting the speed of execution of the sequence. This led older adults to sharply improve their accuracy at the early stages of training, resulting in an accelerated emergence of motor chunks, with the effects of stimulation seemingly limited to the first training session; as such, prolonged exposure to stimulation did not proffer additional benefits. Therefore, our results suggest atDCS can partially restore motor skill acquisition in individuals with diminished learning capabilities by aiding the integration and storage of task-relevant information upstream of the primary motor cortex in the motor network, without directly influencing the motor execution of the sequence.

3-B-11 Data-driven discovery of motor control circuits of locomotion on variable terrains

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Humans and animals possess remarkable abilities to negotiate challenging terrains during walking. Discovering the organisational principles of motor systems that facilitate such efficient and adaptive walking can provide insights to designing artificial robotic controllers for dynamic locomotion in diverse environments. One challenge towards this aim is that flat and variable terrains pose conflicting requirements for motor circuits. While flat terrains favour centralised, feedforward architectures that autonomously generate efficient gaits, variable terrains demand flexible gait adjustments, a property of feedback based architectures. We studied this dichotomy in Drosophila melanogaster using a combination of behavioural analysis, genetic and optogenetic sensory silencing and data-driven mathematical modelling. First, we designed a behavioural paradigm to obtain for the first time 3D limb kinematics during repeatable behavioural epochs in untethered flies. We achieved this through a motorised climbing assay coupled with closed-loop optogenetic stimulation in which the difficulty of the climbing task could be varied by obstacles with different spacing and the silencing of sensory neurons. To extract the 3D poses, we developed LiftPose3D, a computational method using deep learning based monocular (single camera) pose estimation. We observed that on flat terrains flies whose mechanosensory neurons were silenced walked as well as control flies predominantly using the tripod gait, corroborating previous findings. However, obstacles caused gait perturbations, which in control animals resulted either in the rapid recovery of the tripod gait, or gait adaptation, depending on the speed of walking and the inter-obstacle distance. To test whether this observation is consistent with flies switching from feedforward to feedback-based circuits on rough terrains, we screened a library of sensory neurons to identify neuron classes whose silencing allowed flat terrain walking but suppressed gait recovery or adaptation on rugged terrains. To unravel parsimonious circuit topologies, we developed a data-driven mathematical model combining variational autoencoders and sparse symbolic regression of pose dynamics. The distribution of network topologies revealed distinct structural classes, favouring decentralised architectures in challenging terrains and centralised architectures in smooth terrains and sensory silenced flies. Our work provides insight into how freely behaving animals tune their motor circuits for efficient locomotion.

3-B-12 Taskload, workload and biomechanical criteria in movement control

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Key words : motor control, optimality, workload, Fitts task, biomechanical criteria The activity of flying an aircraft is complex and requires a high workload (WL) for the pilot to perform well. Design choices of flight assistance functions are strongly guided by the level of workload (WL). Quantifying WL through physiological measures is not straightforward and few models exist to explain the mechanisms behind it [1]. The effectiveness of assistive devices depends on an understanding of the sensorimotor system, specifically, movement optimality (OPM). OPM represents how the nervous system manages the trade-off between action performance and the cognitive cost related in its execution. It can be quantified through biomechanical criteria [2]. Some studies have characterized motion optimality through analyze of the kinematics. [3] have shown that movement kinematics differs according to the task difficulty (i.e., ID). Increasing task ID is associated with the emergence of a self-sustaining steady state of motion in the form of a phase plane. The change of topology describes the evolution from a limit cycle attractor (i.e. characterizes a continuous motion) to a fixed point attractor (i.e. characterizes a discretized motion). This ID-dependent pattern bifurcation implies that the neuro-musculoskeletal system oscillates between two modes of control to adapt to the spatiotemporal constraints of the movement [4]. Furthermore, other studies on motion amplitude spectrum analysis have shown the change in motion amplitude spectrum with increasing ID. The motion appears to have a 1/f noise type spectrum when the motion produced is controlled by low intensity control processes (i.e. low ID) which is represented by a time structured signal. A switch to a white noise type spectrum is observed when the motion control increases in intensity (i.e. high ID). The objective of this study aims (1) to identify the relationship between task difficulty (ID) and OPM, and (2) to compare biomechanical criteria to subjective measures of WL in different ID conditions. 40 participants performed a reciprocal version of Fitts' task [5]. The participants are instructed to alternatively reach two targets by operating a sidestick on the medial-lateral axis. 5 levels of ID are tested. Biomechanical criteria are calculated from kinematics recordings made on the participant's arm. Results show that ID increases implies (1) decrease of performance, (2) appearance of nonlinearities in movement kinematics, (3) a switch from a 1/f noise spectrum in easy ID to a white noise spectrum in difficult ID. These results validate the hypothesis that biomechanical criteria quantify cognitive workload used in system design ergonomics. Références [1] Berret, B., Chiovetto, E., Nori, F., & Pozzo, T. (2011). Evidence for composite cost functions in arm movement planning: an inverse optimal control approach. PLoS computational biology, 7(10), e1002183. [2] Fitts P.M., Peterson J.R.,(1964), Info

3-B-13 Scalpels, Skillets, and Sports - What Skilled Motor Behaviour Actually Looks Like in the Real-World

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Studies into human movement generally fall into one of two broad categories: laboratory-based rigid predefined tasks in a reductionist environment to probe mechanisms, or real-world motion tasks, e.g. in sports, that are mainly descriptive in nature. Our aim is to understand how skilled human motor behaviour looks quantitatively, what differences and caveats arise vs natural movement, and how to best analyse highly variable skilled movement data that arises only in the real world. We compare the three different motion tasks; 1. expert neurosurgeons undertaking an extraventricular drainage intervention (N=36 ~ 10% of the UK neurosurgeon population), 2. volunteer subjects performing a cooking task in a kitchen (N=7) and 3. volunteers playing a pool billiard shot in a repeated identical trial-framework (N=13). All motion data was collected utilising a full-body motion capture suit. We compared the general statistics of the motor behaviours and found that total variability in the kinematics varied considerably, even among highly skilled and precise tasks such as in brain surgery. The degree of experience in the skill, (e.g. surgeon seniority, previous background in pool playing) showed some correlations in terms of motor variability and movement parameters, but were not consistent with the black-and-white picture painted by studies in reductionist motor experiments. We compared actual kinematics across subjects, despite their high degree of intersubject and intrasubject variability in the movement data, by developing a form of time series clustering using an agglomerative approach using Dynamic Time Warping. Our results showed that human experts did not follow a similar movement paradigm but fell into distinct groups with a few outliers. This work has considerable scope for future data-driven analyses of human motor expertise lending themselves to the development of smart technologies for expert training and human performance studies.

3-B-14 JARVIS: A toolbox for highly accurate 3D markerless pose estimation under heavy occlusion

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The analysis of movements is a crucial element of behavioral science, neuroscience as well as other disciplines. An essential component of movement analysis is the acquisition of movement kinematics. Unfortunately, marker- or sensor-based kinematic tracking solutions either impair natural movements or are altogether impossible to implement for many species. Therefore, markerless tracking solutions based on deep learning, like DeepLabCut, AniPose and Dannce, have recently experienced increased popularity. Despite growing interest, precise and outlier free motion capture is still difficult to obtain. Frequent self-occlusion of the subject and occlusion by objects often lead to severe outliers during pose estimation. Systems that base their predictions on video data from a single camera often lack the multi-perspective information to make accurate predictions in such cases. On the other hand, systems based on pure 3D convolutional neural networks require huge amounts of training data to produce accurate predictions. In addition, all of the currently available toolboxes fall short in providing easy-to-use solutions for recording and annotating multi-camera data at high resolutions and frame rates. Our 3D markerless tracking toolbox JARVIS provides an end-to-end solution to all those challenges. The toolbox consists of three parts: - A GUI based acquisition program enabling the recording of high resolution videos from multiple cameras at high frame rates by leveraging GPU accelerated online JPEG compression. This allows video acquisition at a cumulative frame rate of up to 1500Hz across cameras at a resolution of 1280x1024 on modern GPUs. - A second GUI based application allowing easy multi-camera calibration and annotation of the multi-perspective data set. - A python package to train our hybrid 2D and 3D network architecture and create the final 3D pose predictions. The network is specifically designed to work with limited amounts of labeled data. For systems evaluation, we compared the performance of JARVIS, DeepLabCut and Dannce on a human hand tracking benchmarking task (9360 annotated frames, recorded using a 12-camera system). JARVIS achieved a median prediction error of 2.1mm, compared to prediction errors of 4.4mm and 5.8mm for DeepLabCut and Dannce, respectively. We also evaluated the fraction of miss-tracked joints, defined as joints with a prediction error of more than half of the average finger-segment length (14.2mm). JARVIS miss-tracked 0.7% of all joints, while DeepLabCut and Dannce frequently failed to predict correct joint locations at rates of 5.7% and 13.4%, respectively. Importantly, the additional tracking accuracy achieved by JARVIS significantly increased the captured magnitude and complexity of human and non-human hand movements, suggesting that highly accurate kinematic tracking is essential for studying true movement diversity. Supported by: Ministry of Lower Saxony, Germany, (DeMoDiag) and the German BMBF (CogNetDyn).

3-B-15 Individual and dyadic learning with a Body-Machine Interface

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Body-Machine Interfaces (BoMIs) exploit the large number of degrees of freedom of the body, mapping them into the smaller number of commands that are needed to control a device. Due to this feature, BoMIs can be used to investigate the problem of motor redundancy by evaluating how the users' internal model of the body and device dynamics evolves over time when learning a new skill. Recent studies showed that, despite presenting subjects an ill-posed inverse problem, with practice, BoMI users converged to a single stable internal model. Here, we extend these concepts to a social scenario. Often motor learning is conceived as a process taking place uniquely within the confines of a single person. Thus, no investigation has yet been conducted on how practicing a new skill in a social context affects the concurrent individual and collective learning dynamics. Our aim was to characterize the learning processes of subjects using a BoMI solo or in a synergic manner and investigate the formation and evolution of their internal model through time. To do so, we recruited 40 naïve participants which performed the experiment in pairs. Each participant was seated in front of a computer screen and controlled a cursor on his/her screen. The body signals were recorded by 4 Inertial Measurement Units, positioned one for each upper arm of both users, and the related quaternions were mapped into the positions of 2 cursors, one on each screen. Participants performed a reaching task and underwent a training protocol divided into 3 phases: 1-individual practice, 2-social practice and 3-individual practice. The body-to-cursor map (H) changed according to the type of practice: in phases 1 and 3 participants used an individual H and had complete control of their computer cursor; in phase 2 they had a common H and had shared control of the cursor, i.e. the same cursor positions were displayed on both screens. With practice, all participants learned to control the cursor. When investigating their behaviour during phase 2, we observed how, in each couple, one participant contributed more than the other to the task solution. We compared these 2 responses and, despite not noticing a difference in terms of individual performance either before or after the social practice, we observed a difference in the evolution of their individual inverse model. In the social practice, participants who contributed less to the cursor's control adopted a new model when sharing the cursor, while the ones who contributed more kept a consistent model, similar to that used in the individual practice. Results suggest that synergic learning could affect the evolution of the inverse model even after an initial individual practice of the skill. These preliminary findings provide relevant information regarding social motor learning. Further research will allow investigating how different types of interactions could affect the formation and evolution of the internal model when learning a new skill.

3-B-16 Sensorimotor predictions are dynamically modulated over the time-course of actions to attenuate the expected self-touch

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Self-generated touch feels less intense and less ticklish than identical externally generated touch (Bays et al., 2005; Blakemore et al., 1999; Shergill et al., 2003; Kilteni et al., 2019; Kilteni and Ehrsson, 2022). It has been proposed that this somatosensory attenuation phenomenon occurs because the brain predicts the tactile consequences of our self-generated movements using information from our motor command (i.e., efference copy) and uses these predictions to attenuate, or even cancel, the self-generated tactile sensations (Wolpert, 2001; McNamee and Wolpert, 2019). However, how these predictions are dynamically modulated over the time course of our actions to influence somatosensory perception remains poorly understood. Here we directly addressed this question. Thirty participants (15 male, 29 right-handed, aged 18-34 years) executed reaching movements with their right hand towards their left hand. We quantified the perceived intensity of touch (forces of 2 N) delivered to their passive left index fingers at 5 different phases of their right hands' movement: i) after the onset of the movement but before the right hand reached its maximal velocity (early trials), ii) at the time the right hand reached its maximal velocity (max trials), iii) close to the time of contact between the right and left index fingers (late trials), iv) at the time of contact between the fingers (contact trials), and v) after the contact (post-contact trials). We also quantified the perceived intensity of touch delivered to the participants' passive left index fingers while their right hand remained motionless (baseline). During the time-course of the right hand's movement, touch on the left index finger was perceived as significantly weaker compared to the baseline. This attenuated perception became significantly stronger during the late trials (~ 200 ms before the index fingers made contact), it reached its maximum at the time of contact, and returned to the level of the early trials after the contact. Control analyses revealed that this increased attenuation was not driven by differences in the kinematics of the movement or by changes in somatosensory precision, but by the temporal proximity of the delivered touch to the expected time of contact between the fingers. To further illustrate that this temporal modulation of somatosensory attenuation was due to the participants predicting the contact of their two index fingers based on their movement, we asked thirty new participants (14 male, 29 right-handed, aged 21-37 years) to perform the same movement without ever making contact between their fingers. We observed no temporal modulation of somatosensory perception throughout the movement in this control experiment. Together, our results highlight the predictive nature of the somatosensory attenuation phenomenon, and provide evidence that the brain dynamically shapes and finely tunes its predictions to attenuate expected self-touch.

3-B-17 Pallidal neurons in a vocal motor basal ganglia nucleus reflect motor sequencing

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Skilled motor behaviors such as speaking, writing, or playing the piano require a combination of fine control of moment-to-moment movement kinematics and flexible sequencing of longer behavioral "motifs". The basal ganglia are a group of subcortical nuclei implicated in a wide range of motor and cognitive functions, including motor kinematics and motor sequencing. The songbird Bengalese finch (Lonchura striata) has a song-specialized basal ganglia nucleus (Area X), which contains neurons that are homologous to mammalian striatal and pallidal neurons. Area X sits at the intersection of "evaluative" and "premotor" circuits in the songbird brain, and has been implicated in control of both acoustic structure and sequential features of song. Current hypotheses of Area X's computational role posit that it functions as a site of reinforcement learning, where dopaminergic reward prediction error signals are integrated with efference copies of recent motor commands and information about the broader motor sequence the command occurred in. However, it is not known whether or not Area X neural activity reflects either acoustic or sequential features of song. Of particular interest are Area X pallidal neurons, which are strongly modulated during singing and contain a subgroup that projects directly to the region of motor thalamus that controls song. Using in vivo electrophysiology in adult male Bengalese finches (N=4), we first show that Area X striatal and pallidal neurons can be separated by firing properties. We hypothesized that individual Area X pallidal neuron activity reflects both phonological and sequential information. To test this, we assess the tuning of individual neurons by analyzing activity at points in song where syllable sequencing varies across renditions. We demonstrate a strong relationship between firing rates in Area X pallidal neurons and syllable sequencing. This result is consistent with reinforcement learning models of song learning which predict that Area X integrates dopaminergic reward signals with contextual information about recent motor commands. In contrast, we find comparatively small correlations between Area X activity and syllable phonology. This also contrasts with previous work in the songbird motor cortical nucleus RA, where the activity of individual neurons correlates more strongly with acoustic features of song. Further analysis will examine the relationship between sudden pauses and deceleration of firing rates in pallidal neuron activity and song sequence and acoustics.

3-B-18 Increased visual feedback contribution to online corrections during faster movements

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Current theories suggest that the nervous system weighs different sensory cues and internal priors according to their reliability in an optimal (Bayesian) fashion. Moreover, it has been suggested recently that this principle of multisensory integration can be applied to online state estimation by considering delays and movement dynamics. Here, we investigated if feedback responses to combined force and visual perturbations are similarly influenced by manipulating visual feedback uncertainty. Additionally, given previous reports supporting the presence of dynamic multisensory integration, we decided to study the impact of visual uncertainty across different movement speeds. To test these hypotheses, we varied movement speed and visual feedback uncertainty about hand location in a reaching task, and looked at how these manipulations influenced corrective responses to mechanical disturbances combined with shifted visual information with varying levels of uncertainty. Fourteen participants performed 20cm goal-directed reaching movements with a KINARM Endpoint robot. Each participant performed one session of fast (movement time btw. 300-500ms) and slow (600-800ms) movements. The order of speed conditions was counterbalanced across participants. Upon movement start, we applied a rightward 9N constant load to the hand which participants had to counter to hit the target. Visual feedback of the hand was presented only during a 100ms time window starting when participants had moved 7cm towards the goal. To manipulate visual feedback uncertainty, we displayed either a single cursor, clouds of cursors with increasing spread, or no visual feedback. Participants were unaware that the presented visual feedback could be either aligned with the hand or shifted 2cm to the right or left. During 25% of trials we applied a leftward or no force to reduce predictability. In line with Bayesian integration, we observed an increase in endpoint variability with increasing visual uncertainty. Similarly, the use of visual feedback decreased with increasing uncertainty, shown by a reduced influence of the visual feedback shift on corrections. Surprisingly, endpoint variability was lower and visual feedback contribution to corrective responses was higher during fast movements, while, in principle, the combination of signal-dependent noise and temporal delays could have induced a decrease in sensory reliability and a reduction in feedback corrections. This suggests that there might be two different processes at play, a reliability-weighted integration of visual feedback and an overall increase in precision of estimates with increasing speed. Taken together, our results indicate that the brain might be able to adjust sensory weights for integration based on characteristics of the movement performed.

3-B-19 Reciprocal inhibition in spinal ipsilateral circuits

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Locomotion relies on alternating activity between muscle groups. This alternation, between left and right sides or between flexors and extensors, is enforced by reciprocal inhibition. In the mouse spinal cord, two genetically identified classes of ipsilaterally-projecting interneurons, the V1 (En1) and V2b (Gata3) classes, have been shown to provide asymmetric inhibition onto flexor and extensor motor neurons. Interestingly, these neuron classes are present in fish, as well as throughout the spinal cord of limbed vertebrates, suggesting that they may play a more ancient role in locomotor control. In axial networks, loss of V1 neurons slows down locomotion, whereas loss of V2b neurons speeds up locomotion. We investigated the connectivity of V1 and V2b neurons along the longitudinal axis of the spinal cord in larval zebrafish to examine whether their positions within the spinal network could explain these disparate observations. In recently published work, we showed that V1 neurons project long ascending axons, but only inhibit motor and premotor targets locally, switching to inhibiting sensory neurons at long range. Here we show that V2b neurons, in contrast, project long descending axons that inhibit motor targets both locally and long-range. Furthermore, we demonstrate for the first time that V2b and V1 neurons reciprocally inhibit each other in a longitudinally organized fashion: V2b neurons inhibit V1 neurons located 3-4 segments caudally, whereas V1 neurons inhibit V2b neurons located 1-2 segments rostrally. We furthermore show that V2b neurons, like V1 neurons, are active in phase with local motor activity. Because V2b axons descend (in the direction of locomotor propagation) whereas V1 axons ascend, we predicted that V2b-mediated inhibition arrives coincident with the rising phase of excitation, whereas V1-mediated inhibition arrives coincident with the falling phase of excitation. Through computational modeling, we have shown that indeed this late V1-mediated inhibition is necessary for the precisely timed termination of motor neuron bursts. We are currently exploring how V2b-mediated inhibition affects motor neuron activity. Collectively, these data show that ipsilaterally-directed inhibition inhibition has multiple, distinct functions in axial motor control: late-arriving inhibition from V1 neurons maintains precise timing while long range inhibition from V2bs may modulate gain. This rostrocaudally asymmetric, reciprocally inhibitory connectivity in axial circuits may thus provide a ground plan for evolution of rostrocaudally asymmetric limb networks.

3-B-20 Mental rotation strategies applied during sensorimotor learning incur a distinct cognitive effort cost

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We often apply cognitive strategies to tailor our motor performance, such as when lining up a shot towards a sloped green during a round of golf or when angling a shot to pocket a ball in a game of billiards. These kinds of strategies are also observed in the laboratory during visuomotor rotation tasks (VMR), in which participants readily re-aim their movements to counteract an unexpected visuomotor rotation. These re-aiming strategies share a characteristic of classic mental rotation (MR): preparation time scales with the degree of re-aiming necessary to counteract the visuomotor rotation (Georgopoulos, 1995; McDougle & Taylor, 2019). Although the degree of MR required to counteract the rotations in VMR tasks ought to be within the capacity of most participants, asymptotic performance often falls short of countering the rotation (Langsdorf et al., 2019; Weightman et al., 2022). This suggests that participants may be unwilling to perform the entire MR required to fully compensate for task errors that remain after implicit adaptation has saturated . It is unclear whether any resistance to completing the MR is due to the additional cognitive effort or time required, both of which may compound with task success in estimating the return rate of reward. Here, we conducted a series of VMR studies to test whether MR for re-aiming movements incurs a cognitive cost independent from its potential temporal and performance costs. In all experiments, participants attempted to bring a visually-displayed cursor to a target in a center-out reaching task. The VMR task followed a dual-adaptation design in which participants learned to counteract both a small (25°) and large rotation (75°) on interleaved trials. Additionally, implicit adaptation was blunted by introducing a delay in cursor feedback, forcing participants to use an MR strategy to improve performance. After training, participants were given the choice of counteracting either the small or large rotation. Participants exhibited a strong preference for the smaller rotation. In multiple follow-up studies, this preference for the smaller rotation was observable even when differences in rotation amplitudes were as small as 10°. Furthermore, these preferences persisted when controlling for both the temporal costs of MR and the performance deficits that accompanied larger rotation amplitudes. Taken together, these studies indicate that MR strategies incur a distinct cognitive cost, independent of common factors that are known to influence decision making based on the return rate of reward.

3-B-21 A tripartite motor control strategy governing goal-directed reaching in Drosophila

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Goal-directed reaching is ubiquitous across legged animals, allowing them to grasp and manipulate objects. Until now, most studies of goal-directed reaching have been performed on mammals. However, the mammalian nervous system is too large and complex to decipher underlying neural mechanisms. By contrast, adult Drosophila melanogaster is a powerful and tractable model for studying motor control. Flies have a numerically small and compact nervous system, exhibit a repertoire of complex limb-dependent behaviors, and have neurons that can be recorded, and remotely activated or silenced using genetic tools. Drosophila perform goal-directed reaching during antennal grooming, a self-contained and sequential behavior in which the front legs reach and rub antennae to remove unwanted debris. Mechanosensory neurons in the antennal Johnston's Organ are responsible for sensing antennal deflections, ultimately driving descending neurons (e.g., aDNs) in the brain that target downstream motor circuits in the fly's ventral nerve cord to drive antennal grooming. However, a holistic understanding of body part kinematics during this goal-directed behavior is still lacking. Pose estimation

and biomechanical simulation approaches promise important insights into how body parts coordinate overlapping and large degrees-of-freedom (DoF) during grooming. These insights can potentially inspire solutions to problems in robot manipulation. Here we overcome this knowledge gap by performing 3D pose estimation of full-body kinematics in flies during optogenetically and mechanically-induced antennal grooming. This allowed us to characterize how body part kinematics relate to one another in terms of symmetry, task and joint space. We discovered that antennal grooming depends on the tripartite coordination of the head, antennae, and front legs. In addition to the raising and cyclical movements of the front legs, flies pitch their heads to lower the groomed antenna, and actively lift the other antenna to move it out of the task space. These behaviors persist even when the front legs are amputated, suggesting a feed-forward coordination of anterior body parts during grooming. We further explored this control approach by separately fixing the locations of the antennae, head, and legs. To address the relative contribution of each movement to the behavior, we used NeuroMechFly, a physics-based biomechanical model of Drosophila. We replayed measured kinematics while attenuating or amplifying each joint DoF to infer contacts between body parts and reveal the relative importance of each body part. These results (i) provide the first quantitative, kinematic description of tripartite coordination between body parts during antennal grooming, (ii) demonstrate the relative importance of each movement through kinematic replay in a biomechanical whole-body simulation, and (iii) lay the groundwork to identify neural circuits and computations giving rise to this behavior.

3-B-22 Comparing cortical somatosensory and motor influences on visuo-proprioceptive realignment in the hand

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The brain estimates hand position visually and proprioceptively. Multisensory integration of visual and proprioceptive estimates gives us flexibility to cope with internal and environmental changes. For example, washing dishes with the hands immersed in water creates a spatial mismatch between vision and proprioception, as water refracts light. The brain resolves this conflict by realigning visual and proprioceptive estimates of hand position. This presumably affects movements planned with that hand, but the neural basis of such an interaction is not well understood. Using transcranial magnetic stimulation (TMS), we recently found somatotopically focal changes in M1 excitability accompany visuo-proprioceptive realignment, even after controlling for motor behavior. M1 changes were related to both visual and proprioceptive realignment, suggesting that S1-M1 or V1-M1 connections may be involved. Indeed, changes in inhibitory pathways from S1 to M1 were strongly associated with proprioceptive realignment. However, it is unknown if activity in M1 or S1 plays any causal role in the realignment process, or if changes in these areas are simply a side-effect of activity elsewhere in the brain. We tested three groups of healthy young adults using an inhibitory TMS paradigm (continuous theta burst, cTBS) on M1 or S1 left hand area, or sham. We hypothesized that applying cTBS over S1 would increase participants' variance in estimating proprioceptive targets and their magnitude of proprioceptive realignment. If previously observed changes in M1 excitability play a causal role in realignment, we would expect cTBS over M1 to increase proprioceptive realignment and decrease visual realignment. Participants completed several blocks of trials in a 2D-VR touchscreen apparatus, before and after cTBS. Participants were asked to point, with their unseen right finger, to their estimated location of visual (V), proprioceptive (P), and combined (VP) targets related to their left index finger. There was no direct vision of the hands, and participants received no feedback. Blocks of trials before and after cTBS were veridical (V targets displayed directly on top of P targets). This was followed by a misalignment block in which the V target gradually shifted 70 mm forward from the P target. Data collected thus far (~12 subjects per group) suggests that participants in all three groups realigned both vision and proprioception. Comparing the veridical targets before and after cTBS, participants in the S1 group had relatively higher variance in estimating P target positions compared to the other groups, consistent with an increase in proprioceptive variance. During the misalignment block, the S1 group realigned proprioception more than the other groups. Current results do not suggest that the M1 group performed the behavioral measures differently from the sham group. These results are consistent with a role for S1, but not M1, in visuo-proprioceptive realignment.

3-B-23 The influence of intersegmental dynamics on limb position sense

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During multijoint limb movement, the motion of limb segments can be driven actively, by muscle torque, and/or passively, by interaction torque--rotational force that arises passively at one joint due to motion of an adjacent limb segment about another joint. Proprioception is known to play a critical role in compensating for interaction torques, and deafferented patients have marked deficits in this aspect of motor control compared to their healthy counterparts. This observation is seemingly at odds with the widely-held belief that proprioceptive sense is poor during motion that is not driven by active muscle contraction, and suggests that proprioceptive acuity might be preserved during motion that is driven by interaction torque. We designed a study to determine whether the nature of the torques driving joint motion influences proprioceptive sense at that joint. We quantified proprioceptive acuity at the elbow joint while participants were midway through each of two kinds of arm movements that both involved elbow extension: a 'reaching' movement in which elbow extension was primarily driven passively by interaction torques, and a 'whipping' movement in which elbow extension was primarily driven actively by elbow muscle torques. Differences in the magnitude and direction of shoulder rotation between the movements gave rise to differences in interaction torques at the elbow. Minimal interaction torque arose at the elbow during 'whipping' movements, hence elbow extension was driven primarily by active muscle torque. Conversely, there was minimal muscle torque produced at the elbow joint during 'reaching' movements, hence elbow extension was driven primarily by interaction torque. We delivered equally sized and timed perturbations to the elbow joint during 'reaching' and 'whipping' movements and had participants make two-alternative forced choice judgements about the direction in which the elbow joint was perturbed (flexion or extension). Our findings indicate that participants' ability to correctly sense the direction of an elbow-joint perturbation differed depending on if the perturbation was delivered during interaction torque-driven motion or active muscle torque-driven motion. Specifically, we found that participants had superior perceptual acuity when joint motion was driven by interaction torque, suggesting that proprioceptive sense is preserved during this type of motion.

C – Posture and Gait

3-C-24 Older adults can maintain gait stability when dual tasking

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Gait variability during dual tasking has been revealed as a robust predictor of fall risk in older adults both with and without cognitive decline. So far, findings have been mixed regarding the effects of concurrent cognitive task performance on gait variability. Standard deviation or the coefficient of variation of stride length/time/velocity, which are the most common measures for quantifying gait variability, are too simple to sufficiently capture changes in high dimensional signals such as gait cycle trajectories. This can lead to underestimation or overestimation of the examined effects. Here, the Mobile Brain-Body Imaging modality was used to record kinematic data at high temporal and three-dimensional (3D) spatial resolution, and subsequently Dynamic Time Warping (DTW) was applied to the extracted 3D gait cycle trajectories, to investigate how stride-to-stride variability changed in young adults and older adults when an executive functioning task was combined with treadmill walking. Treadmill walking kinematics of 25 young (YA, age = 22.32 ± 3.34 years) and 25 older (OA, age = 71.24 ± 3.61 years) healthy adults were recorded using Motive 2.1, while participants performed a visual response inhibition Go-NoGo task. Gait cycle was defined as the time interval between two consecutive heel strikes of the same foot. Heel strikes were identified as the local maxima of the heel marker position waveform in the fore-aft dimension of movement. Using MATLAB, the gait cycles of the heel markers were detected for 8 4-minute walking blocks: 7 blocks of walking while performing the task (dual-task/DT), and 1 block of task-free walking (single-task/ST). Stride-to-stride variability was quantified as the mean Euclidean distance between consecutive 3D gait cycle trajectories of each heel, using DTW. DTW measures the similarity between two time series, by warping them to minimize the distance between them. Right-heel and left-heel stride-to-stride DTW distances were pooled to calculate the mean DTW distance per participant. Mean DTW distance was subjected to a 2 (Group: YAs, OAs) x 2 (Load: ST, DT) ANOVA. Mean DTW distance was found lower during DT compared to ST (significant mean effect of Load; F(1,48) = 7.43, p = 0.01). Post-hoc tests revealed that this effect was driven by YAs. No significant main effects of Group (p = 0.96) or Group/Load interaction were found (p = 0.40). These results indicate that OAs do not differ significantly from YAs in terms of stride-to-stride variability. Also, adding cognitive task load stabilized gait in YAs. The present findings align with the U-shaped hypothesis according to which lower cognitive loads improve walking performance by shifting attention away from the quite automatic walking task. However, higher cognitive loads tend to have the opposite effect, since they putatively prompt increased allocation of neural resources to execution of the cognitive task thus conflicting with the resources used by walking.

3-C-25 Express Visuomotor Responses in Hip Abductor Muscles: Evidence for an Intricate Relationship Between Fast Stepping and Postural Control

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BACKGROUND: Our ability to rapidly interact with our environment has been studied in reaching via the measurement of express visuomotor responses (EVRs). EVRs are directionally tuned muscle activity bursts that aid in the rapid initiation of the goal-directed movement. They occur ≈100ms after visual stimulus onset, hinting at the involvement of a direct subcortical pathway via superior colliculus. Fast stepping responses are equally important as reaching, yet the presence of EVRs in the lower extremities has not yet been demonstrated. Stepping is more complex than reaching due to increased postural demands, which usually need to be compensated for via anticipatory postural adjustments (APAs) that involve muscle recruitment opposite to that of the focal stepping movement. We here aimed to investigate stepping-related EVRs and their interaction with the APAs that precede step initiation. METHODS: We used an emerging target paradigm, during which healthy young subjects (N =16) stepped rapidly towards flashed visual targets presented randomly to the left or right. We recorded surface EMG of bilateral gluteus medius (GMed), a muscle that is oppositely involved in APAs and stepping; and bilateral ground reaction forces. Two target location conditions were introduced. First, in a lateral stepping condition with reduced postural demands prior to step initiation, targets were presented in front of and lateral to the stepping leg. Second, in a medial stepping condition with increased postural demands, targets were presented in front of and medial to the stepping leg. Outcome measures were EVR presence, magnitude and latency, APA presence, and stepping reaction times. RESULTS: In the lateral condition, EVRs were robustly and strongly present in GMed contralateral to the target (16/16 subjects, M = .12, ML = 108ms). In medial stepping, EVRs were detected in few subjects (3/16) with low magnitude (M = .05, $p < .001$) and slightly longer latencies (ML = 111ms). APAs could only be identified in the medial condition (M = 167ms), following the EVRs by ≈55ms. These observations coincided with significantly faster stepping RTs in the lateral (M = 323ms) compared to the medial condition (M = 442ms; $p < .001$). We found a strong negative correlation between EVR magnitude and subsequent stepping RT in lateral stepping ($r = -0.63$ $p < .001$). This correlation was absent in medial stepping. CONCLUSIONS: Here we provide evidence for an intricate relationship between EVRs and postural control. In the lateral condition, where APAs were absent due to low postural demands, EVRs aided in the execution of a fast step, as strong EVRs correlated with faster stepping RTs. In the medial condition, results were strikingly different: APAs were essential, as postural demands needed to be accounted for prior to making the step. EVRs were barely present in this condition, implying that higher-order areas suppressed the subcortical EVR network, as they would otherwise hinder APA execution.

3-C-26 Humans Plan Optimal, Multi-Step Control Sequences for Walking on Uneven Terrain

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Uneven terrain perturbs walking speed, if not for compensatory control by the central nervous system (CNS). Whereas optimality principles seem to govern movements such as upper extremity reaching, visual saccades, and steady level walking, it is unknown whether optimality applies or is even feasible for uneven walking. Steady walking appears to minimize energy expenditure with one periodic gait pattern, but on uneven terrain such optimality needs to consider an entire gait sequence, with complexity increasing exponentially with the number of consecutive uneven steps. Optimality may only apply for a limited number of steps, or perhaps not at all. Here we show that humans do economically compensate for uneven terrain with strategic, multi-step action sequences. Optimal planning need only consider about eight upcoming steps at a time, because the momentum of walking persists only a limited distance. Such planning is sufficient to predict compensations by human subjects traversing a variety of artificial uneven terrains. We measured speed fluctuations as healthy adults (N = 11) walked on each of seven different terrain profiles. The task was to traverse the terrain while starting and ending at steady level gait, in roughly normal duration for level walking. This was modeled as an optimal control problem based on the pendulum-like dynamics of walking, with an energy-dissipating step-to-step transition between one pendular stance leg and the next. Active and costly mechanical work is required to restore the dissipative losses, which also explain the limited persistence of momentum. The predicted speed fluctuation trajectories were compared against humans, whose walking speed and timing were measured with inertial measurement units fixed atop the feet. The uneven terrain profiles had up to 16 evenly spaced steps, with heights deviating by up to 7.5 cm. Humans produced distinct speed fluctuations for each terrain that agreed well with model predictions. The speed trajectories approximately conserved overall average speed and walking duration ($p = 0.9$), as subjects were instructed. The speeds fluctuated by about 3 - 5% (coefficient of variation) within each trial, in a pattern that resembled model, as quantified by a significant and positive correlation coefficient for each terrain (0.51±0.11 mean±s.d.; across all subjects and all terrains, $p<0.05$). The compensations were also anticipatory, with significant changes in speed of about 4.5% prior to the first uneven step ($p<0.05$). Humans perform anticipatory control that considers current and future steps, to yield multi-step strategies for maintaining overall speed despite uneven terrain. The control maps a trajectory of upcoming uneven terrain into a control action sequence, and could be interpreted as an optimal, inverse internal model of walking within the CNS. Within that internal model, only about eight steps of look-ahead and working memory are sufficient to economically plan for uneven terrain.

3-C-27 Mapping step-to-step exploration and energetic cost to comprehend human locomotor adaptation

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Humans can adapt to different locomotor contexts, even though exposure to such environmental settings may be novel. This is mainly possible due to the ability to leverage an internal locomotor model, structured hierarchically, that controls the person's whole-body movement while dynamically interacting with the surrounding environment. This two-tiered unified framework consists of 1) a low-level step-to-step controller ensuring a stable gait and 2) a high-level reinforcement learner improving performance, where two layers interact with each other in different time scales. These time frames (short and long) are different because each underlying model has different associated variables and objective functions. For example, the low-level controller regulates the step-to-step foot placement based on the person's body state information, whereas the high-level learner explores the space in the gradient that minimizes the overall cost function (e.g., energetic cost) at a longer time scale. An important feature in this framework that enables 'learning' during locomotor adaptation is the dynamic interaction between these layers where the internal model can update the relevant controller gains based on subsequent energetic cost resulting from step-to-step exploration. Here, we systematically investigated this complex mapping between exploration and energy using human experimental data in novel locomotor tasks: walking on a split-belt treadmill. Utilizing a split-belt paradigm is an efficient means of understanding how humans adapt to a novel walking scenario as well as different contexts (i.e., small vs large speed differences). In our experiment, the participant walked on a split-belt treadmill in varying speed differences ranging from 0.6 m/s ~ 1.4 m/s (speed on one leg set constant at 1 m/s) for 45 minutes across multi-day sessions. During walking, we recorded motion capture and metabolic cost data to evaluate the participant's kinematics, kinetics, and energetic cost. Using this data, we've analyzed multiple variables that dictate the learning algorithms such as foot placement variability, step length asymmetry, and metabolic cost. The results indicate a varying trend in the participant's metabolic cost, which led to a post-hoc analysis in comprehending the relationship between the user's step-to-step exploration and the associated energetic cost. Our key findings indicate that a greater exploration of the fast-belt leg led to a greater decrease in energy. This phenomenon may indicate that a greater exploratory noise is needed to overcome the large signal-dependent sensory noise occurring at a faster walking speed. Our study results provide meaningful contributions to the field as understanding this relationship provides insightful directions for decreasing energy cost based on body states. The next step from this study will focus on developing a data-driven inference of the governing learning algorithm inherent to humans for locomotor adaptation.

3-C-28 Common sensory information encoding balance error drives evoked cortical and muscle activity during reactive balance

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Reactive balance is a robust paradigm to assess shifts in hierarchical motor control, that may be transferrable to different motor behaviors like reaching and walking. Balance control is considered automatic and mediated through subcortical sensorimotor circuits. However, studies in older adults (OAs), suggest top-down cortical mechanisms become engaged, presumably to compensate for inadequate subcortical balance control mechanisms. However, we lack an understanding of how and when cortical resources are engaged during balance control. Cortical activity measured using electroencephalography (EEG) during reactive balance control can provides more mechanistic insight not possible with behavioral measures of cognitive dual-task interference. We previously showed that sensorimotor cortical beta power (β; 13-30Hz oscillatory activity), a signature of sensorimotor processing, has a similar waveform as balance correcting muscle activity and scales with balance difficulty increases. We hypothesize that common sensory information drives both sensorimotor cortical β power and muscle activity during reactive balance recovery. Balance correcting muscle activity is driven by sensory information encoding balance error and explained by a combination of time-delayed center of mass kinematics (CoM). Here we tested whether perturbation evoked β is also driven by balance error. We predict that when β activity increases with balance challenge it will be reconstructed by a combination of time-delayed CoM kinematics. We delivered series of unpredictably timed support-surface perturbations at 3 magnitudes while recording EEG, muscle activity, and body kinematics in 18 healthy young adults (HYAs). β power at the Cz electrode and medial gastrocnemius muscle activity were reconstructed Reconstructions of β power varied in accuracy across participants (R2 0.00-0.84, mean 0.36±0.22), but reconstruction accuracies improved when evoked β magnitude was higher (slope: 0.032, p<0.001). Thus, perturbation evoked β appears to be driven by sensory information encoding balance error, similar to balance correcting muscle activity. Muscle reconstruction accuracies also varied (R2 0.06-0.94, mean 0.70±0.20) and were lowest when β magnitude was highest (p=0.09). The reduction of muscle reconstruction accuracy in conditions that evoked the most β suggest that balance correcting muscle activity can be attributed to a brainstem-mediated template when the cortex is not engaged but deviates from this template when cortical activity is high; thus, β may index when balance correcting muscle activity shifts from being predominantly subcortically-mediated to becoming more cortically-mediated as balance difficulty increases.

3-C-29 Age-related EMG power spectrum changes in leg muscles during walking is not reflected in altered repeatability of gait cycle EMG profiles

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Background: Ageing affects structure, quantity, and function of skeletal muscles [1].Changes include loss of motor units and atrophy of remaining muscle fibres with fast (type II) fibres affected more than slow (type I). Altered muscle characteristics may modify motor control of activities such as walking This may partially explain why walking speed decreases with age [2]. Muscles such as the plantarflexor soleus (SO) have a greater proportion of slow muscle fibres compared to its synergist, medial gastrocnemius (MG) and may be differentially impacted by ageing resulting in altered activation patterns and repeatability. Aim: The purpose of this study was to investigate if there was a difference in repeatability of EMG gait cycle intensity profiles between: a) older and younger adults; b) between muscles. The hypothesis is that older adults will display lower repeatability of EMG patterns compared to younger adults Methods: The study investigated two groups: 6 young females (21-30 years) and 6 older (60 -75 years) females. Muscle activity was recorded from 3 leg muscles (SO, tibialis anterior (TA), MG) using a wireless EMG system (PLUX S.A.). Participants walked for 5-minutes on a motorised treadmill at their comfortable walking speed. Gait events recorded from contact switches on the foot segmented the EMG into gait cycles. Power spectra were estimated using a nonlinearly scaled wavelet transform with a bank of 11 wavelets (7 - 395 Hz) [3]. Total intensity was calculated as the sum of intensities of w3-11. The coefficient of multiple correlation (CMC) was used to quantify waveform similarity and repeatability across gait cycles for EMG signals [4]. Mann-Whitney U tests investigated differences in CMC, between young and older females and between muscles. Results: There were significant effects of age and muscle on the EMG power spectrum. TA and SO had more energy in higher frequencies in older compared to younger adults whereas MG displayed a shift to lower frequencies in older adults. There was no effect of age on CMC ($p>0.05$) of gait cycle EMG profiles for TA, SO and MG. There was a significant effect of muscle with CMC for TA being significantly smaller than MG ($p=0.024$) and SO ($p=0.046$). Conclusion: Results indicate that although there was a difference in the EMG power spectrum with age, it did not reflect in altered repeatability of EMG profile. The older participants were healthy and very active which may account for no difference observed. Muscles however displayed differences in gait cycle EMG repeatability with plantarflexors displaying greater repeatability than the dorsiflexor. As motor control of dorsiflexion is achieved mainly by TA whereas 3 muscles mainly control plantarflexion, this may explain the difference in repeatability. References: 1. Power GA et al., J Sport Health Sci 2013,2:215-226 2. Studenski S et al., JAMA 2011,305(1):50-58 3. von Tscharner V, JEK 2000,10:433-445 4. Walla ME et al., JEK 2020,55:1050-6411

3-C-30 Modeling and simulations of muscle contracture observed during crouch gait in cerebral palsy patients

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The spastic behavior observed in cerebral palsy (CP) patients leads to constant muscle hypertension, generating muscle shortening and higher stiffness. These multiple combinations of impairments make it difficult to understand the specific role of each impairment in the resulting gait deviation. Experimental results in CP patients walking in crouch gait demonstrated that muscle contracture is primarily due to fewer sarcomeres disposed in series with a longer length than typically developed children. Therefore, the muscle is constantly stretched, and more collagen fibers increase muscle stiffness. For this reason, the forces generated in the muscle-tendon unit are mainly due to passive elements with a higher passive response to strain. This study isolates the effects of muscle contracture in hamstrings and iliopsoas by using the framework SCONE for predictive neuromuscular simulations. A previously developed musculoskeletal model and reflex-based controller for sagittal plane simulations of human locomotion is used to replicate pathological gait behavior. A CMA-ES algorithm optimizes the neural parameters to minimize metabolic effort and promote gait stability. The contracture condition is generated by decreasing the optimal fiber length and tendon slack length and increasing the muscle stiffness in the Hill-type muscle models. The results show that the hamstrings and iliopsoas muscles are constantly in a stretch condition since the fiber length is longer than the optimal fiber length. This behavior generates a high passive response that is the main contributor to the force generated in the muscle-tendon units. These experiments showed that a 20% increase in muscle stiffness parameters with a 20-30% reduction of the optimal fiber length could achieve a constant stretch condition. Severe crouch gait could be modeled by reducing the tendon slack length by 5-10% in parallel with the reduction of optimal fiber length. The biomechanical impairments directly affect the model's pathological kinematics showing a knee flexion constantly above 20 degrees and above 40 degrees for severe crouch gait. An increased hip flexion between 5 and 50 degrees is also observed due to the iliopsoas contraction. Excessive dorsiflexion naturally emerged from the crouch gait condition. More severe dorsiflexion typical of crouch gait could be reached by modeling plantarflexor weakness reducing the muscle's maximum isometric force by 20%. In conclusion, this study successfully replicated the kinematic behavior of crouch gait typically observed in CP patients, evaluating each impairment's effect. Furthermore, this study highlights the importance of replicating the biomechanical behaviors of muscles' passive response due to muscle overstretch in modeling contractures. Similar procedures could be used for patient-specific modeling and studying the causes of patients' gait deviations to assist clinical decision-making.

3-C-31 Motor unit coordination during skilled behavior in mice

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A fundamental goal of neuroscience is to understand how the brain flexibly controls and learns motor behaviors. The role of motor unit spiking is not well understood in the context of skilled motor control, but evidence suggests that motor units are coordinated differently across tasks. We used customized electrode arrays that enable the simultaneous, chronic recording of multiple individual motor units to study this coordination across skilled behaviors. We examined motor unit coordination in the mouse forelimb during bimanual force control and locomotion at different speeds. Many learned behaviors require the precise coordination of muscle groups, but we do not understand how the central nervous system controls muscle coordination at the level of the single motor unit. We therefore trained mice in a bimanual forceplate task wherein they must generate a precise combination of forelimb forces in order to receive a water reward. The mice were then implanted with a high-density electrode array in each triceps muscle. Simultaneous recordings of both output forelimb force and single motor unit spiking enable the study of muscle coordination both within and across limbs at the level of the single motor unit. By analyzing single motor unit recordings, we can better understand what strategies the central nervous system employs to generate specific patterns of movement. Further studies will use optogenetic techniques to probe the role of different cortical and subcortical structures during bimanual coordination. The coordination across motor units that underlies the robust features of locomotion at the muscle level has yet to be characterized. Throughout locomotion, mice flexibly adjust their behavior by modifying stride features. Even at a set speed, limb kinematics demonstrate variability. To examine how motor unit coordination generates different locomotor strategies, we recorded single motor units from the forelimb while a mouse freely walked at different speeds on a treadmill. We analyzed differences in spike patterns across strides to determine how their variability contributes to locomotor kinematics. These results along with those for the force control tasks will allow us to better understand how individual motor units coordinate task-specific movements.

3-D-32 Purkinje cell ablation reduces the flexibility of reach trajectories

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The cerebellum plays a major role in motor control. Cerebellar damage yields uncoordinated movements (ataxia), impaired motor adaptation, and general loss of movement precision and timing. The prominence of these deficits has led to a classical view of cerebellum as a sensorimotor predictive machine that operates according to error-based supervised learning rules. However, recent findings, including the observation of reward signaling within the cerebellar circuit, as well as renewed appreciation for cerebellar contributions to nonmotor functions, encourage us to extend this view. Here we asked whether expanding the space of allowed actions might reveal features of cerebellar function not traditionally emphasized in laboratory studies. We trained mice in a classical forelimb reaching task, but relaxed the initial conditions of the movement, allowing animals to use multiple strategies to obtain reward. We then assessed the contribution of the cerebellum under such conditions by ablating cerebellar Purkinje cells with diphtheria toxin (DT) in mice expressing DT receptors selectively in these neurons (DTX, n=6). Wildtype littermates, who also received a DTX injection (but don't express DTX receptors) were used as controls (CTR, n=6). Head-fixed, water deprived animals were trained to freely reach for a water droplet at a fixed position for 4-6 days. The setup was equipped with a high speed (400 fps) camera and 2 mirrors for 3D tracking with DeepLabCut. Reaches were identified by setting a threshold of distance to water, and forepaw movements were organized into 3 categories: i) reach with a resting paw starting point; ii) reach with a lifted paw starting point; and iii) grooming. All animals learned the task, except one CTR which was excluded from further analysis. CTRs and DTXs achieved a similar number of successful reaches, however, they resorted to different approaches: while CTRs tended to reduce the number of lifted paw reaches and increase the number of resting paw reaches over sessions, DTX mice mostly preserved the initial strategy (lifted paw). On average, reaches of DTX mice were slower, and appeared jerkier. Within each category, we found that while the variance of grooming trajectories was significantly increased in DTX, lifted and resting paw DTX trajectories were equally, or less, variable than controls. Finally, we analyzed how trajectories varied across categories, by computing the distance of each single reach to the mean trajectory of other categories (e.g. distance of resting paw to mean lifted paw and to mean grooming). We found that DTX trajectories were more stereotyped across different categories, ie they were less influenced by differences in starting points (resting or lifted), or the action goals (reach or groom). These findings suggest a cerebellar role in the generation of distinct flexible motor strategies.

3-D-33 Hasty sensorimotor decisions rely on an overlap of broad and selective changes in motor activity

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Humans and other animals are able to adjust their speed-accuracy tradeoff (SAT) at will depending on the urge to act, favoring either cautious or hasty decision policies in different contexts. An emerging view is that SAT regulation relies on influences exerting broad changes on the motor system, tuning its activity up globally when hastiness is at premium. The present study aimed to test this hypothesis. Fifty subjects performed a task involving choices between left and right index fingers, in which incorrect choices led either to a high or to a low penalty in two contexts, inciting them to emphasize either

cautious or hasty policies. We applied transcranial magnetic stimulation on multiple motor representations, eliciting motor evoked potentials (MEP) in nine finger and leg muscles. MEP amplitudes allowed us to probe activity changes in the corresponding finger and leg representations, while subjects were deliberating about which index to choose. Our data indicate that hastiness entails a broad amplification of motor activity, though this amplification was limited to the chosen side. On top of this effect, we identified a local suppression of motor activity, surrounding the chosen index representation. Hence, a decision policy favoring speed over accuracy appears to rely on overlapping processes producing a broad (but not global) amplification and a surround suppression of motor activity. The latter effect may help to increase the signal-to-noise ratio of the chosen representation, as supported by single-trial correlation analyses indicating a stronger differentiation of activity changes in finger representations in the hasty context.

3-D-34 Exploring the relationship between sensory information, tactile perception, and action; a TMS study

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Goals: The present study aims to explore the influence of tactile information in the control of action, particularly for a better understanding of the neuronal underpinning of sensorimotor control of actions. Here we apply spTMS while individuals are imagining performing an action while touching or not a rigid surface. Asking people to imagine performing an action (without any apparent actual motion) while receiving perceptual information represents a strategy to distinguish the role of perception from the role of action at the neuronal level. Materials: Biphasic spTMS pulse along with neuronavigator were used. An EMG was used to determine the muscle activity; first dorsal interosseous & the abductor digiti minimi. Methods: Twenty-one healthy subjects were asked to keep their right arm laying on the armrest in a sitting posture, and imagine producing force with the index finger of the right hand, while in one condition having the fingers of the hand lying on a surface and in one other condition without direct contact of the fingers with a surface. A control condition was performed, such as the same tactile situation was considered but subjects were not asked to imagine specific finger pressure. A training session was given before the force imagination task. A total of 60 trials of spTMS have recorded from each participant: 30 trials as no force imagination (15 with touch and 15 no-touch) and 30 trials for force imagination (15 with touch and 15 no-touch). Results: We found the difference in amplitude of Motor Evoked Potentials for imagining force production while touching a surface but this happened only for the muscle FDI the one involved in action imagination while such a difference wasn't present for the ADM muscle. Discussion: The influence of light touch in action performance is still poorly understood and in particular the neuronal underpinning that gives rise to the sensory-motor interaction of touch in force production. We highlighted the intertwined relation between tactile perception, sensory information, and the action component. Conclusion: We found a relevant relationship between sensory and motor information in action performance. Only the muscle involved in the action imagination was presenting a modulation in motor activation when compared with the other muscle. Importantly here we indicated the neuronal underpinning of such a relationship. Moreover, we showed that there is a higher activation of the motor system when an action is imagined and this activation is amplified when a tactile perceptual component is involved.

3-D-35 Optimization of postural accuracy and effort results in anticipatory postural adjustments (APAs) that precede limb movement

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Human sensorimotor systems predictively account for the dynamics of their body and the environment. A well-known example is the proximal muscle activity that accompanies rapid limb movement and counters the movement's perturbing effect on the body. Such proximal muscle activity is predictive, happening earlier than feedback from the perturbation and often prior to the muscle activity of the moving limb. Despite extensive work on such anticipatory postural adjustments (APAs) it remains unclear why motor commands to the body would precede motor commands to the mover. Could this asynchrony arise from a control strategy that considers postural accuracy alone or does it require the consideration of effort as well? To address this question, we simulated an open-loop controller acting on a mass (the body) that was mechanically linked to a smaller mass (the mover) with its own direct controls. The body controller exerted motor commands that satisfied an explicit cost function of body position alone or body position and effort together, in response to rapid displacement of the mover. Optimization of body position alone led to synchronous onset of motor commands to the body and mover regardless of the movement characteristics and the relative mass of the body and mover. In contrast, optimization of position and effort together resulted in asynchronous control signals. Specifically, body motor commands were temporally advanced relative to mover motor commands though by a different amount and magnitude depending on the specific conditions. Temporally advanced motor commands are efficient since they perform positive work on the body and use its momentum to counter the impending (and opposite) reaction force from the mover. This solution mirrors other uses of positive work to reduce effort such as when raising a pendulum to an upright position by swinging it backwards then forwards. Our model-based approach--the first application of optimal control to the study of APAs--identified effort as a critical factor in the temporal coordination of posture and movement. We produced a number of control patterns consistent with previous observations and our approach offers a new framework to test the role of task demands and plant dynamics on temporal coordination of motor commands suggesting the need for further empirical studies.

3-D-36 Proprioceptive sensory attenuation in area 3a during voluntary movement in macaque

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Our sensory systems respond not only to external sensory information but also to self-generated information caused by our movement. For example, we feel less when we move. This phenomenon is known as sensory attenuation. The somatosensory system processes proprioception and tactile. In the past, changes in tactile or cutaneous sensory input during voluntary movement have been well studied in both psychological and electrophysiological experiments. For example, psychological experiments showed that voluntary movement decreases perceptual sensitivity to cutaneous stimulation. Electrophysiological experiments demonstrated that somatosensory evoked potentials (SEP) in the primary somatosensory cortex (area 3b) attenuate during voluntary movement. In contrast, however, changes in proprioceptive signals from muscle and tendon during voluntary movement are less understood, regardless of their importance for motor control. To understand the neural mechanism underlying the modulation of proprioceptive input during voluntary movements, we recorded SEPs from 3a, the first cortical relay from proprioceptive input, by applying electrical stimuli to the cuff electrode

implanted in the deep radial nerve (DR: muscle afferent) in monkeys performing reaching and grasping task with an instructed delay period. Then, we found that the area of SEPs in area 3a was significantly suppressed in the movement phase compared to the rest (t-test, $p < 0.01$, Monkey M: 35%, Monkey A: 54% attenuated from the control). This result indicated that the cortical SEPs evoked by proprioceptive afferents show sensory attenuation during voluntary movement. Next, we compared this result with the modulation of SEPs from cutaneous afferents in the same animals. Interestingly, we found a contrasting result between the SEP in area 3a and 3b. In area 3a, the attenuation of SEP was started after the movement onset, while in area 3b, it started prior to the movement onset. This difference might be ascribed to the neural mechanism of active sensing. Tactile sensing may require changing the sensory gain before the onset of movement, so probably the motor readiness potentials and the attentional signal may attenuate sensory input before during the preparatory phase of the movement, together with the sensory attenuation by the descending motor command (efference copy). In contrast, in the proprioceptive afferent, the sensory modulation is specifically generated by the efference copy since preparatory modulation of proprioception may not always be required in our normal behavior.

3-D-37 Examining optimal integration of vision and proprioception during target localization

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Vision and proprioception provide us with cues about the position of our bodies and objects in the world around us. This information reaches cortical sensory areas and may be combined into a single estimate. It has been suggested that visual and proprioceptive cues are optimally integrated using the rule of maximum likelihood estimation (MLE). According to this model, noisy unimodal cue estimates are weighted based on their reliability to produce a more reliable bimodal estimate. MLE cue integration has been clearly demonstrated in various settings, including visual-haptic and visual-auditory estimation. However, the findings in visual-proprioceptive estimation have been mixed. MLE integration was supported in finger-pointing tasks where the estimated target position is either a visual target, contralateral finger, or both. However, other studies have suggested that this integration may not be based on reliability and is dependent on task parameters. To clarify whether visuo-proprioceptive integration can be considered optimal, we employed a psychophysical paradigm on target localization. In a two-alternative forced-choice task, we presented participants with two sequential targets and asked them to determine which was closer or farther relative to their body. Participants performed 308 unimodal vision and proprioception, and 308 bimodal discrimination trials. For proprioceptive targets, a robotic manipulandum moved the participant's hand to the targets, with a distractor movement in between. Comparison targets ranged -5 to 5 cm from the standard target in 1 cm increments using the Method of Constant Stimuli. The visual target was the center of a cluster of 10 normally distributed gaussian blobs presented against a white noise background. To examine the influence of visual noise, we repeated the experiment with a larger standard deviation among the blobs. A psychometric function was obtained for each modality and compared to MLE model predictions. Our results show that when visual noise is less than half that of proprioceptive noise, bimodal variability is similar to visual variability indicating a visual dominance inconsistent with optimal integration. However, when visual noise is increased to the level of proprioceptive noise, bimodal variability is smaller than both unimodal variabilities. This suggests that optimal integration may occur when visual and proprioceptive noise are similar but not when the visual signal is clearer than the proprioceptive estimate. Perception of visual and proprioceptive cues occurs in different reference frames; retinotopic and body-centered,

respectively. To integrate the two cues, the CNS must transform the signals to the same reference frame. This involves added processes such that if one cue is noisier than the other, a unimodal dominant strategy might be preferred.

E – Disorders of Motor Control

3-E-38 Despite cognitive impairments, stroke survivors do not show deterioration in adaptation savings and explicit learning compared to age-matched controls

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Cognitive control strategies account for significant proportions of learning and retention in complex motor tasks. In sensorimotor adaptation, aiming strategy contributes both to initial learning and to its long-term retention (savings). Subjects that suffer from cognitive deficits (such as older adults) show impairments in motor adaptation and savings that are driven by reduced explicit learning. We hypothesize that chronic stroke survivors, that suffer from cognitive impairments, will show deficits in adaptation compared to age-matched controls that will be associated with explicit learning and correlated with their cognitive deficits. 27 post-stroke, 31 healthy old adult and 30 young adult subjects completed a sensorimotor adaptation task composed of two adaptation blocks separated by a washout block. Explicit learning was assessed by cueing subjects to suppress their strategy. Implicit learning was assessed by improvement in the trials without perturbation in the adaptation blocks. Cognitive abilities were assessed using MoCA (old adults and stroke subjects) and a verbal learning test (young adults). Both stroke and age-matched controls showed inferior performance when compared to a group of young participants: their adaptation, savings, and explicit learning were decreased, whereas their implicit adaptation was comparable. Nevertheless, when compared to age-matched control subjects, chronic stroke subjects did not show impairments in adaptation, savings, explicit and implicit learning. This similarity was observed despite marked cognitive impairments in the stroke group. The explicit learning in the stroke and young groups was correlated with their performance in the cognitive assessments, suggesting that explicit learning depends on cognitive control. Our results replicate previous results by demonstrating a strong and robust effect of age on adaptation and savings, which is driven by a decrease in explicit learning. However, we did not find further deterioration in adaptation due to stroke. We therefore suggest that the stroke-related cognitive deterioration does not affect adaptation, or that stroke survivors utilize their cognitive resources to compensate for adaptation deficits. Nevertheless, the correlation between explicit adaptation and cognitive abilities in the stroke group indicates that the efficacy of motor rehabilitation after brain damage depends on the cognitive abilities of the subjects.

3-E-39 National Center for Medical Rehabilitation Research, National Institutes of Health

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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.

3-E-40 Digital fingerprints of human movements that enable high-resolution patient-by-patient neuromotor disease progression prediction

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In motor disorders, many gold-standard neurological and cardiovascular assessments used to quantify the clinical scales are often measured "by-eye" and are subject to intra-rater variability (the same assessors reporting different outcomes on repeated trials) and inter-rater variability (different assessors scoring the same assessment differently) as well as variability in the patient performance ability (which may vary based on time and days of the week, seasons etc.). This results in higher variability in measuring accurate disease progression, and thus results in long and large clinical trials to validate new treatments of motor disorders. We are proposing here a principled approach for using all-body kinematics, the actual movement of human volunteers obtained from daily life-recordings in their normal life, from which we extracted a set of over 20 digital fingerprints of movement behaviour that capture and reflect the rich spectrum of daily life behaviour. We can show that the same set of digital fingerprints can capture and predict disease progression in diverse degenerative diseases, such as muscular dystrophy in children or ataxia in adults. In genetic movement disorders, we can even show how these digital fingerprints of behaviour allow us to predict a patient's gene expression level of a defective gene, unlike the gold-standard clinical scales, suggesting that our approach can provide direct insight into mechanisms of disease. Moreover, we can show that our digital fingerprints cover a much broader area of all activities that happen during daily life than human-defined activities of daily living (which are not particularly good at reflecting daily living). The practical implications are that by combining an approach that embraces daily life behaviour with machine learning and wearable sensors, we can define new primary end-points that shorten the duration, size and cost of clinical trials but also enables insights into motor disorders that link all the way back to molecular mechanisms. Our approach can be easily applied to other neuromuscular, neurodegenerative or acquired neurological diseases, as well as to the study of natural behaviour for human performance and skill learning studies.

3-E-41 Medication adversely impacts visually guided eye movements in Parkinson's disease

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Previous literature examining the effect of anti-Parkinsonian medication on visually-guided saccades (VGS) has been conflicting and the medication effect is still unclear. This study clarified the effect of anti-Parkinsonian medication on VGS, while examining if task paradigm and target eccentricity differences could explain the potentially conflicting results of the previous literature. Previous studies are split on whether medication increases or has no effect on latency. The 3 classic paradigms (gap, step, and overlap) vary the timing of fixation offset and target onset to manipulate latency and the attentional demand of the task. We wanted to determine if these varying attentional demands may explain the previous equivocal findings. Additionally, it has been suggested that the target eccentricity effect on latency is U-shaped, while increasing eccentricity tends to decrease gain and increase peak velocity. Participants with Parkinson's disease (n = 33) completed the VGS tasks while OFF and ON anti-Parkinsonian medication. Age-matched healthy controls (n = 13) completed the tasks once. The VGS tasks involved fixating on a central fixation point until a peripheral target appeared, cueing the participant to look at the target. Performance was recorded on 3 paradigms and 2 target eccentricities (10 and 15 degrees). Linear mixed models evaluated the effect of medication, paradigm, target eccentricity and their interactions on primary saccade latency, gain, and peak velocity. Medication significantly interacted with target eccentricity such that medication significantly prolonged latency for the 15 degree target eccentricity. We also found that latency increased from the gap to step to overlap paradigm. Latency was positively associated with OFF medication United Parkinson's Disease Rating Scale motor score in Parkinson's disease. Additionally, medication significantly interacted with paradigm such that gain and peak velocity decreased with medication only during the step paradigm. For both gain and peak velocity across all 3 paradigms, we found a significant main effect of target eccentricity, with gain reducing and peak velocity increasing for the 15 degree target eccentricity. Overall, we provided evidence that anti-Parkinsonian medication adversely affected VGS by prolonging latency, reducing gain, and reducing peak velocity. These adverse effects were dependent on target eccentricity and paradigm. However, the prolonging of latency with medication was robust and consistent across the 3 classic paradigms, which are thought to alter the attentional demands of the task. Additionally, we found that irrespective of medication status, latency was prolonged with increasing disease severity. The adverse effects of prolonged latency and decreased gain and peak velocity with medication could be significant, as many activities in daily life require quick oculomotor control, such as driving.

3-E-42 Different time course of recovery in reaching and grasping movement after reproducible cortical infarction in non-human primate

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A major problem of human stroke research is the interpatient variability in the extent of sensorimotor deficit and the time course of recovery after stroke. It is well established the relationship between the extent of the lesion and the degree of sensorimotor deficit, but how the extent of the lesion also affects the time course of recovery is yet to be established. Here, we reasoned that the extent of the lesion could also be a dominant factor in determining recovery speed if the patient with the same lesion area exhibits a comparable recovery time course. To address this problem experimentally, we made highly reproducible lesion over the motor cortex in common marmosets (Callithrix jacchus), a small New World monkey. In the experiment, cerebral infarction was photochemically induced in four adult marmosets.

After photosensitive dye was administered intravenously, we irradiated the primary motor cortex with green light. To evaluate the recovery process of the sensorimotor functions, we assessed their in-cage behavior and pellet reaching task up to eight weeks after infarction. Abnormal behavioral signs in their home cage were scored by two experienced experimenters. In pellet reaching task, their hand movements were continuously recorded by a high-speed camera to evaluate the hand kinematics. The video was analyzed using a machine-learning package that can perform markerless tracking of the animal body parts (DeepLabCut, Mathis et al., 2018; Nath et al., 2019). The positions of the finger joints were tracked, and movement trajectory was quantified. We found a consistent time course of recovery across animals in in-cage behavior as well as the performance of the pellet reaching task. For example, in all animals, the score of their in-cage behavior fully recovered in three weeks, and the performance of their reaching and grasping movements were worsened until four weeks. Moreover, grasping performance was then partially recovered at eight weeks in all animals. These results suggest that the comparable time course of recovery could be expected by the reproducible infarction of the motor cortex. Interestingly, we observed inter-subject variability in the reaching performance at eight weeks. Although impairment of the reaching movement itself was consistent, which was characterized by the increased initial movement direction error and the increasing number of speed peaks in the reaching trajectory, the time course of their transition was heterogeneous among animals. This suggests that another factor besides extent of the infarction may contribute to facilitate recovery only for reaching, but not grasping, movement in the subacute to chronic phase after stroke.

3-E-43 Differences in resting-state functional connectivity underlie visuomotor task performance declines in older adults with a genetic (APOE e4) risk for Alzheimer's disease

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Non-standard visuomotor integration requires the interaction of large networks in the brain. Previous findings have shown that non-standard visuomotor performance is impaired in individuals with specific dementia risk factors (family history of dementia and presence of the APOE e4 allele) in advance of any cognitive impairments. These findings suggest that visuomotor impairments are associated with early dementia-related brain changes. The aim of this project is to examine the underlying resting state functional connectivity (RSFC) associated with impaired non-standard visuomotor performance, as well as the effects of dementia family history, sex, and APOE status. Participants included right-handed older adults with a family history of dementia (n=24, 11 female) or no family history of dementia (n=24, 12 female). Participants were tested on four visuomotor tasks where reach and gaze were increasingly spatially dissociated using two linked touchscreens. These included a standard condition requiring direct interaction with visual targets, and three non-standard conditions (involving either visual feedback reversal, plane-change, or plane-change feedback reversal). APOE genotyping was determined from salivary measures. To quantify RSFC, an echo planar imaging (EPI) sequence sensitive to blood oxygenation level dependent (BOLD) contrast was collected. The networks of interest were the default mode network (DMN), somatomotor network (SMN), dorsal attention network (DAN), ventral attention network (VAN), and frontoparietal control network (FPN). Individuals with the e4 allele showed abnormalities in RSFC between posterior DMN nodes that predicted poorer non-standard visuomotor performance. Specifically, multiple linear regression analyses revealed lower RSFC between the precuneus and posterior cingulate cortex, a posterior functional core of the DMN, and the left IPL ($b = -16.303$, $p < 0.05$) and left parahippocampal cortex ($b = -27.278$, $p < 0.05$). Presence of the APOE e4 allele also modified the relationship between mean DAN RSFC and visuomotor performance for two of the behavioural measures in the plane-change feedback reversal condition. There was a significant interaction effect of mean RSFC in the DAN and APOE status on endpoint error scores ($b = -25.543$, $p < 0.01$) and corrective path length ($b = -59.268$, $p < 0.05$), both indicative of worse visuomotor performance, only in APOE e4 carriers. There were otherwise no effects of family history, APOE status, or sex on the relationship between RSFC and visuomotor performance for any of the other resting networks. The preliminary findings provide insight into the impact of Alzheimer's disease pathology on neural networks underlying complex visuomotor transformations, and demonstrate that the non-standard visuomotor task paradigm discussed in this study may be used as a non-invasive, easily accessible assessment tool for dementia risk.

3-E-44 Assessing finger individuation impairments in children with cerebral palsy

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Children with cerebral palsy (CP) often demonstrate impaired fine motor control. Clinical assessments of dexterity reflect generalized hand function and lack the sensitivity and precision to identify more subtle finger movement deficits in children with CP. Here we used a novel device (Hand Actuation Neuro-training Device, JHU reference #C14603) to assess finger dexterity by tracking subtle isometric forces at all five fingertips in three dimensions (3D). We tested finger individuation, the ability to move one finger in isolation, in children with CP and typically developed (TD) children. We then compared individuation ability to clinical assessment scores to evaluate this new tool's sensitivity in assessing fine motor deficits in children with CP. Fifteen children with CP (age 5-12 y) and ten TD (age 5-11 y) children participated in the study. Participants placed their hand in the device in a comfortable, pronated posture. The more affected hand was tested in the CP group and the dominant hand tested in the TD group. The thumb, index and ring fingers were tested. Participants controlled the movement of a dot in a virtual 3D space on a computer screen by exerting isometric forces with one finger (max=10 N) on each of three axes, while keeping the other fingers immobile. Forces were recorded from all five fingertips during the task. An Individuation Index was derived by regressing non-instructed finger forces onto forces towards the target direction in the instructed finger. Dexterity and fine motor function were assessed clinically using the Functional Dexterity Test (FDT) and Purdue Pegboard Test (PPT). Gross manual ability was assessed using the Box and Blocks Test (BBT). We predicted that our individuation task would be sensitive in detecting fine manual deficits, and would be correlated with FDT and PPT, but not BBT scores. Linear mixed-effect models were used to test the effect of group, digit, and anatomical movement type on individuation. We found a significant effect of group ($p < 0.001$): Individuation was higher for the TD group ($M = 0.27$) than CP group ($M = -0.43$). There were also significant effects of digit ($p < 0.001$) and movement type ($p < 0.001$): individuation was the highest in the thumb and the lowest in the fourth finger, and highest in flexion and lowest in ab/adduction. T-tests revealed group-wise differences in clinical assessment outcomes. In FDT, the TD group ($M = 18.35$) was marginally faster than CP group ($M = 35.35$, $p = 0.07$). In BBT, the TD group ($M = 45.33$) moved significantly more blocks than CP ($M = 35.91$, $p = 0.002$). In PPT, the TD group ($M = 12.07$) moved significantly more pegs than CP ($M = 7.90$, $p = 0.009$). As predicted, individuation was significantly correlated with FDT ($r = -0.64$; $p = 0.02$), and PPT ($r = 0.6$, $p = 0.03$), but not with BBT ($p = 0.19$). These results suggest our individuation paradigm is highly sensitive in detecting the distinct impairment patterns of finger control in children with CP.

3-F-45 Interference between competing motor memories occurs when they are implicitly, but not explicitly, acquired

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Long-term learning of a motor skill requires that the newly formed representation of that skill is protected from interference from interceding tasks. The present study was designed to investigate whether the occurrence of interference is tied to specific mechanisms that operate during learning and drive motor memory formation. First, the classic result was replicated in that learning to successively adapt action to two opposite visuomotor rotations produced substantial interference between the acquired memories. Specifically, when adaptation to rotation A (30° clockwise) was followed immediately by adaptation to an opposite rotation B (30° counterclockwise), the re-learning of A on Day 2 is just as errorful as on Day 1 - the signature of interference. Because it is known that such learning is driven by both explicit / deliberative processes as well as implicit / non-verbalizable mechanisms, subsequent studies then probed whether the observed interference was associated specifically with one of these two mechanisms. In Experiment 2, participants again performed the A-B-A sequence, but error feedback during adaptation to B was restricted only to the end of the movement and was delayed by 2 seconds. Although this approach meant that B was learned entirely through explicit or strategic mechanisms, there was an absence of interference between A and B - a clear preservation of the prior memory of A on Day 2. In Experiment 3, participants were provided with clamped error feedback during B learning such that online feedback was not contingent on actual performance and remained invariant throughout the experiment. Hence, B was learned fully implicitly. Remarkably, substantial interference emerged in this condition, with no difference in performance of A on Days 1 and 2. Finally, in Experiment 4, cathodal hd-tDCS over the posterior parietal cortex (PPC) produced a striking reduction in interference even when B was learned fully implicitly. Collectively, these results indicate that: 1) implicit learning is a necessary and sufficient condition for interference to occur between motor memories, and 2) implicitly acquired motor memories may compete for neural resources within the PPC, and this competition may ultimately underlie the interference observed behaviorally. Preventing interference and separating competing motor memories in the brain may therefore require the engagement of distinct mechanisms (presumably relying on distinct neural substrates) during their acquisition.

3-F-46 An intention-based strategy for grasping prosthesis

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Grasping movements are one of the most essential ways primates interact with the environment and they comprise some of our most complex actions. Despite the remarkable recent progress in intracortical brain-computer interfaces (BCI), algorithmic improvements have not considered the special requirements of hand shape control. The act of grasping is determined by the precise execution of non-linear transitions and the attainment of hand configurations in a high-dimensional state space, yet, existing approaches derive from low-dimensional arm navigation. We introduce the ReMAP (Recalibrated Map to Attempted Path) training algorithm for grasping prostheses. Bred on intention-based training techniques (Gilja et al. 2012; Orsborn et al. 2012), and inspired by variational autoencoders, ReMAP uses the fact that kinematic trajectories during grip type execution tend to stay

within a curved state-space manifold. To preserve the subject's intent, the algorithm projects attempted kinematic transitions onto the intended kinematic trajectory and uses the projection as the training objective function. To test our approach, we trained two monkeys to perform a multi-grasp task in a physics-based virtual environment (MuJoCo) while wearing an instrumented glove tracking 32 joint angles of the arm and hand. After the animals proficiently learned the task, they were implanted with microelectrode arrays in three key areas of the grasping circuit (AIP, hand M1 and F5) and trained in an equivalent BCI task with no movement of the native arm. The ReMAP strategy was superior to traditional training methods in a number of metrics, including success rate and accuracy of the BCI grasps. The effectiveness of an intention-based training approach can be measured by the capacity of the BCI to reflect the user's intent in an environment with obstacles (Gilja et al. 2012; Shanechi et al. 2017). When compared under object collisions to a classic intention-based method that only considers kinematic targets, ReMAP produced fewer collisions and achieved higher performance. Offline data analysis revealed that the effectiveness of our decoding method was supported by an asymmetry in the amount of kinematic information present in the neural data: we found abundant position information in contrast to velocity information during BCI- and native arm grasp control, in line with previous work (Vargas-Irwin et al. 2010; Bansal et al. 2011; Stark-Inbar and Dayan 2017) and in comparison to reaching data (Goodman et al. 2019; Okorokova et al. 2020). When looking at the learning process over sessions, we found evidence that there was a tendency of the activity to evolve as position-like patterns. Given the causal nature of BCI control, our results provide compelling evidence for the special nature of the neural representation of grasping to be explored in future studies. Funding: DFG-FOR1847-B3, DFG-CRC889-C09, and EU-Horizon-2020 GA-965044 project B-CRATOS.

3-F-47 Cerebellar function for recalibrating visual space, motor space and internal movement predictions

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The cerebellum keeps our movements accurate through supervised error-based learning. Accordingly, changes at the Purkinje cell synapse recalibrate an inverse model, i.e. the transformation of a spatial goal position into a motor command. For saccadic eye movements, it was recently revealed that learning is actually a threefold process. Besides motor recalibration of the inverse model, learning also comprises perceptual recalibration of the visuospatial target map, and of a forward dynamics model that estimates the saccade size from corollary discharge. We dissociate cerebellar contributions to the three stages of visuomotor recalibration by fitting a state-space model to the saccades and pre- and trans-saccadic target localizations of eight patients with cerebellar pathology and eight healthy control subjects. Conditions were (1) learning from peri-saccadic inward target steps, (2) learning from peri-saccadic outward target steps and (3) saccade maintenance when the target stayed at its initial position across the saccade. Based on Masselink & Lappe (2021), the model captures recalibration at all three stages of the visuomotor circuitry to reduce postdictive motor error, i.e. the error of the motor command with respect to a postdictive update of visuospatial target position. Results of the learning conditions showed that cerebellar pathology reduces short-term recalibration of the inverse model and completely suspends short-term recalibration of the visuospatial target map. By contrast, the forward dynamics model was well informed about the reduced saccade change in patients. Moreover, the saccade maintenance condition revealed that patients tend to uncompensated oculomotor fatigue. Control subjects sufficiently upregulated saccade duration to counteract a fatigue-induced decline in saccade peak velocity. By contrast, patients compensated by only 46%, resulting in a gradual decrease of saccade amplitudes. According to our model, this could induce long-term compensation at perceptual level, consistent with a significant overestimation of target eccentricity that we observed in the patients' baseline data. Interestingly, this can also explain how saccade amplitudes can recover from initial hypometry induced by cerebellar lesion, as previously observed in monkeys (Takagi, Zee, & Tamargo, 1998; Barash et al., 1999). We conclude that the cerebellum performs short-term learning of the visuospatial target map and of the inverse model and counteracts oculomotor fatigue by within-saccade control of movement duration. The forward dynamics model and long-term perceptual learning may be computed upstream of the cerebellum.

3-F-48 Nociception impedes grasping recovery in the spinal cord injured rat

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Significant deficits in motor control and sensory function diminish an individual's quality of life following spinal cord injury (SCI). A top priority of the injured population is regaining upper limb function. It has been shown that descending motor commands and primary afferent input, such as cutaneous feedback and proprioception, drive plasticity and recovery of function after SCI. Our lab and others have shown that primary nociceptors sprout and facilitate the maladaptive plasticity seen in chronic pain development, but their role in motor control is critically overlooked. The purpose of this experiment was to better understand the role of nociceptive input on recovery of motor function after SCI. Mechanosensitive, non-peptidergic nociceptors were ablated in Sprague-Dawley rats via intraganglionic injections of rIB4 -conjugated saporin or unconjugated (vehicle) saporin into the C7-8 dorsal root ganglia (DRGs). During the same surgery, a subset of rats received an ipsilateral C5 hemicontusion and the implantation of a braided multi-electrode probe for recording in the ipsilateral C8 gray matter. The von Frey test for allodynia and immunohistochemistry, in which cervical DRG and spinal cord sections were stained with antibodies against CGRP and isolectin-B4, confirmed nociceptor ablation. This ablation of nociceptors following SCI improved the rats' ability to grasp food pellets when compared to vehicle-treated controls in the Montoya staircase test ($x2=4.019$, $p=.0449$); however, a cereal manipulation task revealed that individual digit control did not return with ablation. The forelimb mean and max pull force of SCI rats with nociceptor ablation was higher than that of SCI only rats while performing an isometric pull task ($p=.0005$, $p=.0165$). Importantly, the limb extension or "reach" was not impacted by nociceptor ablation at C7-8 as measured by the cylinder paw preference test ($p>0.05$). Furthermore, uninjured rats with nociceptor ablation showed no significant differences in motor control when compared to uninjured rats without ablation indicating that the role of the nociceptor is altered following SCI. Ongoing experiments are focused on measuring changes in neuronal activity within the C7-8 cord in awake behaving rats with and without nociceptor ablation. Multivariate statistical analyses of the behavioral, anatomical, and electrophysiological outcomes are underway. Increasing our understanding of the role nociceptors play in the spinal plasticity related to motor control following SCI will help guide future research and development of rehabilitative techniques.

3-F-49 Transcranial direct current stimulation over motor cortex or prefrontal cortex both facilitate balance training

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The dynamic balance task (DBT) has been established as a beneficial model for complex motor skill learning in balance and gait since the requirement of highly coordinated whole-body movements (1). Further, tDCS over the motor cortex has been established as a promising tool for changing neuronal responses and facilitating static and dynamic balance in YA (for review, cf. 2). With this study, we aimed at replicating findings by Kaminski et al. (3) that a-tDCS over M1 produced improvements in balance performance compared to sham in young and older adults. Second, we extended these studies by targeting the left dorsolateral prefrontal cortex, assuming that this might improve executive functioning and motor control supporting balance performance as well. In addition, we examined potential carry-over effects on training potential and balance performance to the day after. Here we report our findings from the young sample. 43 young adults (18-30 years) participated in this study. On two consecutive days, participants were trained in the DBT on a Wii Balance Board placed on a movable platform (15 trials, each 30 seconds with between-trial rest intervals). On day 1, participants either received a-tDCS (1mA) over Cz or over F3 with the cathode placed over the right frontal orbit or sham stimulation. Before and after training, balance test with either eyes open, eyes closed or one-leg stand with the dominant leg (3 trials,10 seconds each) was done. On day 2 participants underwent the same procedures without stimulation. The canter of gravity was continuously recorded and pathlength per second in x and y direction was calculated as performance measure. GLM analysis revealed that participants improved during training independent of experimental group ($F(14,1831) = 4.07$, $p < .001$, pEta^2 = .027) but that only the tDCS groups showed carryover effects to the second day ($F(2,1831) = 8.12$, $p < .001$, pEta^2 = .009). Pre- and post-tests of performance in the EO but not the other test conditions revealed improvement after training only for the tDCS groups ($F(2,758) = 5.04$, $p = .007$, pEta^2 = .013). No effect of type of stimulation could be revealed. Our results confirm facilitating effects of tDCS on balance training independent of the target region (Cz or F3). Probably the optimal target region could be in the overlap area, e.g., the left premotor area. References 1.Taubert, M., et al. (2010). Dynamic properties of human brain structure: learning-related changes in cortical areas and associated fiber connections. J. Neurosci. 30, 11670-11677. 2.Kaminski, E., et al., (2016). Transcranial direct current stimulation (tDCS) over primary motor cortex leg area promotes dynamic balance task performance. Clinical Neurophysiology, 127(6), 2455-2462. 3.Baharlouei, H., et al.,(2020). The effect of transcranial direct current stimulation on balance in healthy young and older adults: A systematic review of the literature. Neurophysiologie Clinique, 50(2), 119-131.

3-F-50 The influence of conscious awareness on compensating for a visuo-proprioceptive mismatch

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Hand position is estimated in the brain by combining visual and proprioceptive cues. Visual information about the index finger can be spatially displaced from proprioceptive information without the person noticing. For example, when a person views their hand in water, a visuo-proprioceptive mismatch is created by the light's refraction in water. The brain resolves this mismatch by realigning both visual and proprioceptive estimates to close the gap; this perceptual adjustment occurs without the person's awareness and even with no feedback about the perturbation. We might guess that if the visuo-proprioceptive mismatch is large enough, or if the person is aware of the perturbation, visuo-proprioceptive realignment should be reduced or eliminated. However, connections between explicit cognitive processing and implicit multisensory and sensorimotor processing are not well understood.

We recently assessed awareness of a gradual visuo-proprioceptive misalignment of index finger information by asking participants about their perceptions. We found that if the offset was less than 70 mm, spontaneous awareness of the offset was rare, and correctly perceiving the direction of the mismatch was not linked to reduced realignment of vision or proprioception. Here we manipulated awareness of a visuo-proprioceptive misalignment directly, giving three groups of participants different information. In a 2D VR touchscreen setup, participants used their unseen right index finger to indicate where they perceived visual (V), proprioceptive (P), or combined (VP) targets related to their left index fingertip. Participants received no performance feedback or knowledge of results. A 70 mm misalignment was gradually imposed by shifting the visual component 1.67 mm forward on each VP trial. Before beginning the task, Group 1 (control) participants were told that VP targets would always be veridical. Group 2 participants were explicitly told there would be a gradual forward V-P mismatch in Block 2, and shown a diagram. Group 3 participants were informed of the offset and were allowed direct vision of their hands during the misalignment trials by removing the layer under the half-silvered mirror. If awareness of the offset diminishes realignment, we predicted that Group 3 would have little or no visuo-proprioceptive realignment, and Group 1 would realign more than Group 2. Early results (N = 3-4 per group) suggest a similar magnitude of both visual and proprioceptive realignment between Groups 1 and 2. Group 3 participants showed markedly less realignment than the other groups, as predicted. However, despite having full view of their left hand with the offset visual target, realignment was not zero. This suggests that explicit knowledge about the perturbation does not easily overcome the implicit realignment that occurs in response to a visuo-proprioceptive mismatch.

3-F-51 Implicit and Explicit Adaptation Just Don?t Add Up

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People adapt their movements to various changing circumstances quickly, and this is likely supported by many processes such as both implicit and explicit adaptation. Many studies and methods (tacitly) rely on the assumption these two add linearly, but this seems an unlikely neural mechanism and has not been tested rigorously. Here we test this by eliciting different amounts of explicit adaptation in 3 visuomotor reach adaptation conditions: 1) instructed, where people receive an explanation of the perturbation and a counter-strategy, 2) aiming, where people are asked to think about and report their strategy on every training trial, and 3) control, where people do neither. We use the process dissociation procedure [Werner et al., 2015] to gauge implicit and explicit adaptation, and in the aiming group verify that the difference between reach deviations in inclusion and exclusion trials corresponds to aiming reports. We then test both strict and loose models of additivity, and can not confirm either. Within the aiming group, the processes of a state-space model often assumed to be equal to explicit and implicit adaptation can not predict direct measures of either explicit or implicit adaptation. Finally, we re-analyze data from eight other studies (total N=553) and only observe loose additivity in six subgroups (N=82). While the combined data supports some form of combining explicit and implicit adaptation, it does not support linear addition. Participants are also widely spread out so that any predictions of implicit adaptation based on total and explicit adaptation are imprecise at best. In short, if we want to make statements on both implicit and explicit adaptation, we should directly measure both. Perhaps more importantly, the data highlights that we are far away from understanding how various motor adaptation processes combine to shape behaviour.

3-F-52 Dynamic arbitration between model-based and model-robust control in human reaching movements

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It is well known from perceptual choice experiments that the brain uses multiple systems of decision-making to improve task success. Broadly such systems were classified as model-based(MB) and model-free(MF) based on the use of internal models of the task. There is evidence of an arbitration process that selects either of the systems as a function of environmental reliability. However, in sensorimotor research, emphasis has been placed largely on internal models. Recent evidence points towards a model-robust(MR) system influencing arm movements (Crevecoeur 2019). Two issues remain unknown: Is there an arbitration system that handles the transition between MB and MR systems in motor control? If so, what is the mechanism that governs the dynamics of transition? To answer this we performed human arm-reaching experiments. We asked 15 subjects to perform 20cm reaching with a KINARM manipulandum. We manipulated environmental reliability by means of randomly applied force fields(FFs) in unpredictable directions(CW or CCW). Two separate sessions were performed by each participant with low and high probabilities of FFs. We quantified the effect of the MR system by analyzing the hand kinematics, and EMG feedback gain as in previous work (Crevecoeur 2019); while the MB system was quantified by the after-effect in the null-field trials that followed an FF trial. We observed that individuals during high probability FF session displayed a relatively lower MB, a higher MR contribution, and vice-versa. Thus individuals are able to modulate their movement strategies likely to exploit MR and MB control as a function of environmental reliability. We then designed a second experiment to understand if the dynamics of MB and MR systems were dissociable when the FFs transitioned from a random to a consistent FF context. In Exp 2, 15 participants performed 5 blocks of movements where the first two blocks consist of random FFs and the remaining three blocks with consistent FFs. We tracked the MB system using randomly interleaved force-channel trials. We observed that the adaptation was nearly zero during the random FF blocks but the hand deviation decreased exponentially. This was paralleled by a trial-by-trial increase in EMG activity during the random FF blocks. Simulations showed the changes are due to an increase in the MR contribution. In the following consistent FF blocks, the adaptation increased paralleled by an exponential decay in the EMG activity from the robust to the new adaptation level. These observations were in contrast with the control group that performed only consistent FF blocks. Overall, we found that arbitration can be captured as a first-order dynamical system that increases the MR control when an internal model is not useful and decays the MR control as the model adapts. This study is important as we show how a combination of MB and MR systems likely contributes to reducing movement errors during early exposure to novel environmental dynamics.

3-F-53 The P300 event-related potential as a biomarker of sensorimotor memory updating during an object lifting task in which surface material changes.

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Although our motor system is finely tuned to generate accurate movements when interacting with our environment, we inevitably make mistakes on a daily basis when manipulating our surroundings. The motor system is capable of adapting future movement based on the errors experienced in previous interactions with the world. A large component of this adaptive process is the updating of information

within sensorimotor memory to allow for the efficient lifting of the newly encountered object in the future. Our group has previously reported the presence of the P300 ERP component during trials in which sensorimotor memory updating is thought to occur during an unexpected change in object weight. The P300 was chosen as it has long been theorized to relate to the brain activities involved in the updating of working memory in response to incoming stimuli. We examined electroencephalograms (EEG) and kinematic data from participants (N = 12) during an object manipulation task in which the object lifting surface was predictable or unpredictable, based on previous lifts. The epoch of interest when examining the EEG data was time locked to the initial contact with the object - the first point at which feedback related to object texture could be known. When lifting blocks in which an unexpected change in object material was present, sensorimotor memory updating should occur to facilitate future interactions with these objects that are not well represented by long-term motor priors. Offline analysis of lifting kinematics established that participants did require adjustments to their initial grip force predictions when lifting the objects with an unexpected surface throughout the entire experiment. Importantly, as predicted, during those trials in which sensorimotor memory updating is thought to occur a significant effect in the amplitude of the P300 ERP was observed. Taken together, these results further suggest that the P300 ERP may provide an adequate real-time biomarker of the updating of sensorimotor memory in an object lifting task.

3-F-54 How autonomous is the rapid wakeful consolidation of a motor skill?

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Learning of motor skills involves consolidation of motor memory. Boenstrup et al. (2019) have shown that consolidation of a movement sequence can take place within seconds after the sequence has been first practised. This rapid, waking consolidation in humans is evidenced by an increase in performance across rest periods that are interspersed between practice periods (so-called micro-offline gains). As a potential mechanism of rapid consolidation, Buch et al. (2021) have provided magnetoencephalographic (MEG) evidence of neural replay involving hippocampus and sensorimotor cortex during rest periods, at a time scale that appears too rapid to be compatible with cognitive strategies such as motor imagery or mental rehearsal. However, they also found a rapid decrease in replay rates following termination of practice, potentially indicating that replay depends on explicit knowledge of task structure. In our study, we ask whether explicit knowledge and cognitive control influence neural replay, or whether replay ignores knowledge of task structure. We are recording MEG from healthy young adults while they are learning two different finger sequences, one at a time, in alternating blocks, each consisting of four practice and four interspersed rest periods. During each rest period, participants are explicitly informed how many practice periods of the current sequence are remaining before a switch to the other sequence will take place. We are particularly interested to see whether replay rates for a finger sequence that has been practised for a block, decrease during rest periods just before the required finger sequence changes, indicating an influence of explicit knowledge. In addition, our design allows us to investigate whether upcoming finger sequences are "pre-played" during these transition rest periods in expectation of the upcoming practice, and also, whether two sequences can be replayed in the same rest period. Data collected for this ongoing study (currently n=20) show that fingers can be reliably decoded at sensor level during practice periods. We expect data collection to be complete by the time of the NCM conference, and first results regarding the properties of wakeful neural replay.

3-F-55 Physical practice and observation induce similarly stable adaptation of limb dynamics

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Recent evidence suggests that neural representations of novel movement dynamics can be acquired by observing as someone else learns those dynamics. It has been demonstrated that visually-sensed kinematic information about someone else's movements can be transformed into an adaptation of feedforward limb control for the observer; however, little is known about the durability of this adaptation. Despite the longevity of changes in the motor system being a defining characteristic of motor learning, studies to date have only examined observation-related effects immediately after observation has occurred. None have addressed how long the effects of observation might last, leaving unknown whether such effects are transient phenomena or products of learned, durable changes in the motor system. Using a forcefield learning paradigm, we measured 160 human subjects' force generation patterns before and at various time points (1 min, 10 min, 30 min, 60 min, or 24 hrs) after they had either performed or observed movements that were perturbed by novel, robot-generated forces (i.e., a velocity-dependent forcefield). After physical practice or observation of perturbed movements, subject-generated forces adapted to match the distinct, temporal pattern of forces required to oppose the forcefield. The magnitude of the adaptation measured after observing was approximately 40% of that measured after physical practice--and although retention generally decayed with time, we found no evidence of an interaction between delay length and whether participants had performed or observed reaches in a forcefield, suggesting that the adaptation decayed similarly regardless of whether it was induced by observation or physical practice. Further, adaptation after observing was detectable at all delay lengths, including after 24 hours, demonstrating that observation elicits lasting effects on the human motor system. We also examined the rate at which the adaptation washed out during repeated reaching in force channels after each delay period. For 1-, 10-, 30-, and 60-minute delays, the effects of observing washed out significantly slower than the effects of physical practice. After 24 hours, the rate of washout did not differ between observers and those who had physically performed reaches in a forcefield. Our results suggest that observing can have lasting effects on the brain that are similar to those seen for physical practice.

3-F-56 Cerebellar inactivation increases internal noise and impairs motor adaptation

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The motor system rapidly adapts to changes in the body and/or the environment. During adaptation to external perturbations, the motor system continuously calibrates its error sensitivity to allow efficient adaptation. The cerebellum is considered as a key player in adaptation, but the neural mechanism underlying adjustments of error sensitivity during adaptation remains unknown. We previously showed that high-frequency stimulation (HFS) in the superior cerebellar peduncle (SCP) effectively and reversibly blocks cerebellar outflow and impedes motor timing and coordination. Here we used this approach to study the effects of a cerebellar block on behavior and cortical activity when monkeys adapt to an external perturbation. Monkeys (n=2) were trained to wear an exoskeleton (KINARM) and made center-out movements to 1 of 8 pre-cued targets. After training was completed, a recording chamber was attached above the hand-related area of the motor cortex, and a chronic stimulating electrode was inserted into the SCP. High-frequency biphasic stimulation pulses were delivered through the electrode to interfere with the outflow of cerebellar signals. The experimental protocol included an HFS

stimulation condition (on/off) and a velocity-dependent force field (FF) perturbation condition (on/off). In the presence of FF, hand trajectories deviated from the straight line but monkeys compensated for the perturbation and gradually decreased the amount of the deviation. Applying HFS during FF trials significantly impaired adaptation as was evident in the monkeys' decreased capacity to consistently reduce movement errors and the residual deviations in late adaptation trials were significantly higher than control (p=3.36e-08, computed during late adaptation trials). To identify the mechanism(s) through which HFS impairs adaptation we used a state space model, which posits that adaptation is an adaptive process driven by the extent of learning from past errors (i.e., error sensitivity) balanced by the amount of forgetting (i.e., retention factor). The results showed that during HFS, error sensitivity was significantly reduced (22.1%, p=1.2e-27) whereas the retention factor was decreased slightly by 4.7% (p=0.003). Next, we tested the possibility that the increase noise caused by HFS acts as a noisy perturbation on top of the external FF that interferes with the learning process. Although HFS significantly increased motor variability, the increased variability did not trigger an adaptive response, indicating HFS increases internal but not external noise. Finally, error sensitivity for adaptation during HFS was significantly lower than in FF trials even when selecting a subset of sessions with a matching internal noise in control and HFS trials (t-test, p=9.9e-05). These results suggest that blocking cerebellar outflow impairs motor adaptation via two (at least partially independent) processes: by increasing internal motor noise and decreasing error sensitivity.

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3-G-56 Inter-individual variability in strategies for muscular null space control

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The muscular null space, involved in the regulation of limb impedance, represents those components of the muscle activation patterns that do not generate forces or movements. Null space activations could also be used to control additional artificial end-effectors, but it is unclear which strategies underlie the simultaneous control of muscular null space and natural end-effectors. During a multidirectional isometric force generation task, muscular null space can be modulated to regulate the simulated stiffness of a virtual elastic end-effector to attenuate the effect of a random perturbation (Borzelli et al. 2018). Individual muscle activations are cosine tuned, and the increase in the null space activation required for compensating the perturbation is achieved by an increase in the cosine offset, rather than in the amplitude. Moreover, the concurrent generation of hand forces in multiple directions and control of one additional degree of freedom (DoF) by muscular null space is feasible although performance varies significantly across participants (Gurgone et al. 2022). The null space components controlling the additional DoF can be selected as those explaining 80% of muscle pattern variation during null space modulation for stiffening a virtual end-effector. However, the strategies underlying null space control have not been investigated. Here, we hypothesized two possible strategies that participants could use to control an additional DoF: a direction-independent strategy, in which few muscles are activated in all force directions, and a direction-dependent strategy, in which each force direction presents a different null space activation pattern. By fitting a cosine function to the directional tuning of muscle activations during null space control, we associated the direction-independent strategy with an increase in the cosine offset and the direction-dependent strategy with an increase in the cosine amplitude. We found inter-individual variability in the magnitude of null space components not required for control and in the strategies adopted for null space control. Cosine tuning analysis showed that some participants adopted a direction-independent strategy, where the additional DoF was controlled by the same set of muscles independently of target direction, while other participants used a combination of direction-dependent and direction-independent strategies, with different muscle patterns exploited to modulate null space activation while generating forces in different directions. Further investigations will address the question of whether the choice of strategy is related to the dimensionality of the control space and to null space control performance. A better understanding of the null space control strategies and their inter-individual variability may lead to design specific training protocols for improving learning of muscular null space modulation during the generation of limb movements that may be useful for robotic augmentation.

3-G-57 Influence of implicit and explicit feedback response to a visual error on visuomotor learning response

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When encountering a movement error, the motor system corrects the movement within a trial (feedback response: FR) and in the subsequent trial (learning response: LR). A theoretical study has proposed that the motor command for FR serves as a teaching signal for LR (Feedback Error Learning (FEL); Kawato et al., 1987). Consistent with the idea, it was demonstrated that the LR is a time-shifted copy of the FR (Albert & Shadmehr, 2016). However, other empirical results contradicted the idea. First, the LR did not preserve the temporal patterns of FR (Fine & Thoroughman, 2006). Second, the LR is present even when the FR is absent (Burge et al., 2008). To test the FEL further, we modified an experimental paradigm developed initially to investigate the FR (Franklin & Wolpert., 2008). Specifically, the visual cursor was laterally shifted when reaching a target 20 cm away. We measured the force against the force channel in the perturbation trial (FR) and the subsequent trial (LR). This method enables us to arbitrarily manipulate the temporal pattern of visual error and directly compare the temporal profiles for FR and LR by the force output. First, Exp.1 examined if the LR was similar to the FR with a constant time shift (N = 10). The cursor was laterally shifted by ±3 cm at 7 different locations. As reported in the previous study (Albert & Shadmehr, 2016), the temporal patterns of FR and LR were similar regardless of the shift location, and the magnitude of LR significantly correlated with that of FR. However, while the onset of FR depended on the shift location, the LR started equally before the movement onset, clearly indicating that the LR is not the FR shifted with a fixed time. Next, Exp.2 examined if the similarity between the FR and the LR was still preserved when manipulating the temporal profile of cursor-shift (N = 10). After ± 3 cm cursor shift at 1 cm, the shift was maintained, removed, or reversed (∓3 cm). Although the temporal pattern of cursor-shift specifically modulated the FR, the LR did not show such temporal specificity: For example, a biphasic FR pattern was observed for a reversed condition, but the monophasic LR was produced. Exp.1 and 2 assumed that the FR was implicitly induced (i.e., the explicit strategy was not used). Although the explicit strategy for motor learning has been widely investigated (Taylor et al., 2014), no previous study has examined how the explicit FR influenced the LR. In Exp.3 (N = 10) with the cursor shift by ± 3 cm at 1cm, depending on the target color, the subjects were instructed either to voluntarily exert the lateral force in the cursor-shift direction (anti-correction), in the opposite direction (pro-correction) or not to use any explicit strategy. Counter-intuitively, the anti-correction enhanced the LR, while the pro-correction reduced the LR. These results indicate that the motor system produced the LR through the complicated computation based on the visual error information and the FR.

3-G-58 High-performance kinematic decoding and neural-state estimation that leverages general properties of motor-cortex population geometry

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A common goal in basic research and brain-machine-interface engineering is to infer the most likely neural state, and/or the most likely action, from spiking observations recorded from a small set of neurons. Recent characterizations of population-level properties of neural activity in motor cortex suggest a new set of statistical constraints that allow efficient neural state estimation and subsequent kinematic decoding. Neural trajectories in motor cortex are stereotyped and directed. A neural trajectory is traversed in only one direction - never in reverse. Moreover, neural covariance often changes dramatically across tasks, contexts, or trial epochs, such that neural trajectories explore previously low-variance dimensions. These properties allow neural trajectories to spread out and avoid 'trajectory tangling'; similar neural states never lead to dissimilar future neural states. These properties suggest a revised view of neural activity in motor cortex: the embedding dimensionality of neural trajectories may grow large, yet trajectories remain sparse such that the vast majority of neural state space is empty and unused. Thus, despite relatively high linear dimensionality (tens or even hundreds of dimensions) there are very few locations where the neural state can plausibly reside. Furthermore, because tangling is low, a good estimate of the present neural state typically provides a good estimate of the recent past and near-term future. We present a decode algorithm (MINT: Mesh of Idealized Neural Trajectories) that codifies these properties into statistical assumptions. MINT learns a library of idealized neural trajectories, one per condition, that serves to scaffold a geometrically complex underlying manifold. MINT also learns a library of corresponding behavioral trajectories. Each neural state in the library has exactly one corresponding behavioral state. Kinematic decoding uses this direct mapping, avoiding the need to approximate it with a nonlinear function. During inference, MINT first estimates the probability of every state in the library, given past and present spiking observations. Interpolation is then used to improve the estimate's resolution and generalize between conditions as needed. We evaluated offline performance across multiple tasks and brain areas. Performance rivaled or exceeded that of modern neural network state estimators and decoders. Yet MINT is mechanistically interpretable and orders of magnitude more computationally efficient. As the movement repertoire desired for brain-machine interfaces expands, decode methods will face the challenge that correlations between neural activity and behavior are strongly task dependent. MINT provides a unified decode strategy that is aided rather than impeded by changing correlations. This generality demonstrates the utility of scientifically grounded assumptions: cutting-edge performance is readily achieved across a broad variety of situations, with minimal computational cost.

3-G-59 Intentional and conflict-resolution components of movement: an active inference account for the motor control of embodied virtual limbs

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The field of motor control has long focused on goal-directed actions, like the case of reaching for a target location and/or grasping an object. While goal-directed actions are driven by explicit intentions, recent studies in conditions of multisensory conflict revealed the presence of unconscious motor adjustments not driven by goal achievement, but rather aimed at resolving the multisensory conflicts. In this contribution, we will first present experimental evidence for the parallel unfolding of intentional

and conflict-resolution components of movement as observed in human subjects who embody and control a virtual arm that is not necessarily aligned with the physical body. Results from our experiments show how, when introducing subtle visuomotor rotations during the control of an embodied virtual limb, subjects tend to engage in motor patterns that are not exclusively associated with the assigned motor task (e.g., extending/bending the elbow, or reaching a target), and instead tend to suppress - when possible - the sensory conflict so to maintain a unitary body representation. These results, as we will argue, cannot be fully accounted for by classical models of optimal motor control. As an alternative, we will present a model of movement control grounded on active inference, i.e., on a predictive processing account of action generation, that seamlessly integrates intentional and conflict-resolution drivers of action. The model is able to reproduce movements guided by 1) the intention to achieve an external goal 2) the necessity to resolve multisensory conflict, and 3) both drivers at the same time, depending on the task and the configuration. Our simulations reveal a fundamental difference between intentional and conflict-resolution components of movement, which is reflected in distinct dynamics of the inference process. In particular, the two components result to be driven by diverse types of prediction errors, and by the specific way in which they are combined. We will discuss how results from our model may provide new insights about the fact that people are often unaware of their subtle compensatory movements arising from multisensory conflict (e.g., moving the body to fit the visual input). Furthermore, we will discuss how experimental and theoretical evidence from the work presented can guide the design of immersive virtual reality applications for motor rehabilitation and for disabled users inclusiveness, in which implicit motor behaviors tailored to the users' needs can be bring about with minimal impact on the soundness, and thus effectiveness, of the intervention.

3-G-60 The Art of Neuroscience; Two Legs to Stand on!

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The Homer Technique neuromuscular algorithm can be used to help detect movement efficiency. Neuroscientists have collected many interesting observations about the nervous system. In addition to observations, as scientists, I have developed a theory which can account for the observations. The leap from observations to theory is a leap from knowledge to understanding. The possibility of being able to make such jumps is exciting, and computational neuroscience provides tools which are well aligned with the goal of making these jumps. Discovering how gait variability affects stability and keeps the body towards a point of equilibrium can be measured and extrapolated to determine how close we are to equilibrium during every step in persons with neurologic disability. We have already established this modeling in sports and optimal performance. Moreover clinical scientists have discovered that the central nervous system influences movement; people who have central nervous system lesions suffer from movement abnormalities and gait abnormalities. These physical symptoms can be detected using position sensing exoskeletons. Profiling neuromuscular dysfunctions in conjunction with joint work would give us an indication of preferred movement pathways and stereotyped movement patterns. We have built technology that would target specific large muscle groups used for balance, stability, and gait. It would not be difficult for the technology to identify and collect information for simple movement evaluations in humans with neurological dysfunctions. Principles of inverse dynamics dictates that muscle effort has a positive correlation to the acceleration of rigid body segments surrounding a joint. Adversely previous related research studies have found that there is also a negative correlation between muscle rate of force production and muscle effort, including in my recent PhD thesis. Currently, the technology developed enables scientists to detect neuromuscular effort using electromyography (EMG), sensors and joint torque using inertial measurement units (IMU) programmed through computer vision machine learning technology. The machine learning software is designed to create a profile of specific joints in the body using relative data from one of the physiological variables that determine mechanical work. With further development the technology can evolve to be used as a tool to create human movement profiles in specific populations.

3-G-61 Effects of training variability on the use of flexible sensorimotor mappings

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The first problem to be overcome in learning any novel motor skill is to associate particular actions with desired outcomes. This problem has become increasingly complex in the digital age, where the mapping between actions and outcomes can be as arbitrary and diverse as imagination allows - just consider the variety of action-outcome associations underlying digital applications and video games. In this work, we ask how these associations are formed de novo, hypothesizing that under specific training regimes generalizable mappings are more readily formed, while in others, local state-actions associations are favored. To accomplish this, we studied learning in a simple navigation task where participants attempted to move a cursor between various start-target locations by pressing three keyboard keys. Importantly, the mapping between the keys and the direction of cursor movement was unknown to the participants. In Experiment 1, we found that in conditions that required participants to explore multiple trajectory solutions to arrive at the target locations had significantly better generalization than participants that could rely on a single trajectory solution. Computational modeling revealed that the pattern of learning and generalization could be captured by the dynamic interplay between model-free reinforcement learning and Bayesian inference processes. Specifically, the Bayesian process was leveraged early on to learn the underlying mapping but gave way to reinforcement learning over the course of training; however, if conditions changed - as in tests of generalization - the Bayesian process could be reengaged to recover performance. In Experiment 2, we further found that in experimental conditions that never demanded exploration of the mapping, then reinforcement learning processes appeared to blunt learning of the Bayesian process and consequently any knowledge of the underlying mapping. Finally, in Experiment 3, we show that the initial benefit of exploring and learning the underlying mapping remains even after an extended period of training that did not require the flexible use of the mapping. Taken together, these experiments demonstrate that the complexity of the initial learning problem may set the course of how the novel motor skill is ultimately represented.

3-G-62 MotorNet: a Python toolbox for controlling biomechanical effectors with deep learning

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Artificial neural networks (ANNs) are a popular class of computational models for studying neural control of movement. Typically, they are used in conjunction with third-party biomechanical simulation software, with the neural network trained to control the biomechanical effector. This leads to several impracticalities: (1) researchers must rely on two different platforms and (2) biomechanical effectors are not differentiable, constraining researchers to reinforcement learning algorithms despite the existence and potential biological relevance of faster training methods. To date, this has been mitigated by

training multi-layer perceptrons as "forward models" approximating the behaviour of effectors from third-party software. However, this does not address (1) and remains a slow, cumbersome process when iterating over many different models and effectors. To address these issues, we developed MotorNet, an open-source Python toolbox that allows creating arbitrarily complex, differentiable, and biomechanically realistic effectors to train ANNs on user-defined motor tasks. It is designed to meet several goals: ease of installation, ease of use, a high-level and user-friendly API, and a modular architecture to allow for flexibility in model building and task design. MotorNet requires no dependencies beyond typical Python toolboxes available on the Anaconda library, making it easy to get started with. For instance, it allows training ANNs on canonical motor control models such as arm26 within minutes on a typical desktop computer. MotorNet is built on TensorFlow and therefore can implement any network architecture that is possible using the TensorFlow framework. Consequently, it will immediately benefit from advances in the artificial intelligence field through TensorFlow updates. Finally, it is open source, enabling users to create and share their own improvements, such as new effector and network architectures or custom task designs for the ANN to perform. Overall, we hope MotorNet's focus on higher order model and task design will alleviate overhead cost to initiate computational projects for new researchers by providing a standalone, ready-to-go framework, and speed up study progress of established computational teams by enabling a focus on concepts and ideas over implementation details.

3-G-63 Investigating the role of peripersonal space representation in contact-value visuomotor behaviour

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Sensory events occurring close to the body have particular behavioural relevance. An object is more relevant within grasping distance than further away. Perhaps unsurprisingly, the magnitude of several behavioural and neural responses are dependent on the proximity of a sensory event to specific body parts. Such "peripersonal space" (PPS) responses, traditionally interpreted as reflecting the position of the stimulus in egocentric coordinates, may in fact play a role in creating or avoiding contact with objects near the body. Here we provide a comprehensive characterisation of PPS responses across humans and non-human primates (NHPs), with the aim of facilitating the assessment of their role in contact-related actions. We recorded high-density EEG in humans and intracranial neuronal signals in NHPs during the same perceptual task. Visual stimuli were presented along a mediolateral axis centred on the right hand (distance from the hand: ±24, ±12, 0cm). Crucially, eye and hand positions were manipulated to disentangle eye- versus hand-centered encoding. Both scalp and intracortical local field potentials were analysed in the frequency domain by computing power spectral densities. Preliminary results (24 humans, 1 NHP) revealed gaze-independent coding of stimulus position across the two species. In humans, alpha, beta, and gamma band power in posterior regions contralateral to the stimulated where visual stimuli were delivered was modulated by stimulus position. A similar gaze-independent positional coding was observed in NHP ventral premotor cortex. Further, hand position affected alpha and beta power in left-lateralised frontal and posterior electrodes, though this effect was rather independent of the distance to the stimulus. Using an additional modelling analysis that considers the biomechanical properties of the potential action of reaching the visual stimulus with the hand, we demonstrated that these responses reflect not only the distance between the stimulus and the hand, but also action intention. These results support the notion that PPS responses reflect the value of contact-related actions.

3-G-64 Neural code for online corrections to the center-out reaching movements: is it on the manifold?

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Recent studies of motor control have shown that the neural population activity in motor cortical areas has a low-dimensional structure: a low number of latent dynamical factors that explain a large fraction of neural variability. It is unclear, however, whether this low-dimensional structure corresponds to task instructions or to behavioral output, since both variables are strongly correlated with one another. To address this question, we analysed neural recordings from premotor and motor cortices of monkeys engaged in a center-out reaching task with a force field perturbation. The perturbation induced transient deviations from the desired trajectory which required correction in real-time. We decomposed total behavioral variability into two components: the first one related to the instructed reach direction, and the second one corresponding to the trial-to-trial variability in hand trajectories given the instructed reach direction. While the first component is known to be well captured by low-dimensional autonomous dynamical models, the second component must integrate external inputs as it includes online corrections to the hand trajectory that the monkey makes during each trial based on the visual and tactile feedback. We first used an RNN decoder to confirm that the non-autonomous component of behavioral variability can be decoded from neural activity. We next extracted latent dynamical factors with an LFADS model, a sequential autoencoder model with a controller RNN that can infer unobserved control inputs into the neuronal population. We found that the low-dimensional latent dynamics factors extracted by LFADS captured instructed reach direction, but could not explain online movement corrections. We then modified the LFADS model following the ideas from the recently developed Targeted Neural Dynamical Modeling (TNDM) approach, which aims to align the latent dynamical factors with the observed behavior. We also applied additional constraints on the encoder model to demix the information about autonomous and non-autonomous components of the neural activity. We found that our model with a fixed number of factors could either explain more neural variability or more variability in movement corrections, but not both simultaneously. This result agrees with the previous work that found two largely orthogonal subspaces in the neural population: a feedback-driven subspace encoding movement corrections and a subspace with feedforward dynamics encoding the desired behavioral trajectory. While the previous study used linear methods, our model had the flexibility to non-linearly transform and integrate movement correction signals. Yet, capturing movement correction information in our model did not improve the identification of the subsequent latent neural dynamics. This indicates that the low-dimensional dynamics in neural activity mirrors the task structure, but does not dynamically integrate the real-time movement corrections at a population level.

3-G-65 Integration of corticospinal and proprioceptive EPSPs in motoneurons during electrical stimulation of the spinal cord

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Epidural spinal cord stimulation (SCS) is emerging as a novel treatment for motor paralysis as a result of spinal cord injury or stroke. Importantly, contrary to functional electrical stimulation, evidence in animals and humans shows that SCS restores the subject's ability to recover voluntary control of previously paralyzed muscles. Here we utilized computational biophysics to understand how SCS enables residual excitatory inputs from the brain to restore firing rates in a simulated population of spinal motoneurons. It has been hypothesized that SCS increases the excitability of spinal motoneurons, thus amplifying the impact of residual supraspinal inputs that enable volitional movement. We tested this hypothesis by modelling simultaneous excitatory inputs from residual corticospinal fibers and SCS. To do this, we leveraged previous knowledge that shows that SCS directly targets sensory primary afferents in the spinal cord, thus generating synchronous volleys of action potentials in the recruited afferents. We distributed sensory and corticospinal synapses along the dendritic tree of motoneurons following a realistic spatial distribution obtained from animal experiments. We then simulated a lesion by reducing the number of corticospinal fibers to 30% and calculated the impact of SCS parameters on the ability of the motoneurons to produce action potentials. Our analysis revealed three regimes that emerge from the integration of inputs from both periodic residual supraspinal pathways and continuous SCS, which we termed "subthreshold", "near threshold," and "suprathreshold." In subthreshold regime, not enough primary afferents were recruited by SCS, yielding very low motoneuron firing rates to sustain movement. Instead, in the near threshold regime, we found that the firing rate produced during active residual corticospinal fibers was significantly increased. In this regime, motoneurons only fired during concomitant SCS and corticospinal inputs. Instead, when most of the primary afferents were recruited by SCS, we reached a suprathreshold regime. Suprathreshold SCS directly produced action potentials in motoneurons completely dominating their activity, which remained uninfluenced by residual inputs. We validated these results with electrophysiology in non-human primates by studying muscle responses to combinations of SCS and corticospinal stimulation. Our results can be used as a starting point to expand our understanding of the mechanisms underlying the unexpected recovery of neural motor control after severe motor paralysis during SCS.

3-G-66 Long-term motor learning creates structure within neural activity space that shapes subsequent adaptation

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Animals take a long time to acquire new motor skills but can quickly adapt learned movements in response to environmental perturbations. How animals adapt is likely influenced by the movements they already know, but the nature of this interaction is unclear. Long-term learning of motor skills likely causes changes in neural connectivity, which may shape the neural dynamics that can be produced. To examine the interaction between a neural population's existing activity repertoire and its ability to change its activity patterns, we modeled motor cortical neural population dynamics during skill learning and subsequent adaptation using recurrent neural networks. We trained networks to produce motor repertoires of different sizes, from one to four movements. We hypothesized that having larger repertoires would facilitate adaptation since the activity already exists within a larger portion of neural activity space. Indeed, networks with larger repertoires adapted to visuo-motor rotation perturbations more quickly, and multi-movement networks performed significantly better than single-movement networks. To understand how learning multiple movements impacts the underlying network dynamics, we examined the differences between networks initially trained on one and two movements when performing one shared movement. The dynamics of two-movement networks were more constrained than that of one-movement networks, without leading to constraints in the output: two-movement networks had less variance in unit and population latent activity, but greater variance in motor output. They also had more robust and predictable (less "tangled"; Russo et al 2018) neural trajectories that were structurally organized in neural space in congruence with the organization in motor output. Critically, when we reduced this structure in neural space by changing how the network inputs were "encoded"-from angular to categorical target reach cues-, the differences in adaptation between multi-movement networks disappeared. This showed that the structure can facilitate adaptation, but only under certain circumstances. First, adaptation was facilitated only when the structure in the inputs, the neural activity space, and the perturbation were all congruent: networks with angular inputs adapted faster to angular rotations, while those with categorical inputs adapted better to target reassociations. Thus, adaptation is affected by the specific organization of dynamics within neural space, and external cues during learning can shape this representation. Second, adaptation was facilitated only when small changes in output were required: networks with larger repertoires performed worse under larger perturbations. This observation may highlight an inherent trade-off in skill-acquisition: learning more movements creates more defined structure in neural activity space, thereby facilitating adaptation that requires small changes but, consequently, hindering adaptation that requires larger changes.

3-G-67 Effects of semantic priming on involuntary imagery in the reflexive imagery task

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In one version of the Reflexive Imagery Task (RIT), subjects are presented with two line drawings of everyday objects (e.g., HAMMER and CLOUD) and instructed to not think of the name of any of the objects (Cho et al., 2018). For this "Two-Object" RIT, involuntary subvocalizations (RIT effects) occur on a substantive proportion of the trials. We investigated whether this involuntary imagery could be influenced by an object's semantic category and by a priming task manipulation. Specifically, we assessed whether an object's semantic action-related attributes, and whether priming a goal-directed action mindset, increases the rate of occurrence of the involuntary subvocalization of manipulable object names, as opposed to non-manipulable object names, in a Two-Object RIT. Subjects (n = 30) were primed, before a block of 40 RIT trials, with a Cognitive-Motor task (a weight estimation task; WET) or a Cognitive Task (the control condition, a digit-span task; DST). In this RIT, a trial could consist of HAMMER (the Manipulable category) presented along with CLOUD (the Non-Manipulable category). Would apprehension of an objects' action-related features, and goal-directed action priming, render the subvocalization of "hammer" to be more likely than that of "cloud"? A repeated measures ANOVA revealed a significant interaction effect (F(1, 26) = 7.49, p = .011, ηG^2 = .04) between object category and prime task on the rate of RIT effects to the visual stimulus objects. Post-hoc t-tests revealed that the rate of RIT effects to Manipulable objects was greater following the DST prime task (M = .53, SD = .17) than following the WET prime task (M = .46, SD = .18; t(26) = 2.74, p = .051, Cohen's h = .14). Conversely, the rate of RIT effects to Non-Manipulable objects was greater following the WET prime task (M = .55, SD = .18) than following the DST prime task (M = .48, SD = .17; t(26) = -2.74, p = .051, Cohen's h = -.14). We also investigated whether the encoding of an object's semantic action-related attributes, during the time window that immediatley preceded (-400 ms) the occurrence of RIT effects, increases EEG event-related desynchronization (i.e., decreased oscillatory activity; ERD) in the Mu (9-13 Hz) and Beta (14-30 Hz) frequency bands over sensorimotor cortex (electrode sites: C3, Cz, C4). Six subjects participated in the EEG phase of this study. Repeated measures ANOVAs revealed significant main effects of object manipulability on both Mu frequency ERD (F(1,4) = 53.33, p = .002, ηG^2 = .10) and Beta frequency ERD (F(1,4) = 14.35, p = .019, ηG^2 = .15). Post-hoc t-tests revealed that greater Mu frequency ERD preceded RIT effects to Manipulable objects (M = -6.67, SE = 8.31) than to Non-Manipulable objects (M = 5.97, SE = 7.11; t(4) = 7.30, p = .002). Likewise, greater Beta frequency ERD preceded RIT effects to Manipulable objects (M = -4.36, SE = 6.33) than to Non-Manipulable objects (M = 9.94, SE = 5.72; t(4) = 3.79, p = .019).

Poster Session 4

Friday July 29, 2022

B – Fundamentals of Motor Control

4-B-1 Direction and history-dependent learning and generalization of human finger dexterity

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Finger dexterity, fundamental in our daily lives, is manifested by generation of multi-finger multi-directional patterns of muscles activity during various motor tasks, and further, by generalization of learning in one context to other contexts. Tying shoelaces, for example, requires precise coordination of multiple fingers, some active primarily in the flexion direction, others in the extension direction, and some immobile. Nevertheless, whether the control processes of these actions are independent, or interact and potentially generalize across each other, remains unclear. In a set of experiments, we sought to characterize the behavioral principles underlying the control process, learning and generalization of dexterous extension and flexion movements. We quantify dexterity in terms of finger individuation, force accuracy and temporal synchrony between instructed fingers. In Exp. 1, healthy participants (n=13) used a robotic dexterity device to exert isometric finger forces during single and multi-digit chord tasks, in both flexion and extension directions. We found greater finger individuation and force control in finger flexion compared to extension. This was more profound at higher forces (75% maximal force), and when more fingers were involved in the desired action. In Exp. 2, we tested whether mechanical coupling between digits contributed to movement of uninstructed fingers and thereby limited the ability to individuate finger extension. A single digit of each participant (n=20) was moved passively by the robot in each direction while measuring isometric forces of the unmoved fingers. Our data ruled out the possibility that mechanical coupling of the digit extensors explains the reduced individuation in the extension direction, suggesting a neural origin underlying the dissimilar control. In Exp. 3, we investigated learning and generalization ability across flexion and extension. Two groups of participants were trained for 3 days in either the flexion (Flexor group, n=13) or extension (Extensor group, n=13) direction. We found improvement in all dexterity measures in both groups following training, but the Extensor group generally exhibited inferior dexterity. Interestingly, while the Extensor group generalized dexterity to the flexion direction, the Flexor group did not, and the generalization was restricted to the flexion direction of the untrained hand. In Exp. 4, we tested whether the direction-specific generalization pattern is determined by the history of prior actions. In a group of highly trained musicians (n=13), we found that the degree to which learning generalizes between two contexts was affected by history of prior experience. Our data indicate that control of multi-digit dexterous patterns is direction-specific in humans, supporting the hypothesis that control circuits for learning of finger flexion and extension are overlapped in that they partially, but asymmetrically, transfer between directions.

4-B-2 3D pose estimation enables virtual head-fixation in freely moving rats

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Movement is the main mean of an organism to interact with its environment. Due its large impact, neuroscience has long pursued the goal to understand the underlying mechanisms of movement generation, representation, and control. Recent studies indicate that signals related to motion are spread throughout the whole brain (Musall et al. 2019). Also spontaneous movements occurring outside of the task content influence the ongoing neural activity. This raises the need to monitor the behavioral state of the animal to account for movement related changes in neural activity, as our interpretation of ongoing processes might otherwise be confounded (Salkoff et al. 2019). While strongly limiting the animal's behavior, e.g. via head-fixation, allows reducing the number of uncontrolled variables, it also limits our ability to understand naturalistic dynamics of movement. To measure unconstrained movements, we developed FreiPose, a versatile framework to capture 3D motion during freely moving behavior. We applied FreiPose for full-body tracking of rats, mice, cowbirds, and marmoset as well as detailed tracking of rat paws during reaching. By combining precise movement tracking of rats with electrophysiology in forelimb motor cortex and using generalized additive modelling (GAM) we were able to describe the ongoing neural activity as a combination of simultaneous multiplexed coding of multiple body postures as well as paw movement parameters (mean R2 = 0.11 ; up to 0.4 in individual neurons). Head and body postures were represented in an unexpectedly large proportion of neurons (0.10 and 0.06 mean ΔR2). This highlights how movements of not just individual body parts, but the whole body influence the activity in the motor cortex. To distinguish the activity of interest from general movement information, we developed a virtual head-fixation approach. Using encoding models of neural activity, we clamped body and head movements in the model to obtain the impact of the paw movements on neuronal activity. We uncovered a large fraction (44.5 %, 73/164) of neurons in the motor cortex to be tuned to paw trajectories. This tuning was previously masked by the influence of the variable body posture information, resulting in only 17.68 % (29/164) tuned neurons. We conclude that measuring movements of freely moving animals is an essential step towards understanding the underlying neural dynamics. The brain is increasingly viewed as a dynamic system, functions of which need to be understood in terms of populations instead of individual neurons. Adding precise descriptions of ongoing behavior into models of neural activity will enable us to more clearly describe motifs of population activity during sensorimotor integration and decision-making. Musall et al. 2019 Single-trial neural dynamics are dominated by richly varied movements. Nature NSc Salkoff et al. 2019 Movement and Performance Explain Widespread Cortical Activity in a Visual Detection Task. Cerebral Cor.

4-B-3 Generalization reveals asymmetric and history-dependent control networks for multi-finger dexterous movements

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Finger dexterity, fundamental in our daily lives, is manifested by the generation of multi-finger and multi-directional patterns of muscles activity during various motor tasks, and further, by the generalization of learning in one context to other contexts. Tying shoelaces, for example, requires precise coordination of multiple fingers, some active primarily in the flexion direction, others in the extension direction, and some immobile. Nevertheless, whether the control processes of these actions are independent or interact and potentially generalize across each other, remains unclear. In a set of experiments, we sought to characterize the behavioral principles underlying the control process, learning and generalization of dexterous extension and flexion movements. We developed an isometric dexterity task that precisely measures dexterity in terms of finger individuation, force accuracy and temporal synchronization during finger flexion and extension. First, we investigated learning and generalization abilities across flexion and extension directions, both within and across hands. To do so, two groups of participants were trained for 3 days in either the flexion or extension direction. We found improvement in all dexterity measures in both groups following training, though finger extension generally exhibited inferior dexterity. Surprisingly, while learning finger extension generalized to the untrained flexion direction, learning finger flexion did not generalized to the untrained extension direction. Generalization biases of the finger flexion direction was also evident in the untrained hand. Next, we examined whether the asymmetric generalization pattern of multi-finger dexterous movements was history dependent. We thus recruited skilled musicians who showed increased baseline levels of dexterity in both directions and found that the degree to which learning generalizes between two contexts was affected by prior experience. Overall, our data indicate that control of multi-digit dexterous patterns is direction-specific in humans, supporting the hypothesis that control circuits for learning of finger flexion and extension are overlapped in that they partially, but asymmetrically, transfer between directions. This ability, however, is modular as it depends on hand use and the history of prior training.

4-B-4 Evoked-movement biases in human cortex reflects execution history, not plan-based prediction of upcoming actions

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Human motor performance depends not only upon the ability to plan and execute movements that are relevant to the current state of the environment and/or the body, but also upon the recent history of these actions. Accordingly, transcranial magnetic stimulation (TMS) over the primary motor cortex (M1) can evoke thumb movements in a consistent direction, but after participants train repeatedly over minutes in an opposite direction, subsequent TMS pulses evoke thumb movements in the recently practiced direction. The mechanism that drives these profound physiological biases is still unclear. One possibility is that these biases provide a measurable readout of the physiological changes induced by motor practice or learning paradigms. Alternatively, these biases might also reflect changes in planning-based expectation, or prediction, of the most probable action (a hypothesis that was recently supported in goal-directed movement tasks). Here we systematically dissociate these possibilities using novel experimental manipulation of a TMS paradigm and behavioral timed-response task to probe execution-dependent and prediction-dependent history of upcoming actions. During the TMS block, 65 pulses were delivered to estimate the physiological biases. During the goal-directed block, participants were asked to perform 150 timed-response thumb movements toward one of four targets. In each timed-response trial, participants heard a sequence of four tones (500ms apart) while one of four potential targets appeared 50-300 ms prior to the fourth tone, and participants were instructed to move to the target as quickly as possible synchronously with the onset of the fourth tone. Critically, we included a subset of catch trials in which no target ever appeared, and participants were required to move with the onset of the fourth tone in any direction. These catch trials enabled us to assess plan-based expectation of upcoming movement (i.e., guesses). We found that baseline physiological biases shared similar low-level movement kinematics with plan-based expectations, as both distributions largely overlapped (Exp.1, n=20). However, when we systematically manipulated the probability of recent history of executed movements by asking participants to repeatedly make thumb movements toward a new direction (Exp. 2, n=15), we found that only TMS-evoked movements were biased toward the repeated direction. Interestingly, when the amount of repetition was limited, but the probability of upcoming movement plans was modulated by increasing the likelihood of targets presented in a specific direction, we found no effect on evoked movement despite profound biases in plan-based expectation of upcoming movements (Exp. 3, n=10). Our data suggests that repetition-induced physiological changes might provide a readout of the movement-related default state of neural activity, but have little effect on ongoing neural activation related to motor planning.

4-B-5 Spectral Power Fluctuations in the Parietal Cortex during Real World Table Tennis

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Ecologically valid conditions often provide unique insight in the study of natural cognition. We have developed a dual-layer electrode approach to high-density electroencephalography (EEG) that enables high fidelity electrocortical recordings during dynamic human movement. Using this approach, we wanted to determine if we could study brain dynamics during table tennis, a whole-body, goal-directed activity requiring object tracking and interception along with sensorimotor integration. The posterior parietal cortex has an important role in tasks like reaching, grasping, and obstacle walking. Nordin et al. (2019) studied electrocortical dynamics of humans walking and running over obstacles on a treadmill and found theta power (4-8 Hz) increases in the posterior parietal cortex after seeing and negotiating obstacles. Based on their findings, we hypothesized that an increase in theta power in the parietal cortex would correlate with table tennis players' identifying and intercepting the ball in table tennis. We collected and analyzed high-density dual-electrode EEG data from 27 participants who played table tennis with a ball machine and a human opponent. Data pre-processing included 1 Hz high-pass filtering, trial segmentation, bad channel rejection, bad time window rejection, an exploratory dual-electrode noise reduction technique, and average referencing. We decomposed scalp channel data into components using Independent Component Analysis. Components were localized with subject-specific head models, and brain components were selected and then clustered across participants using k-means. In this study, we selected the anterior parietal cluster which had components from 17 participants. We computed an event-related spectral perturbation (ERSP) plot that was time-warped to the average latency of hit and feed events across epochs for trials with the ball machine. The spectral baseline was the average log spectrum from all time points in this condition. We used bootstrap statistics to find significant differences from baseline ($p < 0.05$). Theta power (4-8 Hz) increased in the anterior parietal cluster after the ball machine fed the ball but before the participant's paddle contacted the ball. On average, this spectral power increase occurred approximately 200 ms after the feed event. A decrease in theta power occurred as the participant anticipated the next ball in the 500 ms leading up to the next ball feed. The average latency of the participant's hit event was 700 ms after the ball was fed.

The relative timing of the theta spectral power increase is in line with the findings from Nordin et al. (2019). We both found an increase in parietal theta power soon after the object (obstacle or ball) became visible but before the participant acted on the object (hurdled or hit). These results demonstrate it is feasible to quantify electrocortical brain dynamics during non-locomotor whole body movement tasks involving active cognition.

4-B-6 The vigor of feedback control scales with the uncertainty of physical disturbances during goal-directed reaching movements

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Humans have a remarkable ability to control their actions in uncertain environments, such as prevent spilling a drink when driving on a bumpy gravel road. These disturbances are difficult to anticipate and can jeopardize performance. Recent studies have shown that humans generate faster movements, coactivate pairs of antagonist muscles, and respond more vigorously to the same mechanical perturbations when reaching in uncertain environments. Aligned with the behavioral findings, we hypothesized that the nervous system's control policy is modulated by environmental uncertainty. Accordingly, we expected that the nervous system will increase feedback gains, and thus have greater sensitivity to sensory feedback, in response to increased environmental uncertainty. Here, we examined how healthy humans alter their movements when exposed to physical disturbances that vary randomly throughout movement. We predicted that participants would increase the vigor of their movements and corrective responses with greater environmental uncertainty. Participants performed planar reaching movements in a Kinarm exoskeleton robot. Experiment 1 consisted of a baseline, exposure, and washout phase. Participants (N=16) performed unloaded movements in the baseline and washout phases. Noisy torque pulses disturbed the elbow during the exposure phase. The amplitude of the torque pulses was sampled from a normal distribution ($\mu=0$ Nm, $\sigma=1$ Nm) and changed randomly every 25 ms. Peak hand velocity in the direction of the target was used to assess the vigor of voluntary reaching movements. We probed changes in feedback gains by applying mechanical step-torque perturbations that flexed or extended the elbow (±1.5 Nm) on randomly selected trials. Participants increased the peak velocity of their reaching movements and reduced their peak hand displacement when disturbed by the same step-torque perturbations in the exposure phase. Behavior returned to baseline levels in the washout phase. Motivated by these results, we performed a second experiment to determine if responses scale with greater environmental uncertainty. During the exposure phase, participants (N=28) encountered noisy torque pulses with low ($\sigma=1$ Nm) and high ($\sigma=2$ Nm) environmental uncertainty (counterbalanced across participants). The baseline and washout phases were identical to Experiment 1. In addition to kinematic variables, we quantified changes in coactivation and muscle stretch responses using surface electromyography. We found increased peak hand velocities and coactivation with greater environmental uncertainty. Furthermore, we observed scaled increases in muscle stretch responses and reductions in peak hand displacements when disturbed by the same mechanical perturbations with higher environmental uncertainty. Collectively, the findings support our hypothesis that individuals adjust their control policy to respond more vigorously to sensory feedback when interacting with uncertain environments.

4-B-7 Cerebellar internal models accurately detect errors introduced by small disturbances with a marked transition in encoding

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The ability to distinguish sensory information generated by our active movement (reafference) vs. external perturbations (exafference) is fundamental for ensuring accurate motor control as well as cognition. For example, while it is vital to generate compensatory vestibulo-spinal reflex responses to passive perturbations, these same reflex responses would be counterproductive during active movements. Similarly, the ability to discriminate between 'self-generated' and 'external' sensory stimuli is essential for perceptual stability. The inability to make this distinction has been implicated in psychiatric disorders. Our recent work has shown that the vestibular system distinguishes between reafference and exafference. Specifically, the brain computes an internal forward model of the predicted sensory consequences of the motor command, which is then compared to the actual sensory feedback to compute sensory prediction error (SPE). Thus, during active movement SPE is negligible and the responses of vestibular nuclei neurons that contribute to both perception and postural reflexes are suppressed. In contrast, large unexpected (externally-applied) perturbations produce large SPE and these same neurons robustly encode head motion. To date, however, experiments have only considered the encoding of large perturbations. This raises the question of how neurons respond to small perturbations within versus outside the range of natural variability. To address this, we recorded responses of cerebellar Purkinje cells as well as their target neurons in the rostral Fastigial Nucleus (rFN) while we randomly applied assistive or resistive head perturbations during a fraction of active head movement trials. The perturbations were calibrated such that the smallest level changed head velocity within the band of natural variability, while the largest level doubled or halved head velocity. We found that rFN neurons showed a marked transition to reduced reafference suppression in response to perturbations across levels. Notably, even the smallest perturbation increased neuron sensitivity to values comparable to the passive condition. Interestingly, while we could not detect responses to small perturbations in individual Purkinje cells due to their greater variability, we could detect responses at the population level (~40 cells) that could account for reduced reafferent suppression observed in rFN cells. Taken together our findings suggest that the population of Purkinje cells detect small SPEs and transmit this information to deep cerebellar and vestibular nuclei to cancel reafference. This computation serves to ensure accurate motor control and perceptual stability. These findings have provided new insight into how motor learning can occur in new contexts even in the presence of trial-to-trial variability.

4-B-8 Greater muscular co-contraction but no changes in visuomotor feedback gains in response to visually amplified movement variability

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Humans have a remarkable ability to perform precise and accurate motor actions, such as threading a needle or throwing a fastball. Naturally occurring movement variability poses a significant challenge to the sensorimotor system when attempting to perform precise actions. Further, sensorimotor delays may allow movement variability to propagate and remain uncorrected for a period of time. Two differing, but potentially complementary strategies, are that the sensorimotor system regulates feedback gains or muscular co-contraction to mitigate movement variability. Here we aim to understand if the sensorimotor system uses muscular co-contraction, visuomotor feedback gains, or both to regulate

movement variability. We hypothesized that the sensorimotor system modulates both feedback gains and muscular co-contraction in response to movement variability and time delays. We predicted greater muscular co-contraction and visuomotor feedback gains in the presence of amplified movement variability and greater time delays. Participants were seated with their arm placed on an exoskeleton robot. We collected surface electromyography of six upper-limb muscles. Participants moved their arm to control a cursor on a screen. They kept the cursor within the bounds of a narrow visual channel while reaching towards a target. Participants performed four conditions in a two-way repeated measures design. We manipulated movement variability (amplified or non-amplified) and time delay (delay or no-delay). Movement variability was visually amplified by doubling the cursor's distance from the centerline of the narrow visual channel. Time delays were imposed by delaying cursor feedback 200 ms in the lateral direction, perpendicular to movement along the visual channel. Muscular co-contraction was calculated as the minimum activation between muscle pairs. To estimate visuomotor feedback gains, on probe trials we laterally shifted the cursor and recorded applied hand force against a simulated stiff channel that prevented lateral hand movements. We found movement variability decreased in the amplified condition ($p < 0.001$), but did not change with time delays. Movement variability was negatively correlated with muscular co-contraction ($p < 0.001$, $\rho = -0.437$). Participants did not display changes in visuomotor feedback gains in response to amplified movement variability or time delays. Although we did not find a relationship between trajectory variability and visuomotor feedback gains, we found a significant negative correlation between muscular co-contraction and visuomotor feedback gains ($p < 0.001$, $\rho = -0.493$). In our task, this suggests the sensorimotor system may have modulated muscular co-contraction relative to participant-specific visuomotor feedback gains. Our results support the idea that the sensorimotor system modulates muscular co-contraction to regulate movement variability.

4-B-9 Corticomuscular coherence reflects evidence accumulation in perceptual decision making

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Decision making and motor control are two sides of the same coin [1-4]. Recent work has shown that even spinal reflexes are already pre-tuned during the formation of a decision [1]. Cortico-muscular coherence (CMC), which characterizes the functional connection between the motor cortex and muscles, has been used to quantify preparatory state of the motor periphery in response to a perceptual stimulus [5]: CMC increases between the motor cortex and the muscle relevant for performing the cued response. However, the response cue was discrete and unambiguous in this paradigm, making it impossible to investigate the effect of evidence accumulation on the peripheral state of the motor system. Random dot motion (RDM) stimuli require the accumulation of perceptual evidence and the amount of evidence provided per unit time can be controlled through the coherence. Using these stimuli it has been shown that there is a continuous flow of decision related information to central and peripheral motor areas [1-2]. This continuous flow implies that we should be able to see a correlate of the evidence accumulation in the motor system. In this study, we measured cortico-muscular coherence (CMC) as a continuous read-out of the information flow between the perceptual and the (peripheral) motor system. We expected a build-up of CMC as evidence provided by the stimulus accumulated. Participants (n=10) watched a RDM pattern and were asked to indicate the perceived motion direction by moving a handle to one of two targets. Targets were oriented such that participants had to employ either their triceps or their biceps. We took EEG and EMG measurements and computed time evolving CMC between the left motor cortex and the right arm bi- and triceps. Preliminary data show that the CMC is increased between motor cortex and biceps when the participant will make a decision that involves recruiting this muscle, and triceps CMC is increased when this muscle signals the decision. We plan on comparing CMC between stimuli of low and high coherence, to see if we can detect differences in decision confidence within the CMC. Additionally, we will look for a buildup CMC as evidence accumulates towards a decision. Our findings would confirm the continuous flow hypotheses, as well as provide a new way to quantify the temporal evolution of a decision variable in the motor system.

4-B-10 Corticomuscular Coherence Reveals Engagement of Different Cortical Regions in Transient and Sustained Phases of an Isometric Motor Task

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Background Studies of primate motor systems have shown that the cortical neurons produce motor commands during transient movement, whereas the spinal interneurons take over the control when the movement is sustained (Shalit et al., 2011). However, the contribution of different cortical regions to the control of transient vs sustained motor activity in humans remains poorly understood. In this study, we measured Cortico-Muscular Coherence (CMC), to quantify the strength of synchrony between the neural oscillations in the brain and muscles during transient and sustained phases of a motor task. Methods High-density 128 channel electroencephalogram (EEG) and 8 bipolar electromyogram (EMG) signals were recorded from 22 healthy participants (mean age = 55.59, std = 15.44). Participants performed a simple pincher grip isometric task using their thumb and index finger of right hand. Participants were instructed to increase the force at their preferred pace (transient phase) and hold the force (sustained phase) for 5 seconds at 10% of maximum voluntary contractions. The preprocessing of EEG/EMG signals, and EEG source reconstruction (using Linearly Constrained Minimum Variance beamformer) were performed in Fieldtrip toolbox in MATLAB. Three contralateral cortical regions namely primary motor (M1), primary sensory (S1), supplementary motor area (SMA) and 3 muscles namely abductor pollicis brevis (APB), first dorsal interosseous (FDI), flexor pollicis brevis (FPB) were pre-selected for analysis. CMC at 8 frequency bands was then calculated using our previously published non-parametric procedures (Coffey et al., 2021). Results Transient phase: The results showed a significant ($p<0.05$, corrected for multiple comparison using adaptive false discovery rate at $q=0.05$) CMC between sensorimotor regions and all three muscles at low or high beta band. In addition, significant CMC were observed in other frequency bands i.e., FPB-M1 and FPB-S1 at theta band; APB-M1 and FPB-SMA at low or high alpha band; FDI-M1 at low gamma band. Sustained phase: Significant CMC was observed between all three muscles and SMA at beta bands. In addition, M1-APB CMC at higher beta band was also significant. In summary, the CMC during the transient phase was observed in sensorimotor regions and in the 5-47 Hz range, whereas the CMC during sustained exertion shifted strictly to beta band in the motor regions (M1 and SMA). Discussion Our findings can be explained by selective activation of cortical regions or the spinal interneurons that act as a 'neural filter' (Williams et al., 2009) for a selective communication. This selective activation is then manifested as synchronization in distinct frequencies and regions. The weaker cortical contributions in the sustained stage of motor task can be an indirect implication of a more dominant spinal control (Shalit et al., 2011). The findings unravel the complex underlying mechanisms of neural control during a simple dynamic isometric exertion.

4-B-11 A new view on the spinal network mechanisms underlying rhythmic movements

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Most of the investigations on spinal rhythm generation are based on motor nerve recordings and single neuron recordings. Since flexor/extensor muscles alternate during movements, it is often assumed that the generation is accomplished by neuronal modules that alternate in opposition, which single neuron recordings seem to support. However, here we argue that when many neurons are monitored simultaneously a different picture emerges. We recorded hundreds of neurons from the lumbar spinal cord of turtles during rhythmic scratching and found that, rather than alternating, the neuronal population is performing a "rotation", i.e. cycling continuously through all phases. Rotational dynamics are observed across trials as well as behaviors. Since such rotation is difficult to explain with existing models of alternating neuronal groups, we propose a new theory that accounts for the rotational dynamics. Using a simplified network model, we show that in spinal networks with recurrent excitatory and inhibitory connectivity, there is no need for pacemaker activity or modular structures. Tonic input to the network controls the rhythm and pattern depending on the task. The model also reproduces other experimental observations and provides a mechanism for multifunctionality.

4-B-12 Enhanced efficiency of online motor corrections towards the body midline as revealed by redirected reaching actions

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Reaching objects in a dynamic environment requires fast online corrections that compensate for sudden object shifts or postural changes. Previous studies revealed the key role of visually monitoring the hand-to-target distance throughout action execution: if the apparent location of the target or the hand is altered using prisms or virtual displays, corrections are automatically operated in a way that minimize the visual apparent hand-to-object distance, in spite of the visuo-proprioceptive conflicts. Researchers in virtual reality capitalized on this evidence for smoothly redirecting reaching actions towards a pre-established locations (e.g., to enhance the flexibility of passive haptics). Here we present results from an immersive virtual experiment in which action redirection was adopted to investigate how the efficiency of online corrections depends on sensorimotor asymmetries associated with space perception, brain lateralization, and biomechanical constraints. Participants performed reaching actions while the virtual hand was progressively displaced from the real hand so to trigger online corrections that redirect the action. The efficiency and the degree of awareness of the ensuing motor corrections were taken as assessment variables. The visual displacement of the virtual hand was controlled ad-hoc in a way that allowed us to systematically manipulate the total amount of the redirection, the region of space in which the action unfolded, and the direction of online corrections. Results revealed more efficient visuo-motor corrections for actions redirected towards, rather than away from, the body midline. The effect is independent on the reaching hand and the hemispace of action, making explanations associated with laterality effects and biomechanical constraints unconvincing. More plausible, our results may find an explanation in the finer sensorimotor representations characterizing the space proximal to the body-center, where high-value functional actions, like fine manipulative skills and self-defense, typically take place.

4-B-13 Anticipatory and compensatory control modulation in a virtual catching task

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Catching a moving object requires integrating sensory information about the environment with previous experiences to prepare an appropriate motor response. This information can influence both anticipatory (feedforward) motor preparation prior to initial object impact and compensatory (feedback) responses upon impact. The extent to which information about object properties (such as speed) differentially modulate anticipatory and compensatory motor responses in complex tasks remains unknown. In this study, we explored the influence of object speed and mass on both anticipatory and compensatory motor responses. To address this question, we developed a virtual catching task using a robotic manipulandum (KINARM End-Point Lab, KINARM) where participants had to stabilize their arm against the impact of a virtual object moving towards them on a horizontal plane. We recorded limb kinetics, kinematics, and electromyography during task performance in 20 young participants (10 F, 20.6 ± 2.04 years). On each trial, participants were instructed to move to a predefined area and then keep their arm stationary against a background load while visually tracking a virtual object moving toward them in the transverse plane. When the object reached the hand's position, participants experienced a force and were told to match the impulse (within a ±5% margin of error) to "catch" the falling object. Feedback about whether the object catch was successful was provided at the end of each trial. In each block of trials, we varied object momentum by manipulating either the object speed (low: SLow, or high: SHigh) with a constant mass, or by varying the virtual mass (low: MLow, or high: MHigh) moving at a constant speed. Overall, participants showed similar success rates across all conditions. As expected, anticipatory control of both peak force amplitude and co-contraction of antagonist muscle activity of the shoulder and arm before the collision were higher in the high speed and mass conditions. In contrast, limb force onset (increased above baseline values) occurred when the object was closer to the hand position in the MHigh than in MLow with no significant differences between SHigh and SLow (interaction effect: $F(1,19) = 15.70$, $p < 0.001$). There was an increase in muscle co-contraction of the arm in SHigh and MHigh in both the short (0-50 ms) (main effect: $F(1,19) = 6.12$, $p = 0.02$) and long-latency windows (50-100 ms) (main effect: $F(1,19) = 13.17$, $p < 0.01$), reflecting greater compensatory control in response to higher object momentum. Together, the results from our virtual task mirror previous studies of catching free-falling objects: whereas anticipatory and compensatory motor response amplitudes were modulated by the momentum of the object, independent of the object's kinematics, anticipatory motor response timing depended on object kinematics, independent of the object's momentum.

4-B-14 Cortical control of individual fingers and finger combinations

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One of the most distinguishing features of the human motor system is its unparalleled dexterity in controlling the hand and fingers. There are countless tasks and behaviors that rely on individuated finger control, from buttoning a shirt to playing Liszt, but it is difficult to use animal models to study the cortical underpinnings of that control (a monkey has yet to play even the first bar of La campanella). As a result, we have little understanding of how population activity within motor cortex is organized to flexibly control both individual fingers and finger combinations or grasp postures. To address this question, we recorded neural activity from microelectrode arrays implanted in the motor cortices of two human participants with tetraplegia as part of an ongoing clinical trial. Although the participants do not have overt hand function, they were asked to attempt to flex the fingers on their right hand to perform virtual presses of five on-screen buttons (one button for each finger). The audio and visual cues throughout a session comprised both single-finger (e.g., index, ring) and multi-finger (e.g., thumb + middle, index + ring) presses. When considering only the set of trials with individual finger presses, we found that a low-dimensional projection of the population activity exhibited clear separation between fingers and even somatotopic organization. However, the population activity from trials with multi-finger combinations was not constrained to the same low-dimensional somatotopic manifold; the activity from these trials expanded to include both the previously-observed manifold as well as new, orthogonal dimensions. These additional dimensions contained combination-specific activity, and could be used to classify the various multi-finger postures even if all other dimensions--which accounted for the inter-finger variance across single-finger trials--were omitted. These results indicate that there exists a strong nonlinearity in the cortical control of the hand and fingers, as the cortical population does not follow the superposition principle. That is, the neural state for a given combination of fingers is not a linear combination of the neural states of the corresponding individual fingers. This observation has profound implications for the eventual control of dexterous robotic hands via brain-computer interfaces, as decoders trained using limited training sets will likely be unable to extrapolate to high-dimensional control.

4-B-15 Complexity and high-dimensionality of motor cortex activity during a simple task

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Motor cortex (M1) neural activity during reaching has been extensively characterized. Yet reaching is one component of a large movement repertoire that primates can produce. Furthermore, movement often involves a semi-continuous stream of action that may (or may not) consist of subcomponents. It is presently unclear how to extend the lessons learned from reaching. One possibility is that M1 acts as a low-level controller that performs a unified computation, such as converting intended force or hand-position commands into outgoing muscle commands. Under this hypothesis, M1 response complexity largely reflects the complexity of the controlled limb. This predicts that simpler limb dynamics should yield simpler M1 dynamics. An alternative hypothesis is that M1 performs highly specific computations that can be deployed and composed as needed. This predicts that response complexity should scale not with biomechanical demands, but with the richness and variety of computations used within a task. Observations during reaching are potentially consistent with either view. We thus designed a task where the two hypotheses make opposing predictions. Rhesus macaques performed an isometric force-tracking task with a variety of low- and high-frequency profiles. This task uses a simple one-dimensional output (and essentially no limb motion) yet requires a range of computational strategies that likely must be used compositionally. For example, continuous feedback control is appropriate when force changes slowly, but may not be when force changes quickly. Under the first hypothesis, M1 activity should be simple because limb dynamics are trivial and the low-level goal (match force to a target) is consistent. Under the second hypothesis, M1 activity may be unusually complex due to the need to deploy different computations at different moments. We recorded from 1257 M1 neurons (using NHP-optimized Neuropixels and Plexon S-probes) and 134 isolated motor units, allowing direct comparisons between two populations of spiking neurons. Motor unit activity was low-dimensional: explaining 90% of the variance required only 3 dimensions. Activity in the dominant dimensions closely resembled force. M1 activity was very high-dimensional: explaining 90% of the population variance required ~80 dimensions. Activity resembling force existed only in low-variance dimensions. High M1 dimensionality in part reflected different dimensions being occupied depending on the appropriate computational strategy. For example, dimensions occupied during rapidly changing forces were unoccupied when holding static forces. Consequently, M1 activity was separated into three nearly orthogonal subspaces, each with distinct dynamics, corresponding to three movement motifs (slowly changing forces, ramps, and sinusoids). These results argue that M1 participates in a large repertoire of dynamics that can readily be deployed and composed to suit computational needs.

4-B-16 Flexible multielectrode array for high-resolution motor unit recording during skilled behavior in rodents, songbirds, and primates

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The nervous system can produce an astonishing variety of complex and robust behaviors. Understanding the physiological mechanisms of motor control that generates such behaviors requires examination of the activity of both neurons and muscles at the cellular level. While recent developments in neural recording methods have enabled studies of neural activity at high spatial and temporal resolution, current technologies for recording individual motor units - the muscle fibers innervated by a single motor neuron - are far less precise and typically cannot be employed during complex behavior. Here we present a novel class of multielectrode devices that record muscle activity, called electromyography (EMG), at cellular resolution across a wide range of muscles and species. We have developed a platform that enables us to adapt the design of a basic multielectrode array to record single motor unit activity across a variety of muscle groups (i.e., forelimb, trunk/axial, orofacial, respiratory, and vocal) and species (i.e., mice, rats, songbirds, and nonhuman primates). Thin polymer "threads" are embedded with up to 32 electrode contacts and equipped with micron-scale features that allow them to be easily inserted into muscles as small as 3 mm in length. Moreover, the flexibility and tensile strength of the devices, along with the electrical properties of the low impedance electrode contacts, allow single unit and bulk EMG recordings to be collected for months following implantation. Using different configurations of the novel multielectrode array, we recorded EMG activity across multiple species, anatomical targets, and behaviors. First, recordings in mice during head-fixed locomotion on a running wheel and freely behaving locomotion on a treadmill show single motor unit recordings for weeks after implantation and bulk EMG recordings for months. Second, recordings in the forelimb muscles of nonhuman primates show a population of motor units recorded during a movement task. Finally, recordings of respiratory muscles in songbirds show the stability of recordings across thousands of trials during breathing. These data are enabling us to study motor control across time scales ranging from millisecond coordination between motor units to coordination of multiple motor units over hours.

4-B-17 At-home characterization of kinematic synergies supporting procedural skill learning

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Background: Performing complex motor behaviors likely relies on the refinement of coordinated effector kinematics, i.e. synergies. Performance improvements during motor learning have been linked to changing patterns of kinematic synergies. Here, we examined kinematic synergies during early procedural skill learning, and we predicted that a reduction in synergies supports early learning improvements. Methods: Twenty participants learned to type a numeric sequence (4-1-3-2-4) with the left, non-dominant hand as quickly and accurately as possible over 36 trials. Each trial consisted of 10s of practice followed by 10s of rest. Due to COVID restrictions, the study was run remotely with video supervision. A standardized keyboard and camera were delivered to each participant. Keypress performance was recorded using the keyboard with an online data collection platform. Movement was recorded with the camera, and kinematics were determined using markerless pose estimation software. Kinematic synergies were identified by non-linear dimensionality reduction of the movement data, using cluster totals of t-distributed stochastic neighbor embedding (t-SNE). Behavioral measures included: (a) early learning, the change in typing speed of correct keypresses/sec between trials 1 and 12 (when 95% of the session's learning was reached). (b) microonline learning, the overall change in typing speed during practice periods and (c) microoffline learning, the overall change in typing speed between the end of each practice period and the beginning of the next. In an initial analysis, linear regression was used to evaluate the relationship between the kinematic synergy count and each behavioral measure. Results: Synergy count decreased progressively over the 36 trials (36 trials, R2 (adj.) = 0.89, p-value < 0.01). Synergy count reduction was greatest during early learning (trials 1-12, 10 + 2) and significantly more marked than during trials 13-36. Synergy count reduction over the 36 practice trials and during early learning (but not during trials 13-36) were significantly different from the null (p<0.01 for both). The magnitude of synergy reduction correlated with early learning (p<0.01). Synergy count reduction during early learning occurred largely during microoffline (rest) rather than during microonline (practice) periods (microoffline, p<0.01) in trials 1-12. On the other hand, synergy changes did not correlate with behavioral gains after practice trial 12. Conclusions: Early procedural skill learning develops in parallel with a reduction of kinematic synergies supporting sequential binding of keypresses during rest intervals interleaved with practice. Work under way aims to characterize the specific finger synergies responsible for superior performance. At-home research of human motor behavior in may be of value in the study of patient populations with limited mobility and when in-lab investigations are not feasible.

C – Posture and Gait

4-C-18 Stiff with age: reduced proactive and reactive cognitive flexibility in older adults underlies dual-task walking performance costs

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Background: Coordinated movements comprise sensory and motor processes which can degrade ongoing cognitive tasks (and vice versa). Resultant dual-task costs to motor integrity and task performance worsen with advancing age, but the neural basis for this exacerbation is unclear. Age-related reductions in cognitive flexibility may restrict resource allocation to ongoing cognitive and motor processes as demands increase, limiting older adults' capacities for adaptation. Younger adults may redistribute cognitive resources in response to shifting demands, mitigating performance costs. In this study, the effects that increasing cognitive-motor demands have on proactive and reactive control processes were compared across older and younger adults to explore the neurophysiological basis of age-related differences in cognitive-motor interference (CMI). Methods: 19 younger and 16 older

healthy adults completed cued task-switching while alternating between sitting and walking on a treadmill. Gait kinematics, task performance measures, and brain activity were recorded using electroencephalography (EEG) based Mobile Brain/Body Imaging (MoBI). Results: When older and younger adults walked and performed the cognitive task simultaneously, stride time variability decreased relative to baseline gait measures, and response times were faster. Task performance improved during simultaneous walking in both age groups when the task was easy. As task difficulty increased, younger adults maintained performance while walking relative to sitting, whereas older adults' performance decreased. Walking-dependent changes to neural indices of proactive and reactive control were consistently larger in younger adults. These neural changes systematically increased as task difficulty increased in younger, but not older adults. Summary/Conclusions: The changes to proactive and reactive control processes of younger adults may reflect progressive resource allocation to conserve the integrity of both motor and cognitive processes mediating task preparation and implementation. Stabilization of gait at the cost of task performance, and in the absence of neural changes to control processes, may indicate that older adults reached adaptive limits. Increased cognitive-motor demands may have forced older adults to choose between prioritizing the task and maintaining their posture. As cognitive-motor demands are further increased, we predict performance decline will progress in older adults. We predict younger adults will continue to modify control processes until a threshold limit is encountered, beyond which performance decay develops.

4-C-19 Gaze behaviors during macaque locomotion in the presence or absence of vestibular function

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For sighted individuals, directing the axis of gaze - the summation of the head's position and orientation in space with the orientation of the eyes within the head - to obtain relevant visual information is integral to most activities of daily living. The neural machinery which produces stable and accurate control of gaze involves a complex network of cortical, subcortical, and brainstem regions; this broad connectivity makes tests of gaze control useful clinically for detecting and localizing neurological damage. In particular, vision is critical for guiding locomotion. The vestibular system similarly makes critical contributions to both postural and visual stability. Specifically, the vestibulo-ocular reflex keeps the retinas on-target by driving eye movements to counteract head movement, while the vestibulo-collic and vestibulo-spinal reflexes help keep the head steady in space during locomotion and to counteract unexpected postural perturbations. Here, we investigate differences in locomotion-related gaze behaviors of rhesus macaques with and without bilateral vestibular dysfunction. Specifically, we recorded single-eye video-oculography (VOG), head position and orientation, and 3D posture in 3 rhesus macaques - one female with bilateral vestibular loss, one normal female, and one normal male - during locomotion on either a treadmill at varied speeds or during repeated passages of a linear walkway. VOG was recorded using a head-mounted camera in a custom-built frame for each animal. Head movements were recorded using an analog 6D gyroscope/accelerometer unit mounted to the head, while head position and orientation were recorded via video using head-mounted retroreflective markers. Three-dimensional posture and gait data were captured using four cameras analyzed using the DeepLabCut software package. We assessed the distribution of saccades and eye-head gaze shifts throughout the gait cycle in both natural and treadmill locomotion by calculating two phase-locking indices (vector strength and entropy of phase distribution). This analysis demonstrated that macaques shift their gaze independently of step cycle. Additionally, by comparing the portion of time gaze was held steady versus the portion of time it was moving, we show that bilateral vestibular loss disrupts the ability of animals to keep gaze stable during locomotion, as the loss of stabilizing reflexes increases gaze variability and requires additional, compensatory gaze shifts.

4-C-20 Influence of trunk support and development on the evolution of spontaneous upper extremity behaviors in infants

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Within the first year of life, infants develop head and trunk postural control which is a critical component to the concurrent development of upper extremity coordination in reaching and grasping. While often viewed separately, arm movements can assist in posture by increasing base of support or providing protective extension reflexes. Although a few studies have demonstrated a link between trunk stability and reaching kinematics, little is known about how postural arm movements evolve into exploratory movements and how they are influenced by the emergence of trunk control or external support. In this study, we examine the full repertoire of arm movements (exploratory, posture related, and relaxed (resting)), in relation to development of trunk control and use of external support.. Eight infants (4 male) participated in bimonthly test sessions from two to eight months of age. During each session, the infant's intrinsic trunk control was quantified with the Segmental Assessment of Trunk Control (SATCo) and then infants were given 1 of 4 levels of external trunk support (pelvis, lower ribs, upper ribs, axilla) on each trial. External support helped us understand the influence of trunk stability on arm behaviors and was necessary for most infants. Each trial included 3 minutes of quiet sitting where the infants were entertained with a baby movie or toys while being encouraged to sit quietly in an upright position. Arm behaviors were categorized as exploratory (eg, reaching, grasping, manipulating a toy), postural (eg, holding on or pushing for support, waving arms), or relaxed (hands resting down by one's side). Statistical analyses examined the model effects of intrinsic trunk control, external support, and also included an analysis of bilateral arm behaviors. On average, the total duration of postural, exploratory, and relaxed arm behaviors was 42%, 38%, and 22% of the time, respectively.. Postural arm behaviors occurred significantly less often when infants had more intrinsic trunk control; and when higher levels of external trunk support were provided. In contrast, infants showed significantly more exploration as intrinsic control increased but were not significantly affected by external support. Relaxed arm behaviors increased when infants had more intrinsic trunk control. With increases in intrinsic trunk control, bilateral posture behavior decreased while bilateral exploration increased. Overall, postural arm movements were the most common bilateral behaviors. To our knowledge, this is the first characterization of how posture and relaxed arm behavior evolve across development. Developmental researchers should consider more than exploratory arm movements and should control for the level of intrinsic trunk control and type of postural support when studying arm movements in young infants.

4-C-21 The role of auditory and tactile noise in the control of upright posture

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During upright standing, the postural system relies on a continuous stream of information from the somatosensory, vestibular, auditory, and visual systems. The addition of noise to the auditory and somatosensory systems during upright standing has been shown to reduce postural sway. Within this

study, we sought to look at the effect of tactile and auditory noise on postural stability. Given that the nervous system uses noise to optimize information transfer, adding tactile or auditory noise should lead to increased feedback about adaptations or references used in balance control. In this current experiment, postural sway was analyzed in (N = 22) healthy young adults who were presented with continuous white noise through the auditory system (headphones), tactile system (SubPac4), and a combination of the two. Results show reduced postural sway variability and an increase in overall postural stability (as indexed by the body's center of pressure) in the presence of auditory and tactile white noise even when visual information was not present. Furthermore, nonlinear time series analysis revealed that the tactile noise has an additive effect, independent of vision, on postural sway. Additional analysis performed using recurrence quantification revealed that recurrence and entropy increased when noise was added in the auditory and tactile modalities. However, percent determinism and laminarity were affected by the tactile stimulation only. Lastly, analysis of different frequency domains of postural sway revealed that white noise reduced postural sway in both low- and high-frequency components (> or <0.3 Hz) of sway, suggesting that both spontaneous /exploratory and feedback-driven components of postural dynamics were influenced by the added sensory noise regardless of the modality of input. These results support the idea that auditory and tactile white noise increase postural stability, suggesting that noise may be beneficial in therapeutic and rehabilitation domains for older individuals and those with balance disorders.

4-C-22 Tail motoneurons are targeted by vestibular complex axons in mice

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Tails are a defining characteristic of chordates and play multiple roles critical for animal survival, such as balancing (Schwaner et al., 2021). Previous studies in mice have suggested that their prominent tail is important for balance (Buck et al. 1925, Ewer 1968). However, little is known about its neuronal control in the spinal cord and the relation to balance related brain structures. One of such structures is the vestibular complex in the brainstem, which comprises of 4 main nuclei and several accessory nuclei. As previously shown, the vestibular complex (VC) generates motor programs in the hindlimbs muscles in response to a balance perturbation (Murray et al, 2018). In this work we asked 1) where in the spinal cord the tail motoneuron (tail-MNs) pool is located, and 2) determine if tail motoneurons are targeted by vestibular complex axons, analogously to the motoneurons involved in hindlimb balancing responses.\\ Here, the tail-MNs pool was localized in the sacro-coccygeal part of the spinal cord using retrograde viruses and tracers. Within the labeled neuronal pool, we characterized their sizes in order to identify putative alpha motoneurons. Roughly 60 per cent of these putative alpha MNs were contacted by vestibular complex-originating axon terminals, similarly to what was previously described for other MNs pools (such as hindlimbs extensors). Intriguingly, we also showed previously (Lacava and Uusisaari, JNS 2020) that mice use their tails in movements phase-locked to hindlimbs stepping, suggesting that the vestibular complex may play a role in whole body coordination of fine movements during locomotion as well. Because of the conserved properties of the vestibular complex across many species, our results could lead to a new understanding of the neuronal control of balance in other vertebrates as well.

4-C-23 Brain correlates mediating postural control of balance in traumatic brain injury: a systematic review

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Introduction: Traumatic brain injury (TBI) is one of the commonest causes of chronic disability in young adults. About 50% of TBI report imbalance at 5 years with additional socioeconomic impacts such as reduced return-to-work rates. Understanding brain mechanisms mediating imbalance in TBI is difficult due to non-focal nature of damage to brain networks. Relatively few studies have performed objective balance assessments or linked brain damage to imbalance. Thus, we performed a systematic review of the literature highlighting the current understanding of brain mechanisms mediating imbalance in TBI. Methods: PubMed, Web of Science, and Scopus were searched until 10 February 2022 from the beginning of time on these portals. Inclusion criteria for articles was: peer-reviewed research articles publishing new findings, any TBI (mild, moderate, severe, or concussed), assessed at any time (acute or chronic), performed brain structural or functional imaging (including DTI, resting state fMRI, VBM), performed balance assessment and linked it with brain imaging. Exclusion criteria was: no balance assessment or no comparison of balance measures with brain imaging, animal studies, use of language other than English, SPECT imaging, case reports, conference proceedings, research reports, and letters to editors. Results: Our search resulted in 747 articles from all databases. After initial screening using abstracts, we were left with 35 articles. After detailed screening using full-length articles, 16 research articles were included in the systematic review. Discussion: We found sensory organization test (SOT) (6 of 16 studies) and balance error scoring system (BESS) (5 of 16) to be most commonly used balance assessments. Of the studies using BESS, none found a link between imbalance and brain imaging measures. Noticeably, many studies (7 of 16) only performed regions of interest (ROI) based analysis. Studies using ROI approach often focused on sensory and motor tracts or subcortical brain regions and found these regions to be linked with imbalance. Six studies (of 16) performed whole-brain white-matter analysis; 3 of those 6 studies reported no link of white-matter measures with balance measures; one study (Calzolari et al., 2021) reported damage to widespread white-matter brain tracts linked to impaired balance, whereas the remaining 2 of the 6 studies (Caeyenberghs et al., 2012; Diez et al., 2017) reported predominantly pre-frontal white matter tract involvement in postural imbalance. So far, only one study (Diez et al., 2017) used functional brain imaging of cortical grey-matter, and their functional link to imbalance. Conclusion: Based on this systematic review, studies have not demonstrated a correlation between the commonly used clinical balance assessment (i.e. BESS) with brain imaging measures in TBI. In contrast, a few studies have shown links between white-matter damage and imbalance. Our search revealed only one study that used functional brain im

4-C-24 Postural adaptation to allocentric task demands in a modified basketball paradigm

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Consider a basketball player faced with two conditions. In one condition, they must score baskets with the hoop positioned 10% higher than usual (allocentric manipulation). In the other, they must score a basket with a ball weighing 10% more than usual (egocentric manipulation). In either case, they need to successfully adapt to the increased task demands, however would one of these situations require more consistent execution of a condition-specific posture than the other? As humans physically act in a dynamic world, they perform error updating across their complex musculoskeletal plant output that often integrates both egocentric and allocentric components. Allocentric components communicate external state perturbations, realizable post-hoc from action outcomes and predominantly through perceptual feedback (e.g., changing location of a target). The egocentric component instead operates throughout the action epoch and incorporates proprioceptive feedback (e.g., manipulating a heavier tool). In this experiment, we used a task that modulates demands factorially across these two dimensions. Recreational-level basketball players performed free throws in blocks where either the ball weight (standard weight vs 10% above standard) or hoop height (standard height vs 10% above standard) were manipulated. Simultaneous continuous motion capture allowed us to record posture vectors at the point of ball release, indexed by the spatial coordinates of key joint positions. In addition, we recorded the end-point precision of each shot as it crossed a plane traversing the hoop rim. Using a Bayesian analysis framework pioneered by human brain imaging (pattern component modeling; PCM), we assessed how complex condition-specific postural patterns related to end-point precision as humans adapted to the allocentric and egocentric manipulations. Allocentric (hoop-height) manipulations drove a more striking postural adaptation, both in terms of state-action policy and in terms of rapid adaptation to state changes. I.e., participants varied their posture more to cope with changes in hoop-height than to changes in ball weight. The additional availability of proprioceptive information during egocentric perturbations may offer additional goal-directed flexibility across the plant.

4-C-25 The complexity of plantar pressure distributions during balance and locomotion tasks

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The foot sole acts as an interface between our body and the environment, and its placement relative to the rest of the body determines stability in balance and gait. The foot sole is also a sensory organ innervated by thousands of tactile afferents that transmit information about dynamic contact parameters to the spinal cord and the brain. The importance of this sensory feedback is highlighted when sensation is impaired or lost, such as during peripheral neuropathy, leading to increased sway and higher risk of falling. However, which aspects of contact with the ground are signalled and how this tactile feedback is then used remain largely unclear. A first step towards a better understanding of the nature and function of tactile feedback is to characterise the unique set of spatiotemporal pressure patterns that are typically experienced on the foot, but which are quite different from those on any other region of the body. Here, we quantify the tactile stimuli experienced by the foot sole during a range of sensorimotor tasks and in different environments that span the range of daily activities. 15 healthy participants completed up to 15 tasks, including walking at different speeds and in different environments, where typically a single foot is in contact with the ground, balance tasks with minimal movement and both feet on the ground on both stable and unstable surfaces, and jumping trials that test pressure extremes. Participants wore standardised shoes fitted with TekScan pressure sensitive insoles, which recorded spatiotemporal pressure patterns through more than 400 sensors per foot at 100Hz. We found that a single foot typically experiences between 30 and 120% of body mass, with extremes of up to 400% body mass during jumping. While contact area averages around 50% during all tasks, the centre of pressure can be focused on any region of the foot and shows greater variability during more challenging balance or locomotion trials. Decomposition of the spatial pressure patterns using non-negative matrix factorization revealed a relatively small number of spatially localised components that captured the spatial complexity. The first five components relate to the heel and metatarsal heads, however the precise location differs depending on the task, with components from balance tasks biased towards the arch. More challenging tasks, such as walking on an uneven surface or balancing on unstable support, require more components to explain the same fraction of variance within the data, indicating more complex and variable inputs. Characterising pressure experienced by the foot sole is the first step to revealing the role that tactile feedback plays during walking and balance. These findings will also have implications on prosthetic device design, by helping determine optimal locations for sensor placement as well as defining sensing capabilities necessary for capturing behaviourally relevant force patterns in future studies.

D – Integrative Control of Movement

4-D-26 Frontoparietal involvement in online updating of reach-to-grasp to mechanical perturbations of hand transport: A TMS study

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Humans adeptly adjust their movements to perturbations via integration of multisensory feedback. Contemporary theories of the cortical organization of reach-to-grasp actions postulate that hand transport (the reach) and prehension (the grasp) are spatiotemporally coordinated by parallel, dynamic activation of relatively independent frontoparietal pathways. The putative dorsomedial (DM) 'reach' pathway consists of the dorsal premotor cortex (PMd) and the superior parietal-occipital cortex (SPOC), while the dorsolateral (DL) 'grasp' pathway consists of the ventral premotor cortex (PMv) and the anterior intraparietal sulcus (aIPS). Recent evidence indicates that these assigned roles of the DM and DL pathways may be more interwoven than previously thought. However, this evidence is based primarily on visual perturbations of task goals. The present study tested the differential involvement of frontoparietal nodes (PMv, PMd, aIPS, and SPOC) in online adjustments of reach-to-grasp coordination to mechanical perturbations that disrupted hand transport. Ten healthy right-handed participants (24 ±7.3 years old), after providing informed consent, performed reached-to-grasp movements in a virtual environment towards a rectangular virtual object (dimensions 5.4 × 2.5 × 8.0 cm), located 30 cm from the starting hand position. Mechanical perturbations were applied using a manipulandum attached to the wrist. On a minority of the trials (25%), the manipulandum exerted a 5N continuous force resisting motion along the axis of the reach. Perturbations were applied either 100 ms or 300 ms after movement onset, requiring participants to make online compensatory responses in the transport and grasp. Transcranial magnetic stimulation (TMS) was used to perturb processing, individually, in each of the four nodes (50% of trials) time-locked with the perturbation. Correction magnitude and latency were selected as outcome measures. TMS to PMd and SPOC in the dorsomedial pathway resulted in a reduction of the correction magnitude for late perturbations (3.5 cm/s, $p < 0.05$, 3.4 cm/s, $p < 0.005$, respectively). Conversely, TMS to aIPS decreased correction magnitude to early perturbations (4.1 cm/s, $p < 0.05$). Our results provide evidence that dominance of the DM pathway for processing proprioceptive inputs associated with mechanical perturbations of reach is movement phase-dependent. These findings support other recent evidence that strict assignment of the dorsomedial pathway to reach and the dorsolateral pathway to grasp is likely inaccurate. Future work should consider temporal aspects of DM-DL pathways in the coordination of corrective adjustment of reach-to-grasp actions.

4-D-27 Novel contralateral monosynaptic stretch reflexes in the trunk - physiology and anatomy

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We explored trunk reflexes in rodent to test their roles in spinal cord injury and recovery of function. In the process of this testing we discovered an unexpected aspect of the monosynaptic stretch reflexes in trunk muscles. Using classical reflex methods (nerve stimulation, electromyography and latency measurements) we were able to show novel bilateral effects at monosynaptic latency in the trunk muscles of rats. These rapid contralateral and monosynaptic reflex effects are reliable, and show frequency or rate dependent depression, but show no significant jitter. The effects were seen in both intact rats and in adult spinal transected rats (where we had first observed them). To test for an anatomical correlate of these physiological effects and establish a monosynaptic route across the midline we injected PRV into external oblique on left side and CTB into external oblique on right. Following 3 days for a single monosynaptic transsynaptic step of the PRV, we then retired animals and imaged the two viral expression patterns. The CTB labelled the ipsilateral external oblique motor pool and associated dorsal root ganglia (DRGs) ipsilateral to injection as expected. The PRV co-labeled the DRGs contralateral to injection, indicating the monosynaptic route seen in physiology. PRV was expressed more broadly and evenly (albeit in fewer DRG neurons overall) across contralateral DRGs. This was broader than seen in the DRGs for the CTB expression distribution ipsilateral to the CTB labeled external oblique motor pool on the CTB injection side, indicating multiple converging monosynaptic inputs to motor pool of the PRV injected external oblique muscle. Our data here suggest that much more integrated bilateral reflex control of trunk muscles occurs than seen in limbs, including monosynaptic integration. This is consistent with a need for the highest precision (and possibly fastest) controls in the proximal trunk upon which more distal limb motion precision depends (as discussed by Scott and Loeb). The organization and distribution of trunk reflexes have been under explored, as indicated by our surprising data here. Further, the developmental rules of trunk and limbs are known to show various differences, consistent with potential differences in control organization described here. In summary, our data suggest that trunk monosynaptic reflexes are in part bilateral, and these are broadly distributed and integrated. These reflex networks are presumably then fractionated by inhibition, including primary afferent depolarization and possible branch traffic control as suggested by data of David Bennett. Our data bear on reflex control of trunk, on various trunk motor control disorders, on reflex effects in spinal injury and recovery, and on reflex mechanisms in chronic back pain. Further exploration of the importance of bilateral reflex mechanisms, trunk afferent input distributions and their regulation by descending systems in skill learning is needed.

4-D-28 Sensorimotor feedback loops are selectively sensitive to reward

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While it is well established that motivational factors such as earning more money for performing well improve motor performance, how the motor system implements this improvement remains unclear. For instance, feedback-based control, which uses sensory feedback from the body to correct for errors in movement, improves with greater reward. But feedback control encompasses many feedback loops with diverse characteristics such as the brain regions involved and their response time. Which specific loops drive these performance improvements with reward is unknown, even though their diversity makes it unlikely that they are contributing uniformly. This lack of mechanistic insight leads to practical limitations in applications using reward, such as clinical rehabilitation, athletic coaching, and brain-inspired robotics. We systematically tested the effect of reward on the latency (how long for a corrective response to arise?) and gain (how large is the corrective response?) of seven distinct sensorimotor feedback loops in humans. Only the fastest feedback loops were insensitive to reward, and the earliest reward-driven changes were consistently an increase in feedback gains, not a reduction in latency. Rather, reduction of response latencies tended to occur in slower feedback loops only. These observations were similar across sensory modalities (vision and proprioception). Our results may have implications regarding feedback control performance in pathologies showing a cognitive decline, or on athletic coaching. For instance, coaching methodologies that rely on reinforcement or "reward shaping" may need to specifically target aspects of movement that rely on reward-sensitive feedback responses.

4-D-29 Expectation and attention influence early somatosensory processing in the human spinal cord

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Do attention and expectation operate at the level of the human spinal cord? Functional magnetic resonance imaging (fMRI) has revealed decreased spinal cord responses to pain during distraction, and involvement of the spinal cord in the placebo effect. However, due to its low temporal resolution fMRI cannot dissociate between effects of attention or expectation on early feedforward processing, or on later feedback responses. We recorded spinal evoked potentials and high-frequency (~600 Hz) signals via surface electrodes placed around the neck in response to non-painful electric stimulation of the median nerve during a sustained, intermodal attention paradigm, and during an implicit temporal expectation paradigm. To examine intermodal attention, we presented a train of median nerve stimulation, in parallel to a train of auditory beeps, each consisting of stimuli predominantly separated by irregular, i.e., inconsistent, inter-stimulus intervals. Participants were asked to detect transient temporal regularities (four to five consecutive stimuli presented with regular, i.e., constant, inter-stimulus intervals) in one sensory modality while ignoring the other. Behavioural responses, as well as somatosensory evoked potentials in scalp electroencephalography (EEG), confirmed that participants were shifting attention to the currently task-relevant modality. Importantly, we also found attentional modulation of the amplitude of early somatosensory evoked potentials recorded via neck electrodes, at around 8-13 ms, pointing to a spinal locus. Surprisingly, and in contrast to scalp EEG, we found lower amplitudes of evoked potentials in neck EEG when median nerve stimulation was task-relevant. We are currently testing a second cohort of participants to replicate the effect and examine its laterality. In a separate series of experiments, we are examining whether temporal expectation influences spinal somatosensory processing. To this end, we present median nerve stimulation in separate blocks either with a fixed or variable delay after an auditory cue. Recording via epidural spinal electrodes in patients with neuropathic pain, we have previously found that predictability of stimulus timing enhances power at around 600 Hz and 10-13 ms after median nerve stimulation. We are currently repeating this experiment in healthy individuals, recording non-invasively via surface neck electrodes, to replicate the effect. In summary, our data indicate that attention and expectation influence early, feedforward somatosensory processing in the human spinal cord.

4-D-30 Shared neural population dynamics across animals performing the same behaviour

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Animals of the same species share a characteristic set of behaviours. This species-typical behavioural repertoire is shaped under selection pressures over evolutionary timescales. However, evolution's solution to producing similar behaviours using different brains remains unclear. Here, we hypothesised that preserved neural population dynamics are the basis of species-specific behaviours: animals from the same species possess unique brains that are constrained so they can generate the 'appropriate' neural population 'latent dynamics' needed to produce their typical behaviours. We tested our hypothesis using motor cortical population recordings from three monkeys performing a centre-out reaching task and four mice engaged in a grasping and pulling task. First, we show that individuals from the same species share remarkably similar motor cortical latent dynamics during the same behaviour. Second, these similar latent dynamics across animals are also present in the absence of overt behaviour, as monkeys covertly planned future movements. Third, despite the vast differences in circuit and cellular architecture between cortex and striatum, mice performing the same task shared similar striatal latent dynamics, indicating that our results extend to this evolutionarily older structure that is shared among all vertebrates. Critically, our results are not a trivial consequence of the methodology. First, shared latent dynamics both capture a large fraction of the variance of single-neuron activity and are behaviourally relevant, as they can be used to predict both ongoing movement kinematics as well as future actions. Second, latent dynamics are more similar across different animals performing the same task compared to the same animal performing two related reaching or wrist tasks during the same experimental session. Third, when training a variety of recurrent neural networks on the centre-out reaching task, we could find pairs of models that generated similar behaviour but exhibited latent dynamics that were much more dissimilar than what we observed in the actual neural data. While neural population dynamics have been proposed as the first-level explainers of behavioural and cognitive phenomena, here we extend recent works to show that they are shared across different individuals engaged in the same behaviour. Our results are relevant for the development of brain-controlled devices that can better generalise across individuals to restore motor, affective, or even cognitive functions. Our results also have strong implications for the study of the neural basis of behaviour, suggesting that descriptions at the neural population level, rather than the single neuron level, better capture the features that are selected by evolution.

4-D-31 Uncertainty differentially shapes premotor and primary motor activity during movement planning

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Precise movement execution is central to our lives and is largely dependent on adequately planning the upcoming action. Electrophysiology studies are shedding light onto how neural populations in animals' and humans' brains mediate planning to unambiguous visual targets. Yet, the neural basis of movement planning under uncertainty remains mostly unaddressed. We used simultaneous recordings of neural populations from both the dorsal premotor (PMd) and primary motor (M1) cortices from monkeys performing both a standard centre-out reaching task, as well as a reaching task with uncertain target locations (Dekleva et al 2016). In the "uncertainty task," targets were presented as a series of lines along

a ring that served as probabilistic cues about the actual target's location; spacing between the lines varied the uncertainty, allowing us to probe its effect on cortical activity. We investigated how uncertainty affected movement planning activity by performing Principal Component Analysis separately on the PMd and M1 firing rates in both reaching tasks, obtaining corresponding "neural manifolds" (Gallego et al 2017) and latent dynamics during the instructed delay epoch. While the latent dynamics during the uncertainty and standard centre-out tasks were spanned by largely overlapping neural manifolds, monkeys apparently identified the two tasks as different contexts, as the dynamics occupied separate parts of neural state space, allowing us to decode task identity from neural activity even between trials, especially in M1 -- an observation that held even after matching the actual reaches between tasks. During the uncertainty task, complementary to previous results based on the analysis of single neuron activity (Dekleva et al 2016, Glaser et al 2018), both PMd and M1 latent dynamics contained information about reach direction, as well as the associated uncertainty. However, the relative importance of these signals was quite different across areas: M1 activity was mainly related to reach direction, while in PMd, uncertainty was dominant. Additionally, the axes needed to linearly decode uncertainty and direction from the latent dynamics during movement planning evolved in time but remained orthogonal to each other. This observation supports the emerging view that neural populations may use orthogonal subspaces to separate computations. Visual cue uncertainty influenced the radius and speed of the latent trajectories during preparation, with lower uncertainty being associated with greater radii and faster dynamics -- an effect that was more evident in PMd, the more uncertainty-related of the two areas we examined. Thus, despite their anatomical and functional similarities, the dorsal premotor and primary motor cortices may become primarily involved in different planning-related computations when target information is not clearly specified by the visual cue.

E – Disorders of Motor Control

4-E-32 Connectivity indexes predict the motor improvements in secondary dystonia

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Deep brain stimulation (DBS) is an emerging treatment for movement disorders, including dystonia. The targets commonly used in pediatric patients underwent DBS includes basal ganglia as globus pallidum interna (GPi) and motor thalamus subnuclei as ventral oralis anterior/posterior (VoaVop). Since precise electrode placement affects the efficacy and clinical outcome of DBS, neuroimaging plays a vital role in evaluating the therapeutic effect of surgery and improving the success rate of DBS. This is especially complex in children, whose head size is smaller than adults, and even more so among dystonic children, whose anatomy is often deformed as a result of their disease. These deformations compared to a healthy adult head making that the standard neuroimaging tools to be insufficient to process the images. To solve it, recently we presented a new approach to normalize into a single image; the magnetic resonance (MR) structural, computerized tomography (CT) scans and diffusion tensor imaging (DTI) images. However, this procedure did not provide information about the improvement of dystonic patients under DBS treatment. Therefore, we performed connectivity analysis in fifteen patients with the motor disorders, with the aim of answering if the connectivity analysis based on fiber tracking revels motor improvement in these patients. For that, once the images were normalized to MR anatomy, we performed the connectivity analysis between GPi and VoaVop areas using DSI Studio, those fiber tracking settings were fixed by a threshold of 0.01 for quantitative anisotropy (QA) and 0.10 for fractional anisotropy (FA) and a turning angle at 60 degrees. The QA and FA values of DTI were then correlated with the motor improvement provides from the Burke ‐ Fahn ‐ Marsden Dystonia Rating (BFMDS) scale. The results showed significant relationship for both the QA (t=3.900; $p<0.05$) as the FA (t=2.612; $p<0.05$) related with the motor improvement. Our findings suggest that the connectivity index between the pallidum and motor thalamus nuclei are robustly associated with dystonic symptoms in secondary dystonia and may be a useful biomarker. But also, provide predictive values for the clinical benefit that could be used to improve intraoperative neurophysiological target mapping during electrode implantation prior the DBS surgery.

4-E-33 Ageing affects similarly the sense of force in wrist flexors and ankle plantar flexors

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Introduction The sense of force is a sub-modality of proprioception that represents the ability to correctly perceive and reproduce a given force level. When assessed with a force-reproduction task, the sense of force partly relies on muscle proprioception (1), which is impaired with ageing (2). Only three studies investigated the effect of age on force-reproduction performance and reported divergent results, with a decline in the sense of force in the upper (3,4) but not in the lower limb (5). Therefore, this study aimed at investigating the effect of age on the sense of force with a force-reproduction task performed with the wrist flexors and ankle plantar flexors. Methods Ten young [mean (SD), 25 (2) yr] and 12 old adults [70 (6) yr] matched a target force (5% or 20% of their maximal voluntary contraction, MVC) with visual feedback of their force (TARGET phase), then reproduced the same force without visual feedback (REPRODUCTION phase) after 5s of rest. Participants performed 3 trials for each force level with the wrist flexors and ankle plantar flexors. Before the execution of these trials, participants performed familiarisation contraction with visual feedback. The force reproduction error was expressed as the ratio between the force produced during the REPRODUCTION and the TARGET phases and expressed regardless of the error direction. Results The force-reproduction error was greater in old than young adults for 5% MVC ($p = 0.002$) but not 20% MVC ($p = 0.38$) in wrist flexors [young: 37.9 (13.7) %, old: 68.8 (32.4) %] and ankle plantar flexors [young: 19.4 (10.1) %, old: 42.3 (32.1) %]. Regardless of age, a greater error was produced with the wrist flexors than the ankle plantar flexors at 5% ($p < 0.001$), and a positive association was observed between the amount of error produced with the wrist flexors and the ankle plantar flexors at 5% ($r^2 = 0.43$, $p = 0.001$) but not 20% MVC ($r^2 = 0.10$, $p = 0.15$). Discussion The increase in force reproduction error with ageing may reflect a decline in proprioceptive acuity, resulting from structural alterations (6) or a decline in the processing of the proprioceptive signal (7). However, such an age-related decrease in the force reproduction performance does not differ between the upper and lower limb. Overall, this study indicates that the decline in the sense of force with healthy ageing is limited to low contraction force. 1. Monjo et al. 2018. Exp Brain Res, 236,1997-2008. 2. Henry and Baudry. 2019. J Neurophysiol,122,525-538. 3. De Serres and Fang. 2004. Can J Physiol Pharmacol, 82,693-701. 4. Henry et al. 2022. Exp Brain Res. 5. Franco et al. 2015. Braz J Phys Ther, 19,304-310. 6. Shaffer and Harrison. 2007. Phys Ther, 87, 193-207. 7. Piitulainen et al. 2018. Front Aging Neurosci, 10, 147.

4-E-34 Signatures of motor learning of trunk posture in moderate-to-severe cerebral palsy

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Atypical postural control of the head and trunk is a hallmark of moderate-to-severe cerebral palsy (CP). Motor learning is difficult to predict due to heterogeneity and variable responses across the population. Therefore, we characterized the range of responses to an intervention and evaluated the association between laboratory-based kinematics and clinical tests. Motor learning was assessed in five subjects with CP (ages 8-13 years) who received Targeted Training for Trunk Control (6 months). This intervention simplified the balancing task with individualized external trunk support. The support required few spinal degrees of freedom to be controlled against gravity. The level of support was lowered as subjects gained more trunk postural control. The support devices were sent home and the child practiced balancing in the device 20-30 minutes 5-6 days per week. Laboratory tests were completed every and also included retention tests several months after the intervention. These tests included 3D kinematics of head and trunk in frontal and sagittal plane for 3 minutes of quiet sitting while external support was provided at 4 different levels (L1 = axillae, L2= mid-ribs, L3= waist, L4=pelvis). We measured the standard deviation of head and trunk sway in both the sagittal and frontal planes, alignment of the head and trunk, and path length of the head and trunk. Improvements in kinematics were defined as reduced variability of sway velocity and position, and more time spent upright. The Segmental Assessment of Trunk Control was used as a clinical test. More kinematic improvements were found in subjects with greater clinical improvements; and more kinematic metrics got worse in subjects with less clinical improvement. Improvements in head control were common and more consistent than improvements in trunk control. Head improvements were associated with decreases in velocity (moving slower) and occurred in both sagittal and frontal planes. When improvements in the trunk were found, they were position-based (orienting more upright) and were mostly in the sagittal plane. Finally, kinematic improvements during testing were most common when testing included the same, or fewer, degrees of freedom as those used during the intervention. In conclusion, although improvements in clinical and laboratory kinematics were generally correlated, we found some kinematic measures were more sensitive than others to the intervention. The consistent reduction in head velocity across the intervention suggests head control was a priority, similar to the rostral-caudal development of sitting postural control in typically developing infants. Also, trunk improvements were more common when the testing conditions were similar to (or simpler than) the training (ie, the same or few degrees of freedom). Results suggest that practicing with fewer degrees of freedom is a starting point for better understanding how to probe motor learning in children with moderate-to-severe CP.

4-E-35 Myoelectric interface conditioning in chronic stroke survivors leads to targeted reduction in abnormal co-activation and improved arm function

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Arm impairment after stroke is due not only to weakness and sensory loss, but also to abnormal co-activation between muscles, also called abnormal synergies. Previously, we designed a myoelectric computer interface (MyoCI) to reduce this abnormal co-activation with in-lab training in chronic stroke survivors. The MyoCI mapped EMG from abnormally co-activating muscles to orthogonal components of cursor movements, and training required decoupling these muscles to acquire targets in those mapping directions. Here, we computed muscle synergies using nonnegative matrix factorization and assessed changes from MyoCI training in synergy number, composition, and a new metric of differences between within-synergy weights, called dispersion index (DI). Synergy number and composition did not change consistently. In contrast, DI for the trained muscle pairs, particularly the most abnormally co-activating pair, increased due to training. That is, MyoCI training decreased co-activation specifically between the muscles trained, without affecting other muscles in the synergy. This suggests that the CNS is capable of making highly fractionated changes in motor control, even after a stroke. In addition, we are performing a randomized controlled trial of MyoCI using a novel, wearable version--the Myoelectric Interface for Neurorehabilitation (MINT). MINT is designed for home use to enable high-intensity training that can scale to many users. Here we tested different variants of the "MINT conditioning" paradigm. We included participants who had chronic hemiparesis from a stroke causing severe arm impairment (Fugl-Meyer Assessment of upper extremity of 7-30). Participants were randomized to one of 4 groups, based on how they trained: 2 muscles at a time (2D), 2D + reaching in the direction of the muscle in each trial (Reach), 3 muscles at a time (3D), or one muscle at a time (sham control group). The participants were asked to train 90 min/d, 5 d/wk at home, and 1 d/wk in the lab, for 6 weeks. We identified abnormally co-activating muscles using a reaching task; muscle sets with the highest correlation coefficients that were not normal were chosen for training. A blinded occupational therapist measured arm function using the timed portion of the Wolf Motor Function Test at baseline, end of training and 4-week follow-up. To date, 42 participants have completed the 6-week training. They averaged 85±18 min and ~300 daily repetitions of daily training. At 6 weeks, WMFT showed a trend of greater improvement from baseline in all experimental groups than in sham controls (mean -3.7 vs. -1.9 s, p=0.24, t-test), with a stronger trend in the 3D group (-6.5 s, p=0.13). Improvement was even greater at 4 weeks after the training ended (-12.7 s in 3D group, p=0.02; -8.3 s overall groups vs. -1.7 s for sham, p=0.01). These results suggest that reducing co-activation with MINT improves arm function and is not just overcoming learned non-use.

4-E-36 Cerebellar output to the motor cortex facilitates the control for interaction torques during reaching movements

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During multi-joint movements, the central nervous system (CNS) uses predictive control to compensate for and take advantage of dynamically generated intersegmental coupling torques. The neural substrate for the inverse dynamics model, which facilitates this control, is likely distributed across the cortico-cerebellar loop. These supposition is based on studies of cerebellar patients in which the compensatory mechanism is impaired. We hypothesized that blockage of the cerebello-thalamo-cortical (CTC) pathway leads to incorrect compensation for coupling torques in the cortically generated muscle torque commands during planar reaching. To test this hypothesis, we trained two monkeys (M. fascicularis) to wear an exoskeleton (KINARM) and perform movements in the horizontal plane to eight equidistant center-out reaching targets. The CTC pathway was reversibly blocked by high-frequency stimulation (HFS, 130 Hz) of the superior cerebellar peduncle. Kinematic data was obtained during control and HFS trials. We found systematic clockwise deviation in the hand trajectory during HFS relative to control trials during movement initiation (first 150 ms of movement, i.e., feedforward phase). Using inverse dynamics analysis, we extracted the muscle and interaction torques acting at the shoulder and elbow joints during the task. The interaction to muscle impulse ratio (I-M ratio) was then computed to quantify the impairment in prediction of interaction torques. The movement directions were grouped to assistive (i.e., positive I-M ratio) or counteractive (negative I-M ratio) directions of movements for further analysis. The I-M ratio was found to be lower during HFS for assistive directions and higher during HFS for counteractive directions. Thus, in both types of movement, muscle torques were excessive relative to the interaction torque during HFS. This excessive muscle torques at the elbow and shoulder joints explained the observed directional deviations in the hand trajectory during HFS. Next, we correlated the I-M ratio (response variable) with the peak tangential velocity of the hand (predictor variable). The velocity dependent modulation of the I-M ratio (as measured by the slope of their relationship) was significantly reduced during HFS for both movement types. Finally, we assessed the effect of visual feedback on compensating for the loss of cerebellar signals and computed the I-M ratio 400ms after the movement onset. The absolute difference between the I-M ratio of the control and HFS condition was significantly lower at 400 ms as compared to 200 ms. This demonstrated the corrective effect of visual feedback. Overall, these results show that the CTC pathway is essential for facilitating accurate feedforward control of movement that must consider multi-joint coupling torques. In the absence of CTC signals the motor cortex controls single joints independently, while ignoring their reciprocal interactions leading to impaired joint coordination.

4-E-37 Long-latency feedback responses preserved in Essential Tremor patients

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Essential tremor (ET) is a neurological disorder characterized by involuntary oscillations of the limbs. Previous studies have linked ET with cerebellar disorders, but a specific alteration of cerebellar function has not been identified. Because cerebellum is involved in the modulation of long-latency feedback responses to external perturbations, we hypothesized that the ability of ET patients in this task could be impaired. To test this hypothesis, we investigated patients' behavior in a postural perturbation task based on kinematics and surface muscular activity. Participants had to maintain the robotic handle of a KINARM device inside a visual target. The robot pushed their hand outside of the target (4 directions, 3 load magnitudes: 4, 6.5, 9N, rise time: 5ms), perturbation combinations were randomly interleaved across trials (300 trials total). Participants had to counter the perturbations and steer their hand back to the initial target (in < 2 sec). Each movement was decomposed into movement and stabilization phases, the limit being the time at which the participant crossed the end target.The experiment started with a block of baseline perturbation-free movements (60) during which participants had to reach for a target and come back to the initial target to mimic the perturbation trials. ET Patients' (n=15) and healthy controls' (n=17) behavior was similar during baseline trials, with the only significant differences of a higher average velocity within the target prior to the perturbation ($p<0.001$) and a longer stabilization time ($p=0.01$) for participants with a higher FTM-TRS tremor score. The same difficulties were observed in the presence of perturbations (velocity in the target $p<0.001$, stabilization $p=0.04$) despite similar hand displacement and velocity during the first part of the movement. The path length during the stabilization was higher with higher perturbations for ET patients ($p=0.001$) revealing difficulties for ET patients to stop their hand in the target. To our surprise, we did not observe any significant group differences in surface EMG activity in the short (25-45 ms) and long-latency (45-105 ms) epochs of the stretch responses ($p=0.71$). Thus, external disturbances evoked oscillations and difficulties to stabilize that depended on the load magnitude, which highlights a link between ET and online feedback control, but not in the early epochs of the stretch response. These results suggest that the effect of a potential cerebellar dysfunction in ET arose later, at least 105ms after perturbation, when limb afferent feedback must be combined with the efferent control signals to form a closed-loop estimate of the state of the limb. Future studies should investigate both the afferent and efferent control signals and disentangle

the respective contribution of the different cerebellar regions. This research has clinical implications for physiotherapies targeting sensory versus motor control in order to alleviate the burden of ET.

4-E-38 Binocular coordination of horizontal saccades in mTBI and cerebellar dysfunction

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Mild traumatic brain injury (mTBI) can result in significant problems affecting vision and oculomotor function (Armstrong, 2018; Mani et al., 2018; Stuart et al., 2020), vergence eye movements (Magone et al., 2014; Suhr et al., 2015), saccades (Samadani et al., 2015; Hunfalvay et al., 2019), spatial orientation, movement, and balance (Wallace and Lifshitz, 2016; Hoffer et al., 2010). These issues can result in problems with gaze control, eye-head-coordination, and visual-motor transformations underlying goal-directed movements. This can occur after multiple head trauma events, and in some cases after a single mild TBI event. Also, symptoms can persist years after the original trauma (Danna-Dos-Santos et al., 2018) and can become progressively worse over time. Effects of the natural aging processes probably interact with the pathophysiology resulting from TBI. The general aims of this study are to characterize the coordinated movement of the two eyes during changes in gaze in response to movement of a visual target and to relate the velocity trajectories of the two eyes to vergence dysfunction in mTBI. For this presentation, the horizontal position and velocity of the left eye versus the right eye were analyzed for the data from 20 control participants and 30 participants with mTBI. Saccade targets were presented 5 to 25 degrees left/right of center. Plots of left versus right horizontal eye velocity were quantified with polynomial regressions of eye velocity toward and away from zero velocity. Discriminant analyses of the regression coefficients identified those subjects with abnormal velocity trajectories. Some patterns included the following. For large saccade amplitudes there could be different velocities for the adducting eye versus the abducting eye in mTBI subjects who have convergence insufficiency or convergence excess. Furthermore, there were differences between the acceleration and deceleration phases of the saccades, with the acceleration phase of horizontal saccades being significantly different in mTBI compared to controls, similar to what is present with cerebellar dysfunction. Simulations of the velocity and acceleration profiles suggest deficits in the motor commands for adduction versus abduction movements. These results have identified eye velocity patterns and possible motor command deficits that show promise for characterizing binocular eye movements in mTBI. Further work will evaluate vertical and diagonal saccades and gaze in three dimensions where there are changes in vergence. The results could provide further insight into underlying the pathophysiology affecting the control of gaze in mTBI and suggest possibilities for vision therapy.

F – Adaptation & Plasticity in Motor Control

4-F-39 Transfer of visuomotor adaptation from mouse pointing to first-person shooter games

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The world of computer gaming, where millions of players voluntarily hone their visuomotor skills every day, presents a relatively untapped avenue for investigating fundamental questions about visuomotor learning. Most of these games require mouse movements, either to move a cursor across a static background (henceforth Point movements) or, as in "first-person shooter" games, to pan the player's view of the world so that objects in the periphery are brought into the center of the screen (Look movements). These two game types entail distinct contexts of visuomotor contingency, where the same movement of the hand will result in vastly different visual motion on the screen. Here, we created an experiment analogous to computer gaming and applied visuomotor rotations to examine whether mouse Look and Point contexts require distinct visuomotor memories, or if they share a common visuomotor map. In Experiment 1 (n=30) we examined movement kinematics in an online center-out reach task (8 targets/45° spacing) while participants switched between Point and Look contexts infrequently (every 80 trials) or every other trial. In both Point and Look, the visual location of targets and movement required to reach them were matched. Feedback was only different once movement was initiated. Movements were similar, with only small differences in reaction time and time spent making feedback corrections. Experiment 2 exposed participants (n=68) in either the Point or Look condition to an abrupt 30° visuomotor rotation for 120 target cycles (4 targets/90° spacing). Both showed remarkably similar adaptation curves that approached 90% of asymptote within 60 cycles, with the Look group reaching a hand angle asymptote of 21.6° [95% CI = 20.1-23.0] and Point 22.0° [20.1-23.9]. Both groups also showed similar canonical decay and unlearning in washout. Finally, in Experiment 3 we examined transfer between the two contexts by first adapting participants in the Point condition to asymptote with 120 cycles of a 30° visuomotor rotation, then switching them to the Look condition. A veridical-Look group (n=33) was switched to a condition with no rotation, while a rotated-Look group (n=35) was switched to a condition where the rotation was maintained. Both groups showed behavior consistent with nearly full transfer of adaptation from Point to Look. Asymptotic adaptation for veridical-Look was not different from Exp. 2 (p=.278), and the 2nd cycle of the aftereffect was no different to washout in Exp. 2 where the context did not switch (p=.994). The rotated-Look group showed no difference between their asymptotic hand angle in point and their initial performance in Look (p=.584). These results are remarkable because of the striking visual differences between the Look and Point contexts, which we hypothesized would cue distinct visuomotor memories. Instead, our data are consistent with previous work suggesting that the planned movement vector serves as a primary cue for motor memories.

4-F-40 Visuomotor rotation learning in a real world task using Embodied Virtual Reality

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While motor learning is a complex process involving multiple sensory feedback mechanisms and cognitive processes, it is mostly studied in reductionistic lab-based tasks which cannot address the full complexity of the process. Those low-dimensional and highly-constrained tasks do allow for controlled manipulations and enable isolating different learning mechanisms, as seen in visuomotor rotation and force field tasks. Indeed, it has been shown that depending on whether error-based feedback or reward-based feedback is provided in visuomotor tasks, different learning strategies are employed. To address the complexity of real-life, we developed a program of looking at real-world tasks in motor learning using a game of pool table (Haar, van Assel, & Faisal 2020, Haar & Faisal 2020), but such observational studies lack the ability to manipulate the task to establish causality, which is why we have ported the task into Embodied Virtual Reality (EVR, Haar, Sundar, & Faisal 2021). In the EVR framework, the visual feedback from the real-world task is given virtually and visual perturbations can be applied. In doing so, we are able to benefit from both measuring complex behaviour and the ease of control of feedback, to better establish causality. In this study, we used a simple pool-based game in the EVR setup, where subjects need to hit a cue ball towards a target ball to make it fall into a pocket, and presented a perturbation learning paradigm by applying a 5-degree visuomotor rotation on the trajectory of the cue ball, while supplying full or partial feedback to the user. The error feedback corresponds to the trajectory of the balls, while reward feedback is provided through the pocketing of the target ball. Different feedback (error, reward, or both) is provided during different conditions of the task to manipulate the available learning mechanisms. Performance in the task is assessed by considering the success rate and the directional error of the cue ball as compared to the ideal trajectory that would successfully land the target ball into the pocket. Our preliminary results from the full feedback experiment show that subjects learn to correct for the perturbation in the pool EVR task, showing similar learning curves to those reported in common visuomotor rotation tasks. Furthermore, when providing controlled feedback to have either reward or error, results suggest differences between the respective feedback conditions, due to differing corresponding learning mechanisms. Further analysis of the full feedback conditions suggest differences in the learning behaviour of the different subjects which corresponds with the two feedback groups. Hence, in this controlled manipulation version of the pool paradigm, we replicate one of our main findings from the real-world task, which is that when faced with the complexity of the real-world, different subjects might use different learning mechanisms for the same complex task.

4-F-41 The influence of experience on cerebellar-dependent sensorimotor learning

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There is considerable debate focusing on how experience impacts cerebellum-dependent sensorimotor learning. On one hand, the cerebellum has been viewed as a rigid system that responds in a fixed manner, independent of context. Alternatively, it has been argued that the learning rate is modified in response to recent errors (Herzfeld et al., 2014) or that the system can flexibly switch between context-dependent motor repertories (Heald et al., 2021). Motivated by neurophysiological evidence, we propose a hybrid model in which cerebellar-dependent sensorimotor adaptation is modulated by experience, without assuming a change in learning parameters or context-dependent memory. This model captures three core observations: 1. Movement prediction is coded by a population of Purkinje cells (PC), with each cell tuned to a preferred error direction (Herzfeld et al., 2015). Experiencing an error in one direction will suppress the synaptic efficacy of PCs tuned to that direction. When an opposite error is experienced, the system would exhibit slower learning in response to the second error due to persistent suppression, a form of anterograde interference (Morehead and Smith, 2017). Notably, this occurs even though the response of each PC is invariant. This model would also exhibit attenuation during relearning, arising because participants experience opposite errors in the washout phase following initial acquisition (Avraham et al., 2021). 2. Our model assumes no context-dependent learning and no modulation of the learning rate during training. As such, it predicts that learning should not depend on the specific sequence of experienced errors. To test this, we used perturbed visual feedback that was not contingent on the participant's movement ("clamped feedback"), varying the consistency or variability of the error. At odds with context-dependent models, adaptation was insensitive to both manipulations. Moreover, we did not observe spontaneous recovery or savings in relearning. 3. It has been hypothesized that complex spikes (CS) carry part of the memory in sensorimotor learning, with a higher CS firing rate observed during movement preparation when the preferred error of the PC was experienced in the last trial (Junker et al., 2018). We assume that this CS activation directly suppresses single spike activity during movement preparation, producing a "fast" learning process on top of the slow process induced by the LTD. Consistent with this hypothesis, single-trial adaptation in response to random perturbations shows a forgetting rate of approximately 0.5, precluding significant accumulation of learning across trials. In contrast, a "slow" process allows learning to accumulate across trials in response to a fixed perturbation. Interestingly, both processes exhibit a similar non-linear response to error size, suggesting that they arise from a common source, attributed in our model to the influence of complex spikes on the PCs.

4-F-42 Toddlers' motor learning ability assessed: Adaptation to Coriolis forces in reaching

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Motor learning ability changes with age (Konczak, Jansen-Osmann, & Kalveram, 2003). Quantifying toddlers' motor learning ability has thus far been hard if not impossible due to the lack of age-appropriate tools to measure learning in the lab. To overcome this methodological hurdle, we constructed a room that can rotate in the horizontal plane, hereafter called carousel. Reaches inside the carousel will initially deviate in the direction of transient Coriolis forces generated by the motion of the arm relative to the rotating carousel. Adults quickly learn to compensate for these forces, showing straight reach trajectories after approximately four reaches in a carousel (Lackner & Dizio, 1994). This swift learning in adults makes a carousel a promising tool to study motor learning in young children. The current study investigated motor adaptation in toddlerhood. Fifteen-month-old toddlers were invited to the carousel lab (n = 26, final sample will be 30). Toddlers seated in the center of the carousel were encouraged to reach for objects which were offered one-by-one by the experimenter during and after rotation. Hand movements were tracked at 100 Hz. Rotation direction (clockwise, counterclockwise, or no rotation) was counterbalanced between participants. To test whether reaches were affected by the rotation, the average lateral deviation (ALD) from a straight-line trajectory was calculated per reach. A Bayesian mixed model with fixed factors rotation direction, used hand, and average speed was fitted to the ALD per trial during rotation, and subsequently compared with a model without rotation direction as explanatory factor. Moderate evidence (BF = 8.7) was found in favor of the model including rotation direction, suggesting that rotation perturbed the hand trajectories. To assess adaptation, two alternative models were compared: one with and one without an interaction term for rotation direction and trial number, fitted to only the per rotation data. Moderate evidence for equivalence (BF = 0.10) was found, indicating no clear learning effect. Next, two models were contrasted to evaluate whether per and post rotation reaches were different for the different rotation conditions. Very strong evidence (BF = 291) was found in favor of the model including this interaction term. This might indicate learning, but, a per and post rotation difference might also merely reflect that the hand trajectories were perturbed during rotation and no longer perturbed post rotation. More detailed analyses are needed to verify whether this is a true after-effect. Results of these analyses will be presented at the conference. In sum, we found evidence that toddlers' reaches can successfully be perturbed by the Coriolis force that arises when arm moves while the body rotates. However, whether or not 15-month-olds are able learn to compensate for these perturbations within the timescale of an experiment is yet unclear.

4-F-44 Daily Artificial Gravity is Associated with Reduced Brain Activity during Sensorimotor Adaptation

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The altered vestibular signaling and body unloading that occur in microgravity result in sensory reweighting and adaptation. Aftereffects of these adaptive changes are evident postflight as impairments in sensorimotor behaviors and changes in neural processing of vestibular inputs. Microgravity also induces an upward shift of the brain within the cranial vault; which are well-replicated in head-down tilt bed rest (HDBR), a common spaceflight analog environment. Artificial gravity (AG) is a potential countermeasure to mitigate these effects of microgravity. Thus, we examined the effectiveness of daily centrifugal AG for mitigating brain and/or behavioral changes in response to 60 days of HDBR. The AG group received 30 minutes of AG daily (AG; n=16). The other group received no AG (Ctrl; n=8). All participants performed a visuomotor adaptation while in an MRI scanner. They performed this task 5 times; twice prior to HDBR (13 and 7 days), twice during HDBR (29 & 58 days), and once following HDBR (10 days). The visuomotor rotation task consisted of veridical feedback for 32 trials, then they adapted to a novel 45° clockwise rotation for 128 trials split between an early (64 trials) and late-adaptation (64 trials) portion before re-adapting to veridical feedback for 32 trials. Those who received AG showed similar behavior adaptation effects compared with the controls. Neither group showed a decrease in direction error over subsequent test days, suggesting that HDBR may impede savings of prior adaptation. Initial analyses showed that AG participant's exhibit decreased cerebellar activation for the baseline portion of the task. Due to this, we assessed changes in functional brain activity during adaptation in relation to baseline brain activity, as opposed to in relation to rest. We identified various sensory and supplementary motor regions that had differential BOLD responses during adaptation from pre- to in-HDBR for AG participants but not for controls. Further, we identified a brain-behavior correlation in these regions that differed between groups indicating that those who received AG had, overall, less activation in sensorimotor brain regions at the end of HDBR and less activation in sensorimotor regions was correlated with lower direction errors. This relationship was not evident for controls. Together, these results suggest that while AG may not directly affect behavioral performance, it may reduce the amount of neural resources required for basic motor processes and sensorimotor adaptation. This suggests that AG may be a useful countermeasure to mitigate sensorimotor deficits induced by spaceflight. The mechanisms underlying greater neural efficiency during sensorimotor adaptation for the participants receiving daily AG remain unclear, but may relate to the somatosensory and vestibular stimulation that these participants received daily and the resulting neuroplastic effects. This work is supported by NASA 80NSSC18K0783

4-F-45 Similar oscillatory mechanisms map touch on hands and tools

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Tool use is one of the defining traits of humankind. Tools allow us to explore our environment and expand our sensorimotor abilities. A prominent hypothesis suggests that our brain re-uses body-based neural processing to swiftly adapt to the use of tools. However, little is known about how this is implemented at the neural level. Here we used the ability to accurately localize touch on both tools and body parts as a case study to fill this gap. Previous EEG studies have found that the alpha (7-14 Hz) and beta (15-30 Hz) frequency bands are involved in the spatial processing of touch on the body in distinct reference frames, which are typically isolated by crossing the limbs across the midline. Alpha activity reflects sensorimotor transformations that map touch in external spatial coordinates, whereas beta activity reflects the mapping of touch in skin-based coordinates. In order to determine whether the brain re-uses tactile-localization mechanisms when a tool is touched we investigated if the oscillatory mechanisms used when localizing touch on a tool are similar to the ones used for localizing touch on the body. We aimed at comparing the reference frame-based neural processing--as reflected in alpha- and beta-band activity during body-based and tool-extended tactile localization. To this aim, we used EEG to record oscillatory activity while participants performed a cued tactile localization task where contact was 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, which allowed us to disentangle brain responses related to different coordinate systems as their anatomical and spatial position corresponded in uncrossed, but not in crossed posture. 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 processing of touch in external spatial coordinates. Interestingly, the modulation was identical for mapping touch on the hand or on a tool. Furthermore, source reconstruction of this space-related alpha modulationrevealed a similar bilateral network of parieto-occipital regions involvedin mapping touch on tools and on hands. These regions have previously been implicated in reference frame transformations during tactile localization. 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 are in line with previous work from our team and support the idea that neural processes devoted to body-related information are being re-used for tool-use. Furthermore, alpha-band modulation followed the position of touch into external space. This is thus the first neural evidence that tactile localization on a hand-held tool involves the use of external spatial coordinates.

4-F-46 Interference of motor memories

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Savings refers to the gain in performance upon relearning. In sensorimotor adaptation, savings is tested by presenting the same perturbation over two learning blocks, separated by a washout phase. Saving, manifest as faster relearning, has been attributed to the recall of an explicit strategy (e.g., Morehead et al. 2015). We have recently shown that implicit adaptation does not contribute to savings but is instead attenuated upon relearning (Avraham et al. 2021). Here, we hypothesize that this attenuation is due to the feedback associated with the washout phase. When the perturbation is removed, participants experience an error in the opposite direction, a signal that drives behavior back to baseline. This experience may produce interference during relearning. We used a visuomotor task that isolates implicit adaptation. While reaching to a target, the cursor followed an invariant path with an angular offset from the target. Despite instructions to ignore the cursor, participants show implicit adaptation, with the hand path shifting in a direction away from the target (and cursor). In Exp 1, we replicated the attenuation effect in one group. For a second group, we eliminated all feedback during a long washout phase, resulting in a gradual, often incomplete decay towards baseline. This group did not show any attenuation. Importantly, the absence of attenuation was not due to incomplete washout: The size of the learning decay did not correlate with a measure of attenuation. These results suggest that attenuated relearning is due to interference from the feedback experienced during washout. In Exp 2, we asked if attenuation requires experience with the large and salient opposite errors observed at early stages of washout. We eliminated these large errors by applying a rotation that was contingent on hand position, gradually decreasing the size of the rotation until the feedback became veridical. We then kept it veridical for an extended washout phase. With this design, participants experienced a distribution of small errors that was slightly shifted in the direction opposite from the error experienced during learning. Surprisingly, this group showed robust attenuation, suggesting that the interference effect does not depend on large opposite errors. Lastly, we asked if attenuation requires experience with opposite errors. In Exp 3, we tested learning after a long block of trials with veridical feedback. Interestingly, adaptation to a subsequent perturbation was attenuated. In Exps 4-6, we replicated this effect within-participants: More attenuation was found when reaching to targets that were previously associated with a longer experience with veridical feedback. Thus, veridical feedback can produce proactive interference when experienced in a context of a subsequent perturbation. Overall, the results suggest that the formation and maintenance of motor memories is impacted by interference arising from prior experience in a similar context.

4-F-47 Understanding strategic aiming by measuring it in isolation

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Strategic aiming plays an integral role in visuomotor adaptation. Presented as a group average, aiming appears to evolve smoothly over the course of an experiment. Within individuals, it is more chaotic, as a participant must contend not only with the applied perturbation, but their own motor noise and implicit adaptation. To better understand individual aiming decisions on single trials, we developed an aiming task where execution noise and implicit adaptation could be controlled. Here, online participants rotated a cannon towards a target by pressing 'A' & 'D' on a keyboard and fired it with the 'Spacebar'. In baseline and washout, the cannon fired where it was aimed, but with noise added to direction of the cannonball's flight [sampled from (0,3)°]. Experiment 1 (n=93) included six blocks, each comprising a baseline, rotation, and washout. Participants fired at a single target. The blocks differed by sign or magnitude of the rotation applied to the cannonball's flight path (±15/30/45° or ±45/60/90°). Experiment 2 (n=131) included a single rotation block (±15/30/45/60/90°) between one baseline and washout (8 targets, 45° spacing). In these experiments, participants quickly aimed in the opposite direction of the rotation, reinstating good performance. The time-course of individual aiming indicated participants experiencing an 'aha!' moment rather than a gradual error-minimising process. This behaviour may arise due to the absence of obligatory learning processes which dynamically alter the aiming requirements. In reach adaptation, implicit learning may cause aiming to change more gradually. To mimic this effect, we built a generalizing state-space model (as in McDougle, Bond & Taylor, 2017) that would automatically adapt the cannon to perturbations we applied (based on the difference between the aim and cannonball flight). Thus, if a participant always aimed at the target when perturbed, the cannon would gradually adjust towards the target. In Experiment 3 (n=58) & 4 (n=253), we assessed how this "implicit learning" affected participant re-aiming for one or eight targets, respectively. The latter allowed direct comparison with the explicit aiming measured in the context of reach adaptation by Bond & Taylor (2015). Aiming in these experiments again was consistent with insight learning. Furthermore, aim decreased from an early peak to adjust for the cannon's "implicit" error correction over the perturbation block, and flipped in the opposite direction of the aftereffect caused by the state-space model in washout. This individual and group mean aim showed a remarkable similarity to Bond & Taylor's results. Together, these experiments demonstrate that strategic re-aiming is a cognitive process, altogether different from traditional error-based motor learning, and that our cannon task is a new tool to assess how different implicit learning and execution noise scenarios affect strategic aiming.

4-F-49 Interhemispheric balancing of M1 excitability through BCI-based neurofeedback

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Background. Interhemispheric inhibition (IHI) is a fundamental mechanism to represent the functional cross talks between each hemisphere. Activity in the ipsilateral hemisphere through IHI would affect, for example, functional recovery after stroke. Scalp electroencephalography (EEG)-based neurofeedback as a neural self-regulating technique may have a potential to modulate IHI by balancing the excitability in both hemispheres. To test this hypothesis, we used the recently developed method of spatially bivariate EEG-neurofeedback to systematically enable the participants to modulate their bilateral sensorimotor activities. Approach. Twenty-four right-handed healthy individuals participated in this study. Experimental sessions comprised different conditions as follows: (1) resting state, (2) during right finger motor imagery without visual feedback, (3) high (HIGH), (4) middle (MID), and (5) low (LOW) excitability states of the ipsilateral sensorimotor area (SM1) to the unilateral imagined hand movement. To modulate ipsilateral-dependent sensorimotor excitability reflected by desynchronization of sensorimotor rhythms (SMR-ERD), we developed an EEG-neurofeedback that displays both hemispheric SMR-ERDs, allowing participants to learn to control these two variates at the same time. In each session, IHI from the ipsilateral hemisphere was assessed by the paired-pulse transcranial magnetic stimulation (TMS) paradigm. To confirm the modulation effect of SM1s at EEG level, we compared the ipsilateral and contralateral SMR-ERDs immediately before stimulation onset between five sessions using a one-way repeated measure ANOVA (rmANOVA), respectively. A one-way rmANOVA for five sessions was performed to compare the IHI magnitude from the ipsilateral hemisphere. Additionally, correlation analyses were applied to assess the associations between the ipsilateral or contralateral SMR-ERD and the IHI magnitude, respectively. Main results. A one-way rmANOVA and post-hoc analysis revealed the ipsilateral SMR-ERD in HIGH session was significantly higher than LOW session ($p < 0.001$), while maintaining constant contralateral SMR-ERD. We found that the IHI magnitude in HIGH session was greater than LOW session ($p < 0.001$). Furthermore, a significant within-participant correlation was observed between the ipsilateral SMR-ERD and IHI magnitude in 7 of the 22 participants, but not in the contralateral SMR-ERD. Significance. This approach provides the opportunity to manipulate the inhibitory sensorimotor functions and paves the way for new technologies that allow the user/patient to regulate aspects of their brain function to reach the desired states, e.g., for neurorehabilitation and enhanced motor performance. These results are based on the author's preprint (Hayashi et al., bioRxiv, 2021).

4-F-50 Force synergies with and across the two hands in bimanual skill acquisition

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Bimanual fine-manipulation tasks demand the collaboration of both hands and rely on the coordinated forces applied by fingers from both hands. Despite the abundant degrees of freedom (DoFs) of our hands, humans distribute the roles across hands and apply balanced forces among fingers nearly effortlessly. Multiple fingers often coordinately generate the desired force, namely through force synergies. The concept of force synergy explains well the force profiles in grasping and unimanual manipulation tasks. In this study, we sought to evaluate whether and how force synergies evolve as subjects improve fine bimanual skills. We conducted a longitudinal study by following watch-making apprentices in the first two years of their study. Skills were recorded in multiple sessions, every 6 months. We focused on a typical bimanual fine-manipulation - the assembly of a watch plate. Subject uses one hand to control a pair of tweezers, to pinch and insert the plate into a slot; and the other hand to hold a pegwood to stabilize the watch face by pressing. We analyzed the task performance of 6 right-handed subjects (aged 16-40, 21 /- 8.56), divided in two groups - apprentice and expert, with 3 subjects in each group. Apprentices took part in 3 consecutive recording sessions, 6 months apart, to follow their skill progresses. The three experts took part in a single recording session. In each session, subjects were instructed to perform 8 repetitions of the task as fast and as accurately as possible. A high-resolution camera mounted on the forefront of the subject captured the hands' postures. Soft wearable finger sensors fixed on multiple finger digits of the subject recorded the applied pressure. Comparative analysis of hand postures showed small intra-subject variations of finger placement but no significant differences across experts and apprentices. A temporal analysis of finger forces against performance level reveals that, as subjects gain more experience, they use fewer fingers to apply forces, and with smaller amplitude. This prevents excessive energy consumption, an economy of skilled movements. A principal component analysis was applied to uncover force synergies both within and between hands. We find that as subjects gained more expertise, synergies across the two hands reveal a clear division of task. Task-related activities were concentrated in the dominant hand, while the variance in forces applied by the non-dominant hand largely decreased. For within-hand synergies, novices mainly employ synergies that co-activate multiple finger digits. In contrast, experts tended to use simpler synergies for both hands, using primarily the thumb and index finger. Experts seem to revert to common used synergies, albeit directed to new tool usage. This strategy helps to focus efforts on achieving highly precise control and avoids learning new synergies that require inhibiting existing fingers' bio-mechanical couplings.

4-F-51 Accumulated uncertainty about the task during a task break slows the immediate movement down

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It is usually assumed that short breaks interspersed during a motor task allow one to recover from mental/physical fatigue accumulated during the task and regain focus and preparedness for the immediate following movement attempt. Here, we present a set of observations that may contradict this general intuition. We first analyzed the data from six independent experiments where human participants made straight center-out reaches to a target with/without mechanical perturbations while monitoring their pupil size (Exp1:N=28; Exp2:N=29; Exp3:N=34; Exp4:N=28; Exp5:N=26; Exp6:N=28) (Yokoi & Weiler, bioRxiv, 2021; Yokoi, MLMC, 2021). The experiments included several set-breaks of up to 5 min long. We consistently observed the increased premovement baseline pupil diameter accompanied by longer reaction time (RT; time to initiate reaching after provided go-cue) and movement time (MT; duration from reach initiation to target acquisition) (i.e., slower peak movement speed) at the early trials after the set-breaks compared to the late trials. Thus, despite the larger baseline pupil diameter, which is often interpreted as increased arousal/vigor (e.g., Zekveld et al., Trends in Hearing, 2018), the slower RT and MT indicate the degradation of movement preparedness after set-breaks. As the baseline pupil diameter has also been suggested to reflect subjective beliefs about environmental uncertainty (e.g., Nassar et al., Nature Neuroscience, 2012), the slower RT and MT can be a response to increased subjective uncertainty about the task. We next run another similar experiment (Exp7:N=40) to examine the time-dependent effect of the period where participants are not in the task (e.g., break) by manipulating the length of both inter-trial intervals (ITI: 1, 2, 8, 28, 78, or 238 sec) and inter-set interval (ISI: 60 or 180 sec). We found clear exponential increase in baseline pupil diameter, RT, and MT as a function of ITI length (linear mixed-effects model ANOVA; F(1, 45.9)=27.6, p=3.7e-06; F(1, 71.0)=24.2, p=5.5e-06; F(1, 73.0)=6.5, p=0.01, respectively). On top of this time-dependent effect, there were additional increases in these variables for the set-break, suggesting some discrete contextual effect of set-break. Overall, our data illustrate that the longer one is not in the task (including breaks), the slower one becomes for the upcoming movement. Whether such slowing down of movements is the response to the accumulated uncertainty about the task or the result of degraded movement preparation (e.g., drifting away from the optimal point in the preparatory sub-space) is to be answered in further research.

4-F-52 Effects of viral BDNF, alone or in combination with epidural stimulation, on locomotion and spinal inhibitory RORb interneurons after complete SCI in mouse.

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Spinal cord injury (SCI) disrupts motor control below the level of injury, often resulting in neurological deficits, such as paralysis and/or hyperreflexia, which remain intractable to current rehabilitation strategies. However, spinal networks below the injury which mediate functional hindlimb movements remain intact and serve as therapeutic targets for the recovery of locomotor function in the absence of descending control. Although excitation of silent pathways is often the focus of SCI studies, the restoration of inhibitory gating of sensory information is essential to prevent aberrant signaling and ensure smooth motor control. BDNF-TrkB signaling has known roles in regulating neuronal excitability as well as in the formation of spinal inhibitory circuits. Virally overexpressing brain-derived neurotrophic factor (BDNF) has been associated with significant locomotor improvements in animal models, but also pain and spasticity. Epidural stimulation (ES) delivered below motor threshold reduces hyperalgesia and hyperreflexia but additional excitatory modulation is necessary to maximize locomotor function. Recent intersectional genetic manipulations have linked inhibitory interneurons (INs) expressing the retinoid orphan receptor ß (RORß), and more specifically expression of TrkB receptors on RORß INs, with sensory gating of proprioceptive input during locomotion. Therefore, the goal of our study is to test the hypothesis that exogenous BDNF and ES improve locomotor outcomes in mice with SCI and converge on RORß INs to enhance inhibition and counterbalance concomitant non-specific excitatory effects of BDNF. We use a complete thoracic transection (T8/9) with viral BDNF treatment alone and in combination with daily ES in adult RORßcre;lsl-tdTomato mice to determine chronic rehabilitative effects in vivo and changes in RORß excitability in vitro. We perform weekly measures of locomotor performance and hyperreflexia for 6 weeks post-SCI followed by whole cell patch clamp recordings from RORß INs in spinal slices. Mice receiving BDNF display weight-supported, alternating stepping but also greatly exacerbated hyperreflexia, but the latter is reduced by ES. RORß INs from SCI mice have more depolarized voltage thresholds for action potential generation and higher rheobase, whereas cellular properties in neurons from BDNF-treated mice are more similar to those of uninjured controls. Taken together, our results suggest that BDNF and ES may have synergistic effects to enhance locomotor improvements when combined and identify RORß INs as a potential cellular target by which these strategies exert their beneficial effects for future leveraging.

4-F-53 Difference between explicit and implicit motor learning during force field arm reaching task

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Humans use distinct learning processes when we have to adapt our motions [1]. When motor learning is driven by alterations to the internal model that occur without conscious awareness, we talk about implicit learning [1]. When motor learning is conscious and based on strategic corrections, this is considered as explicit learning [1, 2]. To study the difference between implicit and explicit learning, we used sensory prediction error to encourage implicit learning and reward prediction error to encourage explicit learning [3]. We were interested in how the two prediction errors effect the ability of subjects to adapt to two opposing perturbations. Subjects were performing arm reaching movements and were subjected to a force field perturbation. We hypothesise that the group using explicit learning will be more successful in adapting to the two perturbations compared to the group using implicit learning. Sixteen subjects participated in the study. They sat in front of a screen and moved the end effector of a haptic robot. The screen showed a cursor that represented the location of subject's hand. Subjects' goal was to a hit the target on the screen. They were split into two groups; one was provided with sensory prediction error (represented as the location of the cursor) and the other with reward prediction error (represented as a final position of the movement). Two opposing velocity dependent force fields were used as a perturbation. Subjects were informed about the perturbation direction before each trial. They first learned the opposing perturbations separately and successfully adapted their movements. This was reflected in straight movement trajectories. However, when the two perturbations were presented in a random order, the group that was provided with reward prediction error had straighter trajectories and smaller angles of movements compared to the group that was provided with sensory prediction error. The results suggest that implicit learning alters the internal model in a way that does not allow for agile alterations to the motor commands necessary for successfully dealing with different perturbations. On the other hand, explicit learning uses strategies that can be quickly switched and used for a specific perturbation. Similar results were observed in studies with visuomotor rotations, where they showed that adaptation to opposing perturbations is largely based on explicit learning [2, 4]. These findings highlight the importance of explicit learning in situations where agile adaptations of our movements to the changes in the environment are of outmost importance. [1] Y. R. Miyamoto, S. Wang and M. A. Smith. Nat. Neurosci., 23, 3 (2020). [2] M. Hegele and H. Heuer. Conscious. Cogn., 19, 4 (2010). [3] J. Izawa and R. Shadmehr. PLoS Computat. Biol..7, 3 (2012). [4] R. Schween, J. A. Taylor and M. Hegele. J. Neurophysiol., 120, 6 (2018).

4-F-54 Can the somatosensory system integrate a tactile model for an extra robotic body part?

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Augmentation technology is a rapidly expanding field, and with it there is growing interest in how such devices interface with the body. When using body augmentation devices, the brain gains experience with a variety of different sensory feedback cues. One important input is the tactile information received from where the device is worn on the body, described as intrinsic touch. We asked whether, while learning to control such devices, the brain gathers information from these intrinsic tactile inputs to construct an internal representation of the device. In particular, we wanted to determine whether the brain integrates intrinsic touch inputs with the somatosensory inputs from the biological fingers. To investigate changes in somatosensory functioning following training with a supernumerary robotic finger (the Third Thumb, Dani Clode Design) we utilised a spatiotemporal localisation task. Participants were asked to judge the temporal order of two (consecutive) brief trains of vibrations on their biological finger and the Third Thumb. We first determined how a single session of motor training with the Third Thumb impacts temporal order judgements. For this purpose, participants were trained to collaborate with the Third Thumb using one designated finger. Improvements in localisation ability were seen for the trained finger-pair, but not seen for an untrained finger-pair. This suggests integration of the intrinsic tactile feedback from the Third Thumb and somatosensory inputs from the trained finger had taken place. Next, to thoroughly explore the possibilities of altered sensory representation we examined tactile temporal order judgements in two groups of participants before and after a week of altered finger-synchronisation motor training: either due to extended Third Thumb training, or training to play the piano. To monitor the co-usage of the Third Thumb with the biological fingers, markerless tracking is being used. To further assess changes to inter-finger sensory representation, we use fMRI to study the representational similarity patterns across the biological fingers and the Third Thumb (via intrinsic touch) before and after training. We predict that improvements in localisation ability, as well as increased representational similarity, will reflect participants altered finger co-use. More specifically, we predict there will be improved localisation ability (and representational similarity) in the Third Thumb-training group between the Third Thumb and the biological fingers it collaborates with most frequently, as the brain has gained familiarity with integrating these somatosensory inputs. This work will allow us to demonstrate the brain's ability to integrate an artificial limb into the sensory model of the biological body.

G – Theoretical & Computational Motor Control

4-G-56 Torque-muscular synergies extracted by the mixed-matrix factorization algorithm capture the functional characteristics of motor modules

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In the recent years, a modular architecture has been proposed as a way for the CNS to tackle the complexity of motor control. Such hypothesis has been supported by observations of low-dimensionality in both muscle activation patterns and joint angles underlying a variety of motor tasks and motor behaviors. Although functional movements can be generated through a combination of modules or synergies at both the muscle and the kinematic level, few studies have investigated their relation. Previously, we have explored the modular organization and dimensionality of joint torques and muscle patterns (Russo et al., 2014). As none of the commonly used synergy extraction algorithms can be applied simultaneously to combined non-negative (EMG) and unconstrained (i.e. both positive and negative, torque) data, we had to use two different algorithms, NMF and PCA respectively. To fill this gap, Scano and collaborators (2021) introduced a novel mixed-matrix factorization (MMF) algorithm capable of extracting synergies from such mixed non-negative and unconstrained data. Albeit muscle and kinematic patterns can be accurately described by combined kinematic-muscular synergies, MMF relies on the assumption that it is possible to linearly approximate the relation between muscle activity and kinematics. Such assumption may be more robust when considering the relation between muscle activity and joint torques. To better understand how motor tasks are accomplished by the combination of a few torque-muscular synergies, we applied the MMF algorithm to coupled muscle and torque

signals. We analyzed EMGs data recorded from 19 muscles and kinematic data collected from the arm of 4 participants performing fast reaching movements. We used a dynamic model of the arm with 4 rotational joints (3 at the shoulder and one at the elbow) and 3 translational DoF (shoulder position) to estimate joint torques with an inverse dynamics computation. A few torque-muscular synergies could capture both the biphasic torque profiles and the corresponding muscle contractions, showing biomechanically meaningful relations between muscle activities and torques. Synergies were similar among participants, indicating a reliable and consistent control strategy. One synergy associated elbow flexion torque with the contraction of elbow flexor muscles. A second synergy showed the activation of the triceps and the corresponding elbow extension torque. Shoulder flexion and abduction torques were generated by the third and fourth synergy. In addition, we could capture the tonic muscle activity, well coupled with the gravitational torque also derived from the inverse dynamics computation. This approach allowed to extend the concept of functional synergies (Torres-Oviedo et al., 2006), capturing the relation between EMG and torque, verify the applicability of MMF on real data in a unique factorization and provided novel and meaningful insights on the functional characteristics of motor modules.

4-G-57 A unified mathematical model for locomotor learning across timescales

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Humans learn to adjust their locomotion to new circumstances across many timescales, learning to walk in a manner that improves their performance. We do not yet have a unified model that predicts such locomotor learning. Here, we present a hierarchical multi-timescale modeling framework that explains qualitatively distinct learning phenomena across many locomotor paradigms. We posit a framework in which locomotor learning is accomplished by three interacting hierarchies: (1) a feedback controller that is robust to sudden changes and avoids falling down, despite perturbations. For familiar tasks, there is a default version of this controller, which serves as an inductive bias for subsequent learning, (2) a reinforcement learner that gradually improves the feedback controller via a stochastic gradient descent-like process, estimating the gradient of a performance metric (e.g. energy, symmetry, etc.) with respect to the control parameters via intentional exploratory noise, and (3) a motor memory mechanism that stores the improved controllers as a function of the context in which they were learned. We implement this framework on a biped model, and subject it to a variety of locomotor paradigms: walking on a split-belt treadmill, walking with additional asymmetric masses on the legs, walking with exoskeleton assistance that is feedforward or feedback driven, etc. The model predicts the classic short-timescale transients (over few steps) and long-timescale transients (over many minutes) in symmetry in both split-belt locomotion and with asymmetric foot masses, correctly predicting the step length asymmetry changes over these timescales. The model predicts previously observed entrainment when exposed to time-periodic exoskeletal perturbations. It predicts faster de-learning than learning, and faster re-learning or savings upon exposure to a condition previously exposed to. The model doesn't just learn the specific tasks it is exposed to, but generalizes to neighboring tasks, so that having learned one task results in faster re-learning of neighboring tasks. The model can predict anterograde interference, as well the lack of such interference -- as seen in some locomotor learning, depending upon the function approximation is used in the motor memory. In previous exoskeleton experiments, some subjects learned spontaneously and others only learned after being provided broad experience and training. Our model re-capitulates these phenomena: reinforcement learning is compromised when the gradient is

noisy, say, due to lower exploratory noise than sensorimotor noise. Subsequently, providing broad experience and training allows the motor memory mechanism to store this training, allowing learning when exposed to the condition again, even if the gradient descent is still compromised. Thus we have developed a unified model that predicts both the transients as well as the steady state and captures distinct qualitative phenomena in numerous locomotor learning tasks

4-G-58 Haptic communication improves dyadic collaboration in complex object manipulation tasks

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In collaborative work settings such as manipulating one object between two users, two people have to work together to solve a task, it is unclear to what extent non-verbal, non-social communication cues are used for cooperation. We conducted an experiment to study human-human haptic communication during physical collaborations, and see whether there are differences between two people collaborating or one person performing the task bimanually. We used two haptic devices (Phantom Touch; 3D SYSTEMS) to interface humans with a virtual reality setup involving balancing a ball at given target locations on a board. The task was performed either bimanually by one participant, or dyadically by two participants, with or without haptic feedback. The task requires that the two sides coordinate with each other, in real-time, to balance the ball at the target. We found that with training the completion time and number of velocity peaks of the ball decreased, and that participants gradually became consistent in their braking strategy. Moreover, we found that the presence of haptic information improved the performance (decreased completion time) and led to an increase in overall cooperative movements. While in the dyadic task, there were competitive movements that were not present in the bimanual task, the overall performance (time and smoothness) was similar. One major difference was the delay between coordinating actions which was always smaller, and unaffected by the presence or absence of haptic feedback in the bimanual task. However haptic information significantly decreased the delay in cooperative movements within the dyadic condition. We show that haptic communication plays an important role in the collaboration between humans. It carries valuable information that implicitly allows humans to better understand each other, and decreases the delay between two humans during cooperative movements. Overall, our results show that humans can better coordinate with one another when haptic feedback is available. These results also highlight the likely importance of haptic communication in human-robot physical interaction, both as a tool to infer human intentions and to make the robot behaviour interpretable to humans.

4-G-59 Trajectories and durations of human reaching movements are explained by the minimization of time and energy

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Human reaching movements are thought to be governed by optimality. An objective to minimize movement variance seems to explain smooth hand trajectories (Harris & Wolpert 1998), particularly when accuracy is needed. An alternative objective uses the trade-off between movement expended energy cost and movement reward to explain overall movement duration (Shadmehr et al. 2016). This objective accommodates individual-specific movement vigor and suggests why people should move more quickly to more salient targets (Summerside et al. 2018). However, these two objectives are incompatible with each other: minimum-variance does not explain movement duration, and energy-reward does not explain movement trajectories. We seek a governing principle that explains both movement trajectories and durations at once. We propose a simple mechanistic optimal control objective that combines metabolic energy expenditure, and a subjective cost proportional to movement duration. The energetic cost includes terms for mechanical work and for rapid force production (attributed to calcium pumping in muscle). The duration cost includes an individual-specific coefficient for a valuation of time, that may be thought of as the energy one is willing to spend to save a unit of time. The combined objective predicts smooth hand trajectories similar to minimum-variance (even when accuracy is unimportant), as well as their duration. We tested this objective with normal point-to-point reaching movements. Healthy adults made self-paced reaching movements between targets at a variety of distances, in a task with very low time pressure and accuracy demand. Empirical hand speeds agreed well with model predictions, and an individual's time valuation to be predictive of that person's durations across a variety of distances. The valuation of time (in energy per time, and therefore units of W) is close to the metabolic rate for quiet sitting, sometimes exceeding it by about 2 W. That valuation could be modulated consistently by asking subjects to move more slowly or rapidly than normal. For all conditions, peak movement speed increased approximately linearly over the range of reach displacements (5 to 60 cm). The predicted metabolic cost of movements was also consistent with energy expenditure measured during cyclic reaching. Finally, the metabolic cost per time (in Watts) as a function of movement distance increased approximately linearly, consistent with model predictions. Since the time cost is roughly equal to resting rate, the time spent moving may be valued like an opportunity cost--the time that could have been spent (resting) at destination. Whereas others have proposed that costs and rewards may be modulated by hyperbolic temporal discounting (e.g., Shadmehr et al. 2016), the conditions of our experiment are adequately explained by a summation of linear costs. The proposed objective unifies the planning of movements under a single objective of time and energy.

4-G-60 Body mechanics, optimality, and sensory feedback in the human control of complex objects

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Humans are adept at a wide variety of movement skills including interacting with complex objects. The concepts of optimality and cost functions, contributions of sensory feedback, and effects of body mechanics in the control of actions have been thoroughly scrutinized, but often in isolation and predominantly in the contexts of holding and reaching tasks. The interdependency of these concepts in the control of complex movements has not been fully characterized. This study examined a task with complex dynamic interactions: transporting a 'cup of coffee' without spilling. This object was modeled as a ball rolling inside a circular cup in a virtual environment, and participants had to carry it to a target box via moving a robotic handle that rendered the interaction forces back onto their hand. Additional perturbations, including catch trials, were presented during the movement to probe the controller further. To model the human motor control, we studied optimal feedback control (OFC) that had successfully accounted for many features of movements, predominantly in simple reaching tasks. However, in our dynamically more complex task, OFC was unable to faithfully replicate features of human movement that arose through the perturbations induced by the ball forces and the additional perturbing force pulses. A mechanical impedance element interfaced with the OFC proved necessary.

This linear spring-damper element, as proxy for arm impedance, allowed OFC to replicate key kinematic features in the subjects' movements. Further, if OFC was extended by impedance, the simulated movements were no longer sensitively dependent on the objective function: in contrast to the nominal OFC model, the objectives to minimize effort or movement jerk resulted in similar movements. In addition, only if impedance was included, a feed-forward replay of the optimal control inputs could cope with unexpected perturbations as successfully as the feedback-driven control. These findings suggest that when the information processing of OFC incorporates mechanical properties, the specific objective function and sensory feedback become less critical and complex dynamics can be successfully managed. These results have important implications for motor control studies, especially if the goal is to uncover neural correlates of movements. For this purpose, it is critical to first 'peel back' the contributions of behavior to reveal the structure and objectives of the neural controller.

4-G-61 Simultaneous yet separable population encoding of arm movement direction and kinematics in motor cortex

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Motor cortex has been proposed to control multiple features of movement. However, the encoding of movement features has been commonly studied by analysing one feature at a time. Little is known about if and how multiple features of movement are simultaneously encoded at a population level. Using neural activity from dorsal premotor cortex (PMd) and motor cortex (M1) as monkeys performed a sequential arm movement task, here we report that the direction and kinematics of arm movements are simultaneously but separably encoded in the low-dimensional trajectories of population activity (data from Perich et al., 2018). We found that strongly stereotyped, rotational trajectories of population activity encoded the direction of arm movement, such that trajectories separate from each other according to the angle difference between the movements they evoked. By contrast, trajectories from arm movements in the same direction were temporally scaled to produce different movement kinematics. Consistent with this separability into geometry and speed of population activity, we could well decode the direction and duration of arm movement independently from the same trajectory of population activity. A recurrent neural network (RNN) model of our results replicated this separable encoding of direction and duration, and suggested the two could be independently controlled by respectively rotating the inputs to motor cortex and scaling the effective neuron time constant within motor cortex. Our results propose a mechanism for motor cortex to latently encode multiple arm movement features simultaneously. References Matthew G. Perich, Patrick N. Lawlor, Konrad P. Kording, Lee E. Miller (2018); Extracellular neural recordings from macaque primary and dorsal premotor motor cortex during a sequential reaching task. CRCNS.org. http://dx.doi.org/10.6080/K0FT8J72

4-G-62 Local field potentials reflect cortical population dynamics in a region-specific and frequency-dependent manner

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The activity of populations of cortical neurons is well described by the dynamics of a small number of population-wide covariance patterns, the "latent dynamics". These latent dynamics are largely driven by the same correlated synaptic currents across the circuit that determine the generation of local field potentials (LFP). Yet, little is known about how much is shared between these LFPs and the population latent dynamics arising from the same synaptic currents. We characterised the relationship between simultaneously recorded LFPs and latent dynamics across three sensorimotor areas of primate cortex - the primary motor (M1), dorsal premotor (PMd), and somatosensory (Area 2) cortices- using 96-channel microelectrode arrays. We recorded cortical data as four macaque monkeys performed a centre-out reaching task. We applied Principal Component Analysis to the single unit activity to identify its low-dimensional latent dynamics. We also recorded the LFP signal on each electrode, filtered it into eight bands: 0.5-4 Hz, 4-8 Hz, 8-12 Hz, 12-25 Hz, 25-50Hz, 50-100 Hz, 100-200 Hz, 200-400 Hz, and computed the associated power changes over time. We also included the "Local Motor Potential", the moving average of the broadband LFP. We examined to what extent each LFP band related to the latent dynamics using Canonical Correlation Analysis. We found that the relationship between latent dynamics and LFPs is largely frequency-dependent, and varies across areas. Yet, for any given area, the frequency-dependent LFP-latent dynamics correlations were well preserved across both animals and sessions. They also remained stable across different aspects of behaviour: for both M1 and PMd, the LFP-latent dynamics correlations during movement planning and execution were similar. Interestingly, while for M1 the strength of the association between an LFP band and the latent dynamics linearly predicted the LFP band's ability to decode behaviour, this was not the case for either PMd or Area 2. Finally, we verified that these results could not have been predicted from the relationship between LFPs and the firing rates of single neurons recorded in the same electrode. For every recording channel, we computed the Pearson's correlation between its single unit activity and each of the nine LFP bands. Virtually none of those correlations was significantly larger than the corresponding correlations for randomly selected electrodes, except for the high-gamma band, which still remained quite low (mean $r < 0.3$) and may have simply reflected unfiltered spiking content. In summary, LFPs are fundamentally related to the shared latent dynamics that dominate the activity of a neural population, rather than to the activity of the neurons themselves. These results help to bridge studies of the sensorimotor system that use LFPs and neural population activity, showing that LFP relates to the latent dynamics in a stable, region-specific, and frequency-dependent manner.

4-G-63 Deep reinforcement learning mimics neural strategies for limb movements

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How does the primary motor cortex (M1) achieve generalizable and purposeful movements from the complex, nonlinear musculoskeletal system? Recent research in this field relies on using goal-driven artificial neural networks trained to perform a task designed to be analogous to that performed by M1. The resulting activity and dynamics of these trained goal-driven networks are then analyzed to uncover neural strategies resulting in the movement. However, these models do not consider the role played by the sensory feedback and complex biophysical underpinnings of the musculoskeletal models in shaping the M1 activity. Due to the absence of sensory feedback and lack of biophysical realism, the trained models and resulting neural strategies are not generalizable to movements unobserved during training. In this research, we train goal-driven networks with modeled sensory feedback to drive anatomically accurate musculoskeletal models to produce empirically observed movements. First, we developed an anatomically accurate 39-muscle musculoskeletal arm model of a macaque monkey in MuJoCo physics simulation engine. Next, we used Deep Reinforcement Learning (DRL) to train a recurrent neural network (RNN) controller to deliver muscle excitations to achieve experimentally observed kinematics during a cycling task performed at different speeds [1]. The state-feedback to the controller consists of muscle activations, joint positions and velocities, and hand and target positions and velocities. The trained controller achieved a high kinematic accuracy (mean R^2=0.985) when trained to track a target using cycling movements at multiple distinct speeds with experimentally recorded kinematics. The DRL-trained RNN controller also generalized well to experimentally observed speed conditions not used during training, with a mean R^2 of 0.97. Indeed, traditional strategies to train goal-driven networks failed to generalize to unseen speed conditions. This points to the existence of a well-tuned feedback control policy in the DRL trained controller. Finally, we compared the activity of the trained RNN controller with the experimentally recorded M1 activity during different speed conditions. We showed that the controller and M1 population activities are highly correlated, with mean R^2 of 0.88 on unseen speeds. Moreover, we showed that the single neurons of M1 can be accurately decoded from the controller's activity using a linear decoder, with variance-weighted mean R^2 of 0.95 on unseen speeds. The resulting RNN model outperformed the existing representational and goal-driven models of M1 in single neuron decoding accuracy. This provides a unified modeling strategy for investigating the role of M1 in driving the highly nonlinear musculoskeletal system, and exploring the role of sensory feedback in shaping the M1 neural activity in producing movements in a generalizable manner. Refs:[1]Saxena, S.,Russo, A.,Cunningham, J.P.,Churchland, M.,eLife(Accepted),2022

4-G-64 Motor control can guide learning through feedback-driven plasticity

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A range of evidence suggests that primary motor cortex acts as a feedback controller, enabling the correction of ongoing movements based on afferent sensory feedback. In the laboratory, movement correction can be readily seen using a visuomotor rotation (VR) perturbation that creates a perceived error due to the mismatch of expected and observed reach trajectory. Humans and monkeys can alter their movements to compensate for this perturbation and reach the correct location. On the very first trial following perturbation onset, this is achieved through online corrections of the perceived errors using rapid sensory feedback. However, over time, the subjects progressively learn from their errors, allowing the motor system to adapt the reaches so they predictively counteract the perturbation and begin in the correct direction. Both feedback-based online movement correction and longer-term motor adaptation are crucial for flexible and accurate behavior, and are often assumed to rely on distinct neural substrates. We propose that these seemingly disparate processes can be unified using the same neural substrate with a single learning rule. Here, we investigate the hypothesis that the neural circuitry for feedback control may be exploited to drive plasticity mediating motor adaptation. We address this problem using a recurrent neural network (RNN) model trained not to produce a certain predetermined output, but to control it using a feedback signal based on the error between intended and observed output. An initial training phase that required the model to produce a broad range of outputs enabled it to learn to correct for perturbations online. After constructing this RNN that implemented feedback control, we asked whether the feedback signal could enable learning by guiding plasticity in the network's recurrent connections. We devised a biologically plausible plasticity rule causing recurrent weight changes proportional to the error feedback signal received by the postsynaptic neurons. This rule allowed the network to adapt to persistent VR perturbations by changing its feedforward control -- reaiming its outputs so they began in the correct direction. Comparing our model's adaptation with that of humans revealed several striking similarities: 1) successful generalization to non-learned but similar behaviors (Krakauer et al 2000), 2) existence of two learning timescales (McDougle et al 2015), and 3) sensitivity to perturbation variability (Fernandes et al 2012). Moreover. adaptation led to temporarily dissociated changes in the network activity that we could recover in neural population recordings from monkey primary motor cortex (data from Perich et al 2018), suggesting that a similar phenomenon may be at play. This work not only introduces the possibility of a combined implementation of feedback-based motor control and learning in recurrent circuits, but also unifies several aspects of human behavioural adaptation in a single neural process.

4-G-65 Finger individuation introduces extra motor plan noises in fine finger control that affects trajectory smoothness

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Trajectory smoothness is a hallmark of motor fluency. A prevailing model suggests that smoothness is a by-product of achieving endpoint accuracy given signal-dependent noise (Harries and Wolpert, 1998). Alternatively, Optimal Control Theory (Todorov and Jordan, 1998, 2002; Al Borno et al., 2020) suggests that variability is an inherent part of the central motor plan, and noise in planning decreases smoothness. It thus remains to be elucidated where the sources of motor variability are and how our system produce smoothed movement. Here we investigated this question using a finger-individuation and precision-grip tasks with a sensitive device to measure subtle isometric forces at five fingertips in three-dimension. Healthy younger controls (N=29) and 13 chronic stroke patients participated in the Individuation task, and a subset of younger controls in the Grip tasks (Grip 1: N=22, Grip 2&3: N=17). In the individuation task, participants moved a dot in a 3D virtual space by exerting forces at one of the fingertips to hit a target at 4 force levels (20, 40, 60, and 80% of max force<=10N), while keeping other fingers immobile. In the simple Grip task (Grip 1), participants attempted to grasp a small spherical object in the virtual space with their thumb and index/middle finger (max force < 3N). In Grip 2 task, the two fingers had to enter tunnels before the grip; in Grip 3 task, they first gripped a small dial and then turned it +/-20 or +/-45 degrees to match the 12 o'clock. Linear mixed effect models were used to examine the relationships between trajectory smoothness and endpoint variance, active finger force, Individuation Index, movement time and velocity. In the Individuation task, endpoint variance (p=6.74e-14) and movement duration variance (p=0.009), but not force (p=0.29), were significant predictors for smoothness in healthy hand. In contrast, for paretic hand, both endpoint variance (p=0.006) and force (p=0.009) were significant predictors. When broken to four force levels, consistent with Fitts' Law, peak velocity and variances in endpoint and movement time scaled linearly with increased force levels. However, in consistent with the Minimum Variance Model (Harries and Wolpert, 1998) model, smoothness presented a non-linear relationship with force levels, peaking in the medium force ranges (40-60%) for both healthy and paretic hands. Moreover, in the Grip tasks, trajectory smoothness was modulated by peak velocity (p<2e-16) and individuation (p=0.009), but not endpoint variance (p=0.81), and trajectories became jerkier when the dialing angle to be adjusted was smaller (p = 0.00005). Intriguingly, subjects with higher individuation ability presented more jerkiness in their movement. Our findings suggest that instead of a by-product of endpoint accuracy, trajectory smoothness is embedded in motor planning and that extra levels of task difficulty in fine object manipulation requiring better finger individuation introduces more planning noise.

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