ABSTRACT BOOK

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NCM 2021 Poster Abstracts

Poster Session 1

A – Control of Eye & Head Movement

1-A-1 Gain adaptation and variability of vestibular corticothalamic neurons shape our perception of natural self motion stimuli

Presenting Author: Jerome Carriot

Authors: Jerome Carriot[1], Isabelle Mackrous[1], Graham McAllister[1], Hamed Hooshangnejad[2], Kathleen Cullen[2], Chacron Maurice[1]

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Natural stimuli display complex spatiotemporal characteristics that vary over many orders of magnitude. In order to encode such stimuli efficiently, sensory systems must continuously adapt by changing their response properties. However, the computational role of such adaptation remains poorly understood in the context in which adaptation can increase coding ambiguity. Here we first investigated how vestibular thalamocortical neurons and their afferent input neurons within the vestibular nuclei respond to both simple artificial and more complex natural self-motion stimuli in rhesus macaques. We found that both groups displayed comparable response properties to artificial stimuli which led to ambiguity. However, while such ambiguity persisted for artificial stimuli for vestibular nuclei neurons, vestibular thalamocortical neurons instead faithfully and unambiguously followed the detailed timecourse of natural self-motion stimuli. A mathematical model including known filtering properties as well as gain adaptation successfully reproduced our experimental data, thereby showing that gain adaptation plays an essential role towards removing coding ambiguity. We demonstrate that vestibular thalamocortical neurons are best optimized to encode natural self-motion stimuli as opposed to vestibular nuclei neurons. Our results challenge the common wisdom that adaptation leads to ambiguity by showing that, instead, such adaptation actually leads to faithful and unambiguous encoding of natural stimuli. Second, we investigated the role of these vestibular thalamocortical neurons in the perception of self-motion. Specifically, we tested whether their responses can account for a violation of Weber's law, namely that discrimination performance is enhanced at higher stimulus amplitudes. To do so, we quantified how neuronal gain and variability varied as a function of stimulus amplitude and computed neural discrimination thresholds. While neural gain strongly decreased as a function of stimulus amplitude, neural variability instead initially increased at low values but saturated at high values. As a result, neural thresholds were not proportional to stimulus amplitude as they also saturated at higher values. Further, while single neuron discrimination thresholds were two-fold higher than those of perception, values computed from neural populations agreed with perception for all amplitudes. Thus, overall, the dependency of neural population discrimination thresholds on stimulus amplitude can explain why vestibular perceptual performance is better than that predicted from Weber's law. Our results uncover a novel role for neural variability in shaping how sensory pathways generate perception. Taken together, we further provide novel insights as to how variability and gain control contribute to adaptive encoding of natural stimuli with continually varying statistics.

1-A-2 The effect of spatial frequency on visual-vestibular conflict detection and self-reported simulator sickness

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Perception of a stable visual environment depends on mechanisms that monitor the agreement between visual and non-visual cues to head movement. Visual cues include a combination of optic flow and oculomotor signals needed to bring retinal motion into head coordinates. Non-visual cues include vestibular signals as well as efference copies of motor commands to rotate the head on the body. Conflict between these signals is associated with debilitating conditions such as motion or simulator sickness. Here we investigate how characteristics of the visual scene impact observers' ability to detect visual-vestibular conflict and the corresponding levels of subjective simulator sickness. Experiments were conducted using a head-mounted display (HTC Vive Pro Eye) with fixation behavior monitored by its embedded eye tracker. On each trial, participants made active yaw head movements of ~30 deg over 1.5 sec while fixating a scene- or head-fixed point. During the head movement, the gain on the visual scene motion was manipulated. Participants were asked to report whether the gain was too low or too high, that is, if the environment appeared to be moving with or against head movement, respectively. Additionally, participants were asked to report their relative level of sickness approximately every 3 minutes during the experiment based on a 1-10 Discomfort Score scale. Finally, participants also filled out a Simulator Sickness Questionnaire immediately after each of the condition blocks. Fitting a psychometric function to the resulting data yields the gain perceived as stationary (PSE) and the range of gains that are compatible with perception of a stationary visual environment (JND), referred to by Wallach as the Range of Immobility. Participants were tested using a virtually rendered optokinetic drum with either a low or high-frequency stripe pattern. Our results revealed higher visual gains were seen as stationary (lower PSEs) in the low-frequency condition suggesting slower perceived speed of scene motion. This is consistent with the known effect of spatial frequency on perceived speed of retinal image motion. Sensitivity to conflict was also best (lower JND) in the low-frequency condition consistent with the idea of signal-dependent noise on estimated scene motion. These results quantify the relationship between spatial frequency, detection of visual-vestibular conflict, and self-reported simulator sickness. Acknowledgments: Research was supported by NIGMS of NIH under grant number P20 GM103650 and by NSF under grant number IIS-1911041.

1-A-3 Second-order attribute of head motion is encoded at single-neuron level in the vestibular nuclei

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The vestibular system provides essential information about head movements that is vital for maintaining posture, computing spatial orientation, and perceiving self-motion. Whereas previous studies have instead focused on first-order features of vestibular stimuli, few studies to date have focused here on second-order attribute that consist of changes in vestibular stimuli amplitude or envelope. Here we investigated if and how neurons in the vestibular nuclei (VN) encode the envelope attribute of the head motion stimulus. Because envelopes are critical for perception, we recorded the activity of the vestibular-only (VO) neurons, known to project to the ventral posterolateral (VPL) nucleus of the Thalamus and thereby, mediating self-motion perception. Specifically, we studied neural responses to stimuli consisting of a noisy waveform whose envelope varied sinusoidally at lower frequency.

Importantly, stimulus amplitude was kept low such as not to elicit static nonlinearities from afferents (e.g., rectification, saturation). Our results show that the envelope attribute of the stimulus is encoded at single-neuron level in the vestibular nuclei by the neurons that show greater coefficient of variation (CV). The response of the neurons with greater CV shows larger coherence with the envelope than the neuron with lower CV. On average, we found that the gain of the neuron's response to the envelope remained constant across frequencies (0.05Hz = 1.1, 0.1Hz = 0.56, 0.2Hz = 0.7, 0.5Hz = 0.40 spk/deg/s; p = 0.11). Moreover, the neuron's response shows a slight phase lead that increases as the frequency of the envelope increases (0.05Hz = 2.7o, 0.1Hz = 13.5, 0.2Hz =11.0, 0.5Hz = 32 deg). We hypothesize that responses to envelopes are due to a previously described nonlinearity in VO neurons. Overall, our results will have important implication in our understanding of how early processing of vestibular signal can encode second-order attributes of head motion that will further be used to ensure stable perception of the world and accurate motor control.

B – Fundamentals of Motor Control

1-B-4 Conscious detection of "freedom from immediacy" is limited

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Since the famous Libet experiment, the question to what extent a movement is voluntary has been tied to the question as to how well can we introspect our own decision-making for movement consciously and report on it. Given that "freedom from immediacy" is a defining factor of volition, previous research has typically avoided tight experimental control of that decision. This, however, makes it difficult to know what exactly participants are reporting, e.g., when they report an "urge" to move in the Libet experiment. In our study, we used subliminal motor priming to control to what extent a decision to move, or to withhold movement, was objectively "free from immediacy". In a series of behavioural experiments, healthy human participants were repeatedly asked to make a choice between "go" and "no go", i.e., to either move their right index finger or not. We biased that decision using subliminal primes, informing participants that their own choice would sometimes be biased by primes, while ensuring that prime perception was indeed subliminal. Following each "free" decision to move, or to withhold movement, participants were asked to report, whether that decision felt biased ("immediate" to a prime), or not ("free", i.e., unprimed). Specifically, participants reported whether their own choice was "not influenced" by a prime, or whether they "gave in" to, or "resisted", a prime-induced bias. Preliminary results of this ongoing study confirm that subliminal primes systematically bias participants' "free" decision-making, as well as their eventual choices. However, this bias seems imperceptible to humans. Instead, there was a strong effect of eventual choice, i.e., participants reported consistently being less influenced when they decided to move, compared to when they decided not to move, irrespective of prime-induced biases. Humans seem to have limited, if any, conscious access to their own decision-making pro vs. contra movement, at least when asked retrospectively, and when degrees of freedom for that decision are relatively restricted. We are currently extending this study using different modes of subliminal priming.

1-B-5 The effect of reward on cortical representations of action planning

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People are capable of rapid improvements in skill performance when they are presented with large prospective incentive cues. This capacity suggests that people update their expectations of future reward prospectively, leading to more attention and effort being invested in the task, and ultimately increasing the probability of success. Motor skill learning can be studied in the context of motor sequencing tasks such as the serial reaction time task (SRTT) or the Discrete Sequence Production (DSP) task. In these tasks, participants train to quickly and accurately perform specific sequences of finger movements. Studies show that discrete motor sequences can be decoded from patterns of brain activity in in the frontal cortex using multivariate techniques such as pattern classification and representational similarity analysis. A recent study using the DSP task showed that the performance of explicitly trained (cued) sequences was enhanced more by reward than the performance of implicitly trained (uncued) sequences. Since advanced planning was possible only for the cued sequences, this result suggests that reward enhances performance through cognitive control processes. Here we examine the specific hypothesis that reward enhances representations of action used in motor planning. To test this hypothesis, we administered a discrete sequence production (DSP) task during functional magnetic resonance imaging (fMRI) to 30 healthy human participants. Critically, participants performed trained motor sequences with opportunities for reward ($5, $10, or $30. We found that behavioral performance was enhanced for $30 trials compared to $5 trials. Our fMRI analyses revealed a widespread network of brain areas whose activity scaled linearly with reward magnitude. From this reward-responsive network, we decoded information about upcoming action and performance from patterns of activity preceding movement. This distributed representation included clusters in movement planning areas such as LPFC, pre-supplementary motor area (pre-SMA) and supplementary motor area (SMA). We then examined whether action decoding in specific ROIs was influenced by reward magnitude. We focused on regions that have been previously implicated in studies of skilled action, including LPFC, pre-SMA, SMA, dorsal premotor cortex (PMd), M1, and SPL). We found that action decoding in pre-SMA was enhanced for trials with large reward cues. Furthermore, decoding in SMA was associated with improvements in behavioral performance. Our results suggest that reward may improve performance by enhancing action coding prior to movement.

1-B-6 The influence of reward prediction error on reach vigor

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Dopamine cells increase their activity in response to a reward prediction error (RPE). Increased dopaminergic activity has also been linked to greater ensuing movement vigor, indicating that RPE is modulating movement vigor via its influence on reward related dopamine firing. Indeed, saccade reaction times are faster in the instant immediately following a positive RPE, compared to a negative RPE. Here we investigate the vigor of reaching movements and ask whether vigor is modulated not only by the sign of the RPE (+RPE vs. -RPE), but also by its magnitude (lo vs. hi). Subjects (n=24) made 10 cm out-and-back reaching movements to one of four cued targets arranged equidistantly on the perimeter of a visible circle. The experiment consisted of four blocks of 180 trials; in every block each target was cued 45 times in pseudorandom order. Subjects were informed that in each block, every target was associated with a different probability of being rewarded (100%, 66%, 33% and 0%), and that probabilities would shift between targets with each new block. The reward consisted of a target flash and pleasing tone after reach completion. The targets with probabilistic reward allowed us to broadly categorize reaches in terms of reward prediction error (RPE). Rewarded reaches to the 66% and 33% targets led to a positive RPE, whereas unrewarded reaches led to a negative RPE. Further, rewarded reaches to the 33% target led to a greater positive RPE than rewarded reaches to the 66% target, and vice versa for the unrewarded reaches. We asked whether reach vigor after an RPE event, was influenced by the sign and magnitude of the RPE. First, we looked at the movement immediately after the RPE event: the return movement back to the home circle. While subjects? return movements were consistently slower than their outward movement to the target ($p = 1.42e-10$), the extent of this slowing scaled with the sign and magnitude of RPE on that trial. Movements slowed the least after the largest +RPE and slowed the most after the largest -RPE ($p < 2e-16$). Next, we investigated whether the effect of RPE on vigor carried over into the next trial. Remarkably, peak velocity on the following trial, compared to the previous trial, increased with increasing RPE ($p = 1.46e-7$). Additionally, we observed an effect of the expected value of the reward, i.e. the probability of the reward for each target. Focusing solely on the probabilistic targets, average peak velocity increased with increasing expected value of the reward ($p = 6.76e-5$). Our findings demonstrate that the vigor of movement is modulated by reward prediction error. This effect is not fleeting, but rather persists into the following movements. Therefore, vigor reflects not only the immediate expectation of reward, but our recent success in predicting that reward, providing evidence for an intriguing link between the predictability of the outcome of our actions and the vigor of the movements that follow.

1-B-7 Neural population dynamics in premotor, motor and somatosensory cortices during locomotion in primates

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The sensorimotor cortex plays a crucial role to execute a rich repertoire of motor behaviors. While single unit activity patterns vary across tasks, neural manifold can capture preserved features within task-independent subspaces in primary motor cortex (M1). We investigated whether preservation of such structure and dynamics were also present in dorsal premotor (PMd, F2) and primary somatosensory (S1, area 1 and 2) cortical areas. We recorded from populations of neurons as monkeys performed five different locomotor tasks. S1 displayed robust neural activation patterns across tasks. Neural population activity for different tasks resided within similar subspaces of the neural manifold, and most neural variance was associated with locomotion-dependent parameters. In contrast, neural activation patterns in PMd differed across tasks, resided within distinct task-dependent subspaces, and only 30% of neural variance was associated with locomotion-dependent parameters. Neural population activity in M1 also resided within task-dependent subspaces. However, like in S1, most of the neural variance was captured by locomotion-dependent parameters. Interestingly, few locomotion-dependent components encode the majority of information relevant for decoder generalization in the three cortices suggesting that the locomotion subspace carries cortical contributions towards behavior that remain stable across tasks.

1-B-8 Artificial partner to investigate the development of optimal forms of collaboration in joint action

Presenting Author: Cecilia De Vicariis

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Joint action is pervasive in our daily life as we coordinate our actions with peers all the time. Most studies address interactions where players share the same goal, but in real-life situations the goals are often not the same and, to establish a collaboration, we need to understand (and to account for) our opponent's actions and intentions. Personal traits, emotions, presence of short- and long-term goals also contribute to shaping the interaction, which makes the study of joint behavior extremely challenging. Very much like virtual ion channels in dynamic clamp1 , simulated human-like partners can be used to study joint action in scenarios where interaction modalities and personal traits can be manipulated experimentally. Early examples of this approach - referred as virtual partner interaction or human dynamic clamp2 - have been applied to joint rhythmic actions, but did not address the underlying perceptual and control mechanisms. Here we go one step further, by describing a biomimetic artificial partner (AP) architecture, based on a previously proposed computational model of joint action3, with the capability to develop collaborative strategies with a human partner. We modelled interaction as a non-cooperative differential game and optimal collaboration as Nash equilibrium, which is achieved gradually through an iterative process (fictive play). The AP involves a synthetic body, sensory system, a state observer and an optimal feedback controller. The state observer also estimates the partner's ongoing action - as an additional state variable. An adaptive representation layer maintains a model of dyad dynamics (dynamics model), partner actions (partner model) and the task requirements (as a quadratic cost functional). We focused on a scenario where the players, artificial and human, performed partly incompatible reaching movements between the same start point and target by crossing different via-point while mechanically coupled through a virtual spring. We found similar behaviors to that observed in the human-human interaction. In particular, they converged to a collaboration gradually reducing the interaction force and exhibiting trajectories which crossed both via-points. To do this, the AP developed a model of the HP's motor command, which was incorporated into its motor plan. This approach may provide insights for the development of novel neuro-rehabilitative solutions and more efficient and natural human-machine interface. 1. Prinz, A. A., Abbott, L. F. & Marder, E. The dynamic clamp comes of age. Trends Neurosci. 27, 218-224 (2004). 2. Kelso, J. A. S., de Guzman, G. C., Reveley, C. & Tognoli, E. Virtual partner interaction (VPI): Exploring novel behaviors via coordination dynamics. PLoS One 4, 1-11 (2009). 3. Chackochan, V. T. & Sanguineti, V. Incomplete information about the partner affects the development of collaborative strategies in joint action. PLoS Comput. Biol. 15, e1006385 (2019).

1-B-9 Investigating the role of the posterior parietal cortex in hand choice: Insights from fMRI and cTBS

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Hand selection is a prerequisite for the execution of any manual action. Current conceptualisations of how decision-making for the purpose of action unfolds in the brain have not reached a consensus. An emergent class of decision-making models suggests that the same brain mechanisms responsible for the parameterisation of actions mediate selection. Here, we investigate this issue and test a new model of hand choice: The Posterior Parietal Interhemispheric Competition (PPIC) model. The model posits that bilateral posterior intraparietal and superior parietal cortex (pIP-SPC) represents potential actions with both hands that compete for selection via a process of excitation and inhibition within and across hemispheres. A hand action is executed once its associated motor plan reaches an excitability threshold. Functional MRI data from our lab provide support for the PPIC model of hand selection. Participants performed a reaching task in the scanner, and conditions involving free hand-choice were compared to when hand-use is instructed. Consistent with the PPIC model, bilateral pIP-SPC was preferentially modulated in the free-choice condition, and for actions performed with the contralateral hand. Critically, free-choice and instructed conditions were matched for motoric and attentional features. Further, behavioural - time to movement onset - and fMRI data were consistent with the hypothesis that hand choice is resolved via a competitive process. In a second study, these pIP-SPC areas were targeted using continuous theta-burst stimulation (cTBS), a high-frequency repetitive form of TMS thought to reduce cortical excitability. Across three separate sessions, participants' hand choice was quantified using highly-sensitive psychophysical methods after cTBS was applied to Left-pIP-SPC, Right-pIP-SPC, and Sham stimulation. According to our interhemispheric competition model, reducing the excitability of unilateral pIP-SPC is expected to increase the likelihood of ipsilateral hand choice. However, cTBS to Left and Right-pIP-SPC was found to have no reliable influence on hand choice compared to Sham stimulation. The hand ipsilateral to targets was predominately selected, independent of stimulation condition. When hand choice is compared to a no-TMS control condition, the data show a reduction in right hand selection following cTBS to Right-pIP-SPC. This result is inconsistent with the predictions of the PPIC model, which postulates a decrease in contralateral hand choice (i.e. left hand selection, in this instance) following a reduction in the cortical excitability of unilateral pIP-SPC. Together, while our fMRI data reveal the involvement of bilateral pIP-SPC in hand choice, our cTBS results call in to question whether this involvement is necessary.

1-B-10 Using nonlinear dynamical analysis to show early motor learning differences between elite and non-elite athletes

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Elite athletes are recognized for their ability to learn new motor tasks with greater speed, accuracy, and agility relative to non-elite athletes. It has also been shown that motor learning ability can be predictive of future athletic success. Our aim is to characterize differences in the dynamics of early motor learning in elite vs. non-elite athletes performing a novel skilled task in order to improve the techniques for elite talent assessment. Nonlinear analyses have proven to be a powerful tool to examine neuromechanical systems1, allowing the extraction of dynamical information such as approximate entropy (ApEn) to characterize continuous datasets. Hypothesis: elite athletes will show higher ApEn values, indicating a more stochastic system, compared to the non-elite athletes. This would imply that their neuromotor system possessed greater adaptability to novel, complex skill. Motor learning by 12 elite (NHL prospects) and 12 non-elite male athletes was assessed using a Phantom 3.0 haptic 6D robotic arm, running a custom software program. Participants grasped the robot handle to move a ball in a 3-D virtual force environment through a slalom course with six pylons, using full 3-D arm motion. The pylons would jump slightly as the ball drew close, forcing the player to react quickly to avoid hitting the pylon or the surrounding wall, which would add a time penalty. The haptic robot provided force feedback when a pylon or wall was hit. Participants were instructed to perform 10 trials as quickly and smoothly as possible from a start to an end target. Our within (early, middle, late trials) and between group nonlinear analyses focussed on the evolution of jerk values to assess early motor learning. Contrary to our hypothesis, we observed significantly lower ApEn values for the elite versus non-elite athletes ($t_{22} = 7.97, p < 0.01, \phi: 3.25$). In addition, we found no significant differences in ApEn values from the beginning to the end of the experiment amongst the elite group ($F_{2,22} = 0.51$, $p=0.895$). However, within the non-elite group a significant increase in ApEn values was observed from initial trial to late trials ($F_{2,22} = 4.46$, $p<0.001$). Previous work has suggested lower ApEn values reflect a constrained system using fewer degrees of freedom (DFs) when early in the learning of a visuomotor task.1,2 Our findings indicate that rather than using a more random strategy when learning the new dynamic space, our elite athletes constrain their DFs to facilitate learning. Our within groups analysis suggests that the non-elite athletes were still at an early stage of motor learning, given their greater ApEn values compared to the elite athletes. Overall, this analysis shows the utility of nonlinear dynamical analysis in examining the effect of experience on motor learning and performance. 1.Stergiou N (Ed.). Nonlinear Analysis for Human Movement Variability. Boca Raton: CRC Press. 2016:173-259.2.Montesinos et al. J NeuroEng Rehabil 15:116 (2018).

1-B-11 Influence of feedback control on the integration of visual and proprioceptive errors for motor adaptation

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Research on multisensory integration has shown that the brain combines sensory cues to reduce its uncertainty about the environment. However, recent studies on motor control and adaptation have highlighted that the standard, static cue combination model does not generalize to multisensory integration during movement. Importantly, it remains unknown how sensory feedback is combined into a 'teaching signal' to drive adaptation and whether this process is modulated by the way the brain engages feedback to correct movement errors. To this end, we asked 19 participants to perform visually guided reaching movements with a robotic manipulandum. Visual feedback was provided in form of a cursor on a screen. Each trial began by moving the hand into a start location. Upon a go cue participants initiated a movement to a target presented 15cm straight ahead. During movement we applied combined force field perturbations and lateral cursor shifts to induce proprioceptively and visually mediated feedback corrections. The direction of these perturbations was randomized across trials. Proprioceptive and visual errors were defined as maximum lateral limb and cursor deviations, respectively. We correlated these errors with limb displacements observed in baseline trials following a perturbation to evaluate the relationship between sensory feedback and adaptation. To assess if feedback control modulates behavior, we varied the task instructions. In one version of the experiment participants were instructed to counteract perturbations to land inside the target ('reaching task'). In the other version, they were told to aim for the target but not correct their movements when they encountered a perturbation ('shooting task'). Overall levels of feedback correction were clearly greater in the reaching task, whereas the average size of errors and subsequent after effects were larger in the shooting task. Yet, within each task, larger visual errors led to more vigorous corrections during the movement resulting in smaller limb displacements. Consequently, adaptation scaled positively with the size of the visual error and negatively with the size of the proprioceptive error on the preceding trial. Strikingly, a linear mixed model analysis showed that limb displacement alone predicted adaptation in the reaching task, while adaptation in the shooting task depended on both, limb displacement and visual error size. These results show that the signal driving adaptation was not simply a linear combination of visual and proprioceptive errors as suggested by the static cue combination model. Rather adaptation depended on the size of proprioceptive errors and on the vigor of feedback corrections which was influenced by visual errors. The observation that visual errors had no additional influence on adaptation in the reaching task suggests that the extent to which sensory errors are used for control and adaptation may differ depending on whether feedback is actively used for control.

1-B-12 GABA content in thalamus correlates with choice reaction time in the ipsilateral hand

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The availability of the principal inhibitory neurotransmitter gamma amino-butyric acid (GABA) in primary sensorimotor cortex (SM) and thalamus may be important for determining how actions are selected, initiated, and executed. Moreover, the functional significance of inhibition in ipsilateral motor circuits to speeded behavioral responses and stopping are uncertain. The purpose of this study was to evaluate relationships between reaction times derived using psychological tasks and GABA content in SM and thalamus. There were 15 right handed, healthy young adult participants (25.67 ± 4.06 years, 3 female). Behavioral reaction time data was gathered from the right hand using choice Go and Stop tasks. On each trial of both tasks, subjects were cued to choose between a speeded index or pinky finger button press response. In the Stop task, a stop signal followed the Go stimulus on 33% of trials at a variable stop signal delay, and subjects were instructed to attempt to stop the button press. Electromyography (EMG) was collected from the responding first dorsal interosseus (FDI) and adductor digiti minimi (ADM) muscles to derive EMG onset reaction times preceding button presses. GABA was measured in the right SM (n=15) and right thalamus (n=13), ipsilateral to the responding hand, using a MEGAPRESS magnetic resonance spectroscopy (MRS) sequence. We did not observe relationships between GABA in SM or thalamus and stopping performance measures (stop signal reaction time or stopping accuracy). However, we observed a negative relationship between thalamic GABA content and reaction times (both button press and EMG onset) in the Go task, with individuals who demonstrated higher GABA content also demonstrating faster reaction times. Thalamic GABA content did not correlate with Go trial RTs from the Stop task, and no significant relationships were observed between SM GABA and reaction times in either task. The pattern observed for thalamic GABA was present for both ipsilateral index and pinky finger reaction times and was robust to different reference molecules (H20 or Cr) and correction for tissue content, supporting the interpretation that this relationship is specific to GABA content. Overall, all twelve total comparisons exhibited this negative relationship (FDI RT, FDI EMG RT, ADM RT, and ADM EMG RT for each of the 3 different GABA referenced measures), with seven reaching significance ($p<0.05$). These results suggest thalamic GABA content ipsilateral to the responding hand supports speeded selection and execution of cued choice responses.

1-B-13 Early brain responses to visual targets for reaching are differentially modulated by reward and repetition of movement

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Many characteristics of goal-directed movements, such as their initiation time, initial direction, and speed, are influenced both by the details of previously executed movements (i.e. action history), and by the degree to which previous movements were rewarded or punished (i.e. reward history). When movements are specified externally, action and reward history define the probability and magnitude of positive/negative outcomes, and therefore the expected value, of potential movements. Here we studied how reach behaviour and early brain responses to target presentation are affected by the expected value of movements by independently varying action and reward history. Circular targets were presented in one of four locations (45 deg from cardinal axes) relative to fixation. In alternate blocks, participants either moved the handle of a robotic device to targets, or counted occasional stimulus features (green crosses). Following a baseline period, we increased the expected value of one target location (for reaching trials only); in one sample (N = 19) we increased the probability of the target appearing in one location (3:1), and in another sample (N = 19) we increased the reward associated with one target (10:1). We used 64-channel EEG recordings to compare event-related potentials as a function of expected target value, and a multivariate linear decoding model to estimate of the precision of target location representations in the brain. We found that movements were initiated earlier for both more frequently repeated and more rewarding targets, but only movements to more rewarded targets had higher movement speeds. Early visually-evoked EEG potentials (P1/N1) were not affected by either reward magnitude or repetition of movement, suggesting that movement and reward history have little impact on gross brain responses that reflect early visual processing. However, the spatial tuning curve representations decoded from EEG data were more precise for the target location associated with higher reward than for a control target location (~150-300ms following target onset). Critically, there were no differences between the decoded spatial tuning curves of the more frequent target location and a control target location. Location decoding was also much less precise when participants were not required to move, and no differences were observed between target locations as a function of their associated reward or probability (as established in reaching trials). These results suggest that precise decoding, and the differences in spatial tuning curve representations during active movement conditions, reflect visuomotor planning rather than (purely) visual processing. Thus, manipulations of expected value are associated with distinct changes in the early brain responses that reflect visuomotor processing of target location, suggesting that the neural underpinnings of the reward and probability components of target-value are likely distinct.

1-B-14 Express visuomotor responses appear bilaterally on the upper-limb muscles regardless of hand-choice

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When required, humans can generate short latency reaches towards a visual target, for example, when reaching to catch a ball rolling off a desk. During these rapid responses, the first wave of upper-limb muscle recruitment is the stimulus-locked response (SLR). SLRs occur at latencies approaching the minimum afferent and efferent conduction delays, with target specific information reaching the muscle ~80-100ms after target appearance. There is accumulating evidence that SLRs are initiated by the superior colliculus. The phenomenon of SLRs share many similarities with the generation of express

saccades, suggesting that SLRs are a type of express response at the upper-limb. The superior colliculus projects to the skeletomotor periphery via the tecto-reticulospinal tract, but the involvement of the reticulospinal tract in the SLR has not been well-studied. Here, based on the fact that the reticulospinal tract projects bilaterally, we studied if the SLR can be expressed bilaterally in a reaching task where either hand may move. Human participants (n = 15) performed visually-guided reaches in a modified emerging target paradigm, where a target travels down a chute, disappears behind a barrier, then emerges at one of seven possible locations below the barrier. Participants began each trial with their left/right hand to the left/right of the barrier and were free to reach to the target with either hand once it emerged. We recorded electromyographic activity bilaterally from the pectoralis major muscle. As expected, the choice of which hand reached was influenced by the location of the emerging target, with the closer hand reaching to catch targets emerging from the left or right side of the barrier. Our analysis focused on targets emerging close to, or at, the center of the barrier, as participants reached such targets with the left hand on some trials, and the right hand on others. In support of the involvement of the reticulospinal tract, the SLR persisted on both left and right muscles regardless of which hand reached to the target. While the SLR latency was the same, SLR magnitude was slightly larger on the reaching arm across our sample, but this was not observed in all participants. The difference in SLR magnitude may be due to anticipatory activity related to hand choice as we found that SLR magnitude was positively correlated with the magnitude of anticipatory activity. Our results support the involvement of the reticulospinal tract in mediating the SLR, and we surmise that the increased magnitude of the SLR on the reaching arm in some, but not all participants, arises from convergence of cortically-derived signals anticipating hand choice at either the reticular formation or the spinal cord.

1-B-15 The ability of musculotendons to undergo eccentric contractions is a critical enabler of learning for the control of movement

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The neural control of movement is particularly challenging due to the underappreciated fact that it is simultaneously under- and over-determined. In biological tendon-driven systems, where multiple muscles act on a few joints, the production of net joint torque is under-determined (i.e., many muscle forces produce few joint torques), but the control of joint movement is over-determined (i.e., few joint rotations determine the lengths of all muscles). This becomes a fraught mechanical situation when the tendons are driven by viscoelastic and afferented musculotendons that resist extension, as limb movement will be disrupted or locked if muscles fail to lengthen appropriately. As taught by Sherringon, inhibition is as important as excitation. Therefore, learning to produce a movement with a tendon-driven limb controlled by N muscles can be conceptualized as finding and following a trajectory in N-dimensional muscle activation space that produces the necessary joint torques over time, while permitting the necessary concentric and eccentric contractions. Although optimal control and machine learning approaches seek to identify such trajectories, to our knowledge most computational approaches do not explicitly consider resistance to eccentric contractions. We used a robotic bio-inspired 2-joint, 3-muscle tendon-driven leg to explore autonomous learning of motor activation trajectories for locomotion on a treadmill. Back-driveable DC motors pulling on the tendons emulated muscles that produce joint torques while resisting eccentric contractions. We used our general-to-particular (G2P) algorithm to learn directly in hardware via limited experience--and agnostic to energetic cost and the mechanics of the leg and task. We find that it is possible to learn motor activation trajectories for the highly-constrained control of movements and forces for locomotion in tendon-driven limbs--without an explicit or analytical control policy. More importantly, the back-driveability of the DC motors enabled the system to explore the solution space and converge to solutions that yielded high reward. Subsequent work in simulation shows that elastic tendons accelerate learning (more compliant tendons enable exploration better than stiffer ones). We conclude that the passive and afferented properties of musculotendons play a critical role in motor learning and performance. This work enables a systematic study of the neuromechanical interactions responsible for healthy and pathologic movement in the context of passive and active resistance to eccentric contractions.

1-B-16 Savings in human reaching is linked to feedback adaptation

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Savings has been described as the ability of healthy humans to relearn a previously acquired motor skill faster than the first time, suggesting that the learning rate in the brain could be adjusted when a perturbation is recognized. Alternatively, it has been argued that apparent savings were the consequence of a distinct process that instead of reflecting a change in the learning rate, revealed an explicit re-aiming strategy. Based on recent evidence that feedback adaptation may be central to both planning and control, we hypothesized that there existed a feedback adaptation component that could genuinely accelerate the learning in the context of force field. We used a standard velocity-dependent force field paradigm consisting of adaptation-washout-readaptation phases with two groups of healthy volunteers. Each group performed the task with a randomly assigned force field direction (clockwise or counterclockwise). First, we found that readaptation was faster, confirming the presence of savings. Second and most importantly, we demonstrate that the very first readaptation movement displayed the characteristics of better-adapted movements to the perturbation, in the absence of any anticipation or explicit cognitive strategy. Specifically, the first readaptation trial has smaller path length, and higher correlation between commanded and applied forces, compared to the first adaptation trial. Additionally, we verified that the late washout trials were statistically indistinguishable from the baseline trials, suggesting that deadaptation was complete. That is, the online corrections in the first readaptation trial carried imprints of feedback adaptation from the previous sessions without any explicit strategy. Thus the feedback-mediated component contributes to savings in human reaching adaptation.We conclude that feedback adaptation is a medium by which the nervous system can genuinely accelerate learning across movements.

1-B-17 Flexible electrodes for acute in vivo small animal muscle recordings

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To acquire a skilled behavior, the brain must learn to generate precise patterns of activity across multiple muscles. Currently, it is unknown how cross-muscle coordination develops and changes during learning. To address this fundamental question in motor control, it is necessary to simultaneously record electromyographic (EMG) activity across multiple muscles. Most experiments rely on implanting fine wires or non-invasive surface skin electrodes to measure EMG activity. There are many limitations to these current EMG methods. Wire electrodes typically cause tissue damage at the insertion site. Although surface electrodes do not cause injury to the muscle, they are not capable of recording EMG activity from small or deep, internal muscles. Additionally, it is difficult to record single motor units, where one motor unit consists of the muscle fibers innervated by a single motor neuron, with traditional fine-wire and surface EMG electrodes in experimental paradigms involving freely-behaving small animals. We have developed innovative electrode systems to measure EMG activity from multiple small (4 mm x 2 mm) vocal and respiratory muscles simultaneously in songbirds during an acute experimental paradigm. One technology uses two single Parylene-C coated carbon nanotube (CNT) fibers, fabricated by a wet spinning process, twisted together to create a bipolar CNT electrode. Single- and multi-unit motor unit activity can be recorded for long periods of time (~3 hours) by placing the electrode directly on top of the muscle without removing fascia. This recording method, along with the strength, flexibility, and small size (14-24 microns) of the CNT electrodes, creates an environment to easily move the electrode for optimal single motor unit recordings, resulting in high signal-to-noise ratio (SNR), without damaging the muscle tissue. Furthermore, we compare the advantages of CNT electrodes relative to those of a complimentary recording technology we have developed, flexible multielectrode arrays (MEAs). Hybrid polyimide-polydimethylsiloxane is used to create flexible MEAs that can be inserted into the muscle or placed on top of the muscle for EMG recordings. Similar to the CNT electrodes, the flexible MEAs have high specificity and low impedance at each recording site, allowing us to record multiple single motor units for an extended duration of time. In addition, the MEA array design features, such as the shape of the array and the size of the contact site, are easily adaptable, making the array morphologies muscle- and species-specific. The two novel electrode technologies, CNT electrodes and flexible MEAs, allow us to better understand how activity patterns in motor units produce a learned behavior.

1-B-18 Motor decisions between potential targets are reflected in visuospatial attention

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Neurophysiological and behavioral evidence suggests that in situations of target uncertainty, the brain simultaneously represents specifics of multiple potential actions before selecting one of them. According to this view, sensorimotor decisions reflect a biased competition between alternative actions that are held active in parallel. Here, we utilized the tight coupling between motor preparation and spatial attention to track how motor goal selection unfolds in situations of target uncertainty. We combined a delayed cueing paradigm, in which participants performed center-out reaching movements, with a covert spatial attention task. For the reaching task, two out of multiple target locations were pre-cued. After a delay, one of the pre-cued locations was designated as the final movement goal, and participants initiated their reach. Concurrently during the trial, a discrimination target was presented at a variable time that was either located at the movement goal, the other pre-cued location, or any of the remaining, uncued locations. Participants reported the identity of the discrimination target after they completed the movement. The results show that during the delay phase, discrimination performance was enhanced at both pre-cued target locations. This suggests that both targets had been simultaneously selected by spatial attention while the final target was not known. After final goal specification, discrimination performance further increased selectively at the movement goal. The peak of perceptual sensitivity was related to movement onset, such that the highest perceptual sensitivity was reached at the time of the motor decision. Furthermore, in trials with fast reach initiation, we observed an earlier increase of perceptual sensitivity compared to trials with slow reach initiation. These characteristics resemble the presumed integration of evidence during perceptual decisions as it is proposed by many models of decision making. Therefore, our findings suggest that attentional selection does not only reflect the selection of one final movement goal, but that attentional selection also reflects multiple potential movement alternatives and the competitive decision processes between them.

1-B-19 VR Lag - Understanding motion-to-photon latency for sensorimotor experiments with popular virtual reality systems

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Consumer virtual reality systems are increasingly used in the laboratory as a research tool for sensorimotor experiments. However, the available technical information for these systems often lacks the precision necessary for their validation as a scientific tool. Some aspects of performance, such as spatial tracking accuracy, are easily verified with simple tools in the lab. However, performance metrics such as motion-to-photon latency (how much time a user's movement takes to be visually displayed in the user's headset) are not so easily determined. Such sensorimotor delays are important, as they can not only decrease a user's sense of "presence" and increase cybersickness, but 50ms delays reduce the rate of adaption to prism displacement (Kitazawa, Kohno & Uka, 1995) and even latencies as low as 17ms have been shown to degrade manual tracking performance (Smith, 1972). There have been some attempts to measure the latency of individual consumer-grade headsets, but these mostly focussed on now outdated individual headsets, and employed different software and hardware approaches across studies, making direct comparisons impossible. Moreover, modern virtual reality systems employ motion prediction algorithms to functionally reduce latency, and this motion prediction has never been properly taken into account prior to our study. Here, we present measurements of the latency between the motion of controllers and corresponding visual feedback in the Oculus Rift, Oculus Rift S, HTC Vive, and the Valve Index, using the Unity game engine and SteamVR. We developed a novel high-speed camera-based latency measurement technique to co-register real and virtual controller movements, allowing continuous assessment of the latency through a movement. For the start of a sudden movement, we found all measured systems to have mean latencies in the range of 20-42ms, which was reduced to 2-13ms once motion could be accurately predicted in the intermediate phase of a movement. This reduction in functional latency occurs within around 50ms of movement onset. The Oculus Rift consistently had the lowest measured latencies (20 ± 5ms sudden , 2 ± 4ms intermediate), while the Valve Index had the highest (42 ± 5ms sudden, 13 ± 4ms intermediate). Preliminary application of simulated delays from the Oculus Rift and Valve Index to an exemplar dataset of arm reaches (Wei & Kording, 2009) indicates that reaction times determined from motion onset may be delayed systematically, with the nature of these delays depending on the system used. Our findings suggest that commercial virtual reality systems are suitable for most human sensorimotor tasks. However, parts of movements with sudden changes, such as movement starts or fast reversals, will suffer from higher latency/lower spatial accuracy. This can be especially important for measures focused on movement start like reaction time, which may be differentially affected depending on which VR system is used.

C – Posture and Gait

1-C-20 Muscle synergies during isometric maintenance of upright standing posture under directional pulling forces

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Muscle synergies have been defined as coordinated recruitment of groups of muscles with specific activation balances and time profiles. They have been proposed as building blocks employed by the CNS to simply the generation of task-specific forces and movements with a redundant neuromuscular system. Muscle synergies capture muscle coordination during reactive postural responses under mechanical perturbations and across different biomechanical contexts. However, the characterization of muscle synergies during static upright standing posture has not been investigated yet. Here we explore a novel experimental paradigm to characterize muscle synergies during isometric maintenance of upright standing posture while directional pulling loads are applied to modulate EMG activity in leg and lower-back muscles. Eleven healthy adults (24 ± 2.4 years, mass 69.9 ± 12.3 kg, height 1.74 ± 0.11 m), 7 males and 4 females, participated in the experiment. Participants were asked to stand on a force platform while feedback on the 2-D position of center of pressure (COP) was provided as a circular cursor (0.5 cm dimeter) displayed on a monitor. Pulling forces of two different magnitudes (5% and 10% of body weight) were applied at the level of the waist in 8 evenly spaced directions in the horizontal plane. As soon as the pulling force was applied the participant was asked to maintain the COP within a circular target (2.5 cm diameter) for at least 15 seconds. The target represented the participant's COP position in the steady-state upright standing posture. Surface EMG signals were recorded (sample rate 1000 Hz) from 16 muscles of the participant's dominant side: rectus abdominalis, tensor fascia latae, biceps femoris long head, tibialis anterior, semitendinosus, semimembranosus, rectus femoris, peroneus, medial gastrocnemius, lateral gastrocnemius, erector spinae, external oblique, gluteus medius, vastus lateralis, vastus medialis, and soleus. Five trials for each of the 16 conditions were recorded (8 horizontal directions x 2 pulling forces). Muscle synergies and activation coefficients were extracted for each condition using non-negative matrix factorization. Preliminary results show that isometric contractions of postural muscles under small external forces during static upright standing posture can be characterized by a set of muscle synergies. The synergies recruitment coefficients demonstrate a subject-specific tuning related to the direction and magnitude of pulling forces. These results lay the foundations for further studies investigating the use of myoelectric control and muscle synergies for the development of novel rehabilitation tools for recovering functional postural control.

1-C-21 The dynamic motor control index is a better marker of age-related neuromotor impairments than the number of muscle synergies: Toward early detection of walking deficits

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Functional decline, including slower walking speeds and increased risk of falling, is characteristic of aging. To promote healthier aging, there is a need for the timely detection of the changes in mobility that precede a functional decline. Recent evidence suggests that changes in neuromotor control precede functional changes. A popular method to measure neuromotor control has been the coordinated co-activation of muscles during walking (i.e. muscle synergies). While the number of muscle synergies--a measure of neuromuscular complexity--is typically reduced in individuals with neurological disorders, older adults do not show a significant reduction in the number of synergies, despite visible walking impairments. More recently, the dynamic motor control index--which provides a continuous summary metric of muscle co-activations during walking--has emerged as an alternative measure of neuromuscular complexity. This measure calculates the variability accounted for (VAF) using the one-muscle synergy solution and scales the VAF to a z-score based on a reference group. Previous work has demonstrated that the one-synergy VAF can differentiate between younger and older adults who completed a complex balance walking task. To expand upon this work, the primary aim of this study was to use the dynamic motor control index (i.e., a scaled version of the one-synergy VAF) to quantify age-related differences in neuromuscular complexity during treadmill walking (i.e., a simple walking task) and compare its ability to differentiate age groups to the number of muscle synergies. We hypothesized that the dynamic motor control index would be better than the number of muscle synergies at differentiating between younger and older adults. Non-negative matrix factorization of electromyography data collected from 37 healthy individuals during treadmill walking was used to calculate the number of muscle synergies and the dynamic motor control index. Study participants were grouped into young (18-35 y), young-old (65-74 y), and old-old (75 y) subsets. Young, young-old, and old-old groups had, on average, 2.78 ± 0.43, 2.92 ± 0.49, and 2.83 ± 0.75 muscle synergies and a dynamic motor control index of 100 ± 10, 96.4 ± 10.79 and 83.4 ± 15.93, respectively. We found that the dynamic motor control index ($X^2(2)$= 9.41, p= 0.009), and not the number of muscle synergies ($X^2(2)$= 5.42, p= 0.067), differentiates between age groups ($X^2(4)$= 10.62, p= 0.031, Nagelkerke R^2= 0.30). Moreover, age groups significantly differed based on an impairment threshold set at a dynamic motor control index of 90 (i.e., one standard deviation below the young healthy adults) ($X^2(2)$= 9.35, p= 0.009). These results suggest that neuromuscular complexity as measured by the dynamic motor control index can better identify age-related impairments than the number of muscle synergies and may enable more timely detection of changes in mobility that precede age-related functional decline.

1-C-22 Periodic Median Filter to remove power line interference in force plate and bioelectric recordings

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Summary Power line interference ("hum noise") is a common source of noise in recorded biological data. It has a main frequency of 50 or 60 Hz, as well as harmonics and tem-poral fluctuations in frequency, amplitude and wave shape. State-of-the art filters for removing this hum, suf-fer from two main drawbacks. First, they inadequately handle the slow phase fluctuations typical for power line noise. Second, when there are sharp transients in the rec-orded data (for example in the force recorded during jumping), the filters introduce border and rippling arti-facts ("ringing") which distort the signal. We propose a Periodic Median Filter (PMF) to reliably remove hum of any harmonic composition. We compare the performance of this filter to that of two state-of-the-art filters on a combination of recorded and simulated force plate and EMG data. Our filter is robust to fluctuations in hum fre-quency and unstable harmonics. It does not introduce "ringing" during the transients recorded in jumping. The PMF thus outperforms the best hum filters currently in use. Introduction Hum noise is present in diverse biological recordings, including force plate and bioelectric (EMG, EEG, ECG, and MEG) signals. In addition to the classical "Notch" filter, modern numerical filters have been proposed for removing hum [1,2]. Methods To remove the hum from a signal, the waveform of the hum over each period of the hum frequency is estimated. First, a high-pass filter is applied to the signal (20 Hz cut-off, 4th order two-way Butterworth). The waveform of the filtered signal is then averaged on a sliding window of 50 successive periods of the hum frequency. For averaging, we take the median rather than the mean to improve ro-bustness. This Periodic Median is then subtracted from the signal. The PMF is compared to two state-of-the-art filters: the Spectrum Interpolation Filter (SIF) (Leske & Dalal 2019) and the Fourier Decomposition Method (FDM) (Singh et al. 2019). We compared the performance of the 3 filters on 1. artifi-cial signals with a realistic frequency spectrum and hum, 2. hum-free EMG recordings (ground truth) with super-imposed hum, 3. force plate recordings of jumping (with hum). Results When evaluated on artificial signals with constant ampli-tude hum, all three filters had similar steady-state per-formance. The performance of SIF and FDM deteriorated at the beginning and end of the signal, and at sudden changes in the amplitude of the hum, whereas that of the novel PMF did not. On the EMG recordings with added hum noise, FDM showed considerable errors, particularly during strong muscle contraction. Both SIF and the PMF performed well. When applied to force recordings of jumps, both SIF and FDM showed substantial ringing in the vicinity of the jumps. The novel PMF showed no ringing. Conclusion The novel PMF is highly accurate in all tested conditions, and outperforms state-of-the-art filters.

1-C-23 Prefrontal cortical activation patterns during dual-task stepping in older women with and without osteoarthritis

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Background: Little is known about dynamic balance control under dual-task conditions in older adults with osteoarthritis (OA). For example, it is unclear how higher-order cognitive processing changes during challenging motor tasks for OA patients, such as stepping up and down. Current studies suggest that the center of higher-order cognitive processing which controls lower limb movement is located in the frontal lobes. This study's objective was to evaluate prefrontal cortex (PFC) oxygenated hemoglobin (HbO2) levels during single and dual-task stepping up and down in older women with and without OA. We hypothesized that older women with osteoarthritis (OA) would show higher PFC HbO2 during single task stepping in comparison to healthy older adults (HOA) and lower HbO2 during dual-task stepping in comparison to HOA. Methods: We recruited eight older women with OA and twelve healthy controls in the study (age>60). The experimental paradigm consisted of four tasks, which were combinations of the following two sets of conditions: 1) Continually stepping up and down for 25 seconds in anterior-posterior (AP) direction leading by the left or right foot. 2) Subtracting a number by seven while performing the motor task (DT) or performing the motor task only (ST). Functional Near-Infrared Spectroscopy was used to quantify PFC HbO2 levels. A linear mixed effect model was conducted to investigate the effects of cohort, task, and interaction between cohort and task on HbO2. To control for multiple comparisons, post-hoc Least-Squares Means tests were carried out using Kenward-Roger method. Results: The linear mixed effect model suggested that HbO2 levels during stepping tasks differed significantly between DT and ST condition ($p < 0.01$). In particular, when stepping in the DT condition older adults had 28.7% higher HbO2 levels than the ST condition. There were two significant two-way interactions in HbO2 level:1) cohort and task ($p< 0.001$); 2) cohort and leading foot($p<0.001$).

Post-hoc tests suggested that: 1) OA exhibited lower HbO2 levels during DT condition when compared to OA in ST ($p < 0.0001$), while HOA exhibited higher HbO2 level during DT condition when compare to HOA in ST ($p < 0.0001$); and 2), where no significant differences in HOA, OA exhibited higher HbO2 levels when stepping with left foot leading when compared to stepping with the right foot leading ($p < .0001$). Conclusion: In challenging motor tasks like stepping up and down, OA may be focusing on motor task execution in dual-task conditions and fail to adequately increase their attentional resources to meet high demands, in contrast to HOA who are better able to modulate attentional resources to meet the demands of concurrent cognitive tasks.

1-C-24 Learning to stand with unexpected sensorimotor delays

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The nervous system learns and maintains motor skills by forming estimates of self-motion based on the inferred relationships between sensory and motor signals. Due to neural conduction times, these self-motion estimates must accommodate for the inherent delay between motor commands and resulting sensory input. While standing, sensory feedback associated with lower-limb motor commands is delayed by ~100-160ms. Using computational models of standing balance, previous authors have predicted that the balance controller cannot adjust its sensorimotor gains to stabilize stance when delays exceed ~300ms. This prediction, however, contrasts with the adaptive capabilities of the nervous system during upper limb control, which can accommodate imposed delays up to and including 430ms. The aim of this study was to characterize the destabilizing effects of imposed delays past this critical delay during standing balance and to determine the mechanisms underlying subsequent adaptation and learning to such delays. Here, we performed a series of experiments where participants (N=39) balanced in a robotic balance simulator with imposed delays ranging from 20-500ms. We first characterized how human standing balance behavior is affected by imposed delays. With delays ≥200ms, whole-body sway variability increased and participants repeatedly fell into the virtual limits of the balance simulation (i.e. 6° anterior and 3° posterior). We then explored potential learning to imposed delays and assessed how the brain adapted to and processed delayed sensory feedback. Participants trained to balance with a 400ms delay for 100 minutes over 5 consecutive days. Prior to, after and three months following training, we probed the vestibular control of balance (using electrical vestibular stimulation) and tasked participants to report instances of perceived unexpected standing motion while standing with imposed delays. Initially, imposed delays ≥200ms attenuated vestibular-evoked balance responses (42% reduction at 200ms) and elicited consistent perceptions of unexpected standing movement (>85% detection at 200ms). During the first minute of training with the 400ms delay, participants fell on average 18 times (±5) into the virtual limits. By the end of training (100th min), participants could balance the robot on average for 43.5s (±14.3) without falling. After training, vestibular-evoked balance responses increased (at delays ≥200ms) and larger delays were needed for perceptions of unexpected motion (<70% detection at 200ms). Finally, these effects were retained ~3 months later. Our results demonstrate that imposed sensorimotor delays initially destabilize standing, reduce vestibular contributions to balance and lead to perceptions of unexpected standing movement. Through training,

the brain can learn to maintain upright stance with imposed delays (beyond the previously proposed critical delay ~300ms) by associating delayed whole-body motion with self-generated motor commands.

1-C-25 Functional Data Analysis: A tool for assessing muscle activity during reactive stepping

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This study aimed to determine the effect of perturbation magnitude on stance and stepping limb muscle activation during reactive stepping using functional data analysis. While research to date has investigated the impact of perturbation magnitude on muscle activity, it has used variables such as peak or average activity. These discrete variables limit the interpretability of findings and do not provide insight into when these differences may be functionally relevant. Functional data analysis is a statistical approach that continuously assesses differences in data by transforming signals into curves comprised of basis functions. Functional data analysis evaluates the smooth functional behaviour of data to further model and understand the time-series signal in an easily interpretable manner. In this study, 19 healthy, young adults responded to 6 small and 6 large perturbations using an anterior lean-and-release system, evoking a single reactive step. Muscle activity from surface electromyography was compared between the two conditions for medial gastrocnemius, biceps femoris, tibialis anterior, and vastus lateralis of the stance and stepping limb. Electromyography data was scaled to peak activity during maximal voluntary isometric contractions (MVIC). Warping functions were applied to time normalize the electromyography data such that perturbation onset occurred at 0% and foot contact occurred at 33% of the data. Following time registration, 19 basis functions were composed to represent each curve. To assess statistically significant differences, the difference between the pairwise comparison functions (large perturbation condition - small perturbation condition) were graphed along with the 95% confidence intervals. Differences between conditions were considered statistically significant when the 95% confidence interval did not cross zero. Functional data analysis revealed that stance limb medial gastrocnemius and biceps femoris activation increased by 20-40% MVIC in the large compared to small perturbation condition immediately prior to foot-off and by 2-5% at foot contact. In the stepping limb, significant increases of 5-10% MVIC in medial gastrocnemius, biceps femoris, and tibialis anterior activity occurred immediately prior to foot-off during the large perturbations. Similar to the stance limb, medial gastrocnemius and biceps femoris activity significantly increased during and following foot contact in the large, compared to small, perturbation condition (~5-10% MVIC). Lastly, vastus lateralis activity significantly increased by ~10% MVIC for large, compared to small, perturbations during foot-off and immediately following foot contact. These findings highlight unique functional increases in lower limb muscle activity, particularly at foot-off and foot contact, with heightened perturbation magnitude. Future work should consider using functional data analysis when assessing signal changes over time during reactive balance testing.

1-C-26 Does brain activity during imagined walking correlate with walk speed in young and older adults?

Presenting Author: Valay Shah

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Degradations of the central nervous system are widely reported in healthy aging and impact the neural control of walking and overall mobility. The Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH) describes two observable age-differences in brain activity while individuals perform cognitive tasks of increasing difficulty: 1) there is an over-activation of brain regions at low difficulty, and 2) a lower "ceiling" of brain activity that occurs at moderate difficulty. These age-differences are associated with poorer task performance at higher difficulty levels. Whether and how CRUNCH can explain brain-behavior relations during walking has yet to be investigated. The current study uses functional magnetic resonance imaging to record brain activity. In the MR scanner, participants performed motor imagery (MI) of walking on increasingly difficult uneven terrain. Participants also performed an N-back (NB) spatial working memory task, where N increased up to three, representing the number of spatial targets to recall. The NB task was done to replicate previously reported CRUNCH effects. In addition, participants performed a timed 400 m walk out of the scanner, on another day. To date, 11 younger adults (20-33 yrs old, 5 females) and 19 high functioning older adults (71-86 yrs old, 8 females) have participated. We performed region of interest analysis on the left and right dorsolateral prefrontal cortices (DLPFC) and the anterior cingulate cortex (ACC) to identify age-differences in brain activations during each task (MI and NB). Preliminary results showed that both younger and older adults reached ceilings in brain activity during MI and NB as difficulty increased. In the NB task, younger adults had higher ceiling levels than older adults in both the left and right DLPFC and ACC regions (1.6, 0.6, and 1.7 units higher, respectively; not statistically tested yet). For the MI task, younger adults had higher ceiling levels in the left and right DLPFC (0.23 and 0.22 units higher, respectively) and reached these ceilings at higher difficulties (difficulty level 2 in younger compared to difficulty level 1 in older). In the ACC, younger adults only had higher ceiling levels than older adults (0.27 units higher; not statistically tested yet). Additionally, a larger percentage of older participants experienced a reduction in brain activity during MI as task difficulty increased (relative to the least difficult MI condition), possibly pointing to dysfunction in utilizing brain resources effectively. There were no significant correlations between activity in our brain regions of interest and 400 m walk time, but our sample size to date is relatively small. Overall, our preliminary results show age-differences in brain activity during MI and NB task performance, which were modulated by task demand. We are continuing data collection to further investigate our hypotheses. Supported by NIH U01AG061389 and NIH T32AG062728.

1-C-27 Energetic costs of performing negative work and swinging the leg trade off against walking passively on a split-belt treadmill

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Split-belt treadmills are widely used to study motor adaptation during walking. While this adaptation has traditionally been interpreted as the nervous system minimizing a sensory prediction error, recent studies have found that it may be driven by energy minimization. When the speeds of the two belts of a treadmill are made unequal, healthy adults adapt from taking longer steps on the slow belt, defined as negative Step Length Asymmetry (SLA), to taking longer steps on the fast belt (positive SLA) resulting in lower energetic cost. Taking a longer step on the fast belt allows the treadmill to perform net positive work on the person, that the person can use to reduce their energetic cost of walking. However, while the work from the treadmill continues to increase with more positive SLA, the energetic cost of walking does not continue to decrease but is minimized at a slightly positive SLA. Here we aim to understand what contributors to the energetic cost of walking trade off against using the increased work from the treadmill at more positive SLA. Towards this aim, we used computer simulation and numerical optimization of a physics-based dynamic walking model. Our model is an extension of those developed by Kuo (2001) to study the contributors to the energetic cost of overground walking and how preferred overground gaits are consistent with minimizing energetic cost. Our walker consists of a point mass torso and two legs with distributed mass and curved feet. It loses energy with each foot strike collision that can be replaced with a push-off impulse from the stance leg. The speed and asymmetry of the leg swing is determined by the stiffnesses and equilibrium position of two springs connecting each leg to the torso. A repeatable gait requires the walker to match kinematics at the beginning and end of a stride while staying in place on the treadmill. We selected a belt speed difference of 1m·s-1 comparable to split-belt walking experiments. To find the optimal gait, the optimization minimizes a cost function by tuning the step times, push-off impulses, spring stiffnesses and spring equilibrium position. We found that if the only contributor to the cost function is the work of pushing-off, the walker can completely replace it with the work from the treadmill. This gait has the maximum possible SLA of 1 and is entirely passive - something not possible overground or when the belts are tied). Therefore, walking with unequal belt speeds can be cheaper than walking at any equal belt speed. However, this requires large negative work, and fast, asymmetric leg swing. If we modify the cost function to include the physiologically likely contributions from negative work and the effort to swing the legs, the optimal gait is no longer passive and has SLA less than 1. We are developing and testing physiologically realistic cost functions to better understand the important contributors to the energetically optimal split-belt walking gait.

1-C-28 Replicating physiological characteristics of standing balance with a reinforcement learning controller

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Reinforcement learning (RL) frameworks are popular tools to depict how we explore and adapt to new environments and tasks. These frameworks learn to control movement by reinforcing successful actions through exploring the environment. Although many controllers are successful at controlling human balance-like behavior by optimizing the control as a time-invariant system, they typically don't incorporate adaptive structures to account for changes in the environment. To address these shortfalls, we proposed an RL model to represent human standing in the anterior-posterior direction. The goals of our modeling approach were to determine if RL frameworks can be used to replicate key time and frequency characteristics of standing balance and identify parameter combinations that yielded the simulations resembling the physiological control of standing balance. Simplifying the biomechanics of standing as an inverted pendulum, we represented the state space with ankle angular displacement and angular velocity and the action space with ankle torques. We trained the model to select actions that kept the pendulum upright and minimize excessive ankle torque. The optimal mapping between the states and actions was acquired using a Q-learning algorithm, which learns how good each state-action pair is while exploring the environment. At each time step, the controller selected the action with the highest action value and updated the action value using received feedback. We performed a grid search of 625 simulations that manipulated 1) motor noise (i.e. noise from muscle activity producing torques),

2) angle noise (i.e. sensory uncertainty when detecting joint angle), 3) angular velocity noise (i.e. sensory uncertainty when detecting joint angular velocity) and 4) metabolic cost. To quantify the simulation results, we examined the peak frequency and median power frequency of the center of mass (CoM) displacement as well as the distribution of generated torques. Overall, 30 out of 625 parameter combinations yielded a controller that resembled the characteristics of human postural sway. For example, one particular set of parameters (motor noise = 0 Nm, angle noise = 0.015 rad, angular velocity noise = 0.06 rad/s, metabolic cost = 2) resulted in a peak frequency of CoM displacement of 0.12 Hz, median power frequency of CoM displacement of 0.16 Hz, and a unimodal distribution of generated torque (mean: -4.5 Nm, SD 12.7 Nm). In general, our preliminary results revealed that increasing motor noise, angle noise and angular velocity noise decreased the peak frequency and median power frequency of the CoM displacement. While RL can produce a controller that mimics physiological features of human standing balance, it also presents a framework for motor learning and adaptation. Thus, we can exploit this property to model the learning and adaptation of standing balance and related tasks under novel sensorimotor environments.

1-C-29 Movement variability constrains locomotor use-dependent learning

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Practice is widely recognized as an indispensable component of motor skill acquisition. However, it is unknown how consistent repeated movement patterns must be to engage a 'use-dependent' learning mechanism. We tackled this question by testing two competing computational frameworks of use-dependent learning. In the Strategy plus Use-Dependent (SU) model (adapted from Diedrichsen et al., 2010), use-dependent learning is viewed as a slowly updating and slowly decaying bias in the direction of repeated movements. The Adaptive Bayesian (AB) model (Verstynen and Sabes, 2011) frames use-dependent learning as an emergent property of quickly adapting prior probabilities of target step lengths. Critically, the AB model is much more sensitive to variable practice than the SU model. As locomotion is a naturally repetitive process, it provides an ecologically-valid means to compare these two competing hypotheses. To this end, 12 healthy, young participants practiced visually-guided treadmill walking under 3 conditions with differing amounts of practice consistency. During the Practice phase of each condition, visual targets guided participants to walk with a Step Asymmetry (SA; i.e., a limp), where SA=((Left step length - Right step length) / (Left step length + Right step length))*100%, and 0% SA indicates perfect symmetry. In the Constant condition (Cc), target SA remained at 22% for the entire Practice phase. In the Low Variability condition (LVc), targets were sampled from a normal distribution with a mean of 22% and standard deviation of 5% SA. In the High Variability condition (HVc), targets were sampled from a uniform distribution between 5% and 39% SA. We confirmed that mean SA was similar and only SA variability differed across conditions during the Practice phase. Immediately following the Practice phase, visual feedback was removed and participants were instructed to walk normally during Washout. We quantified Initial Bias as the mean SA during the first 5 strides of Washout. Consistent with the AB model, our results indicated that Initial Bias decreased as a function of practice variability, with participants demonstrating the greatest bias in the Cc (SA mean ± SD: 2.5 ± 1.7%), followed by the LVc (1.7 ± 1.0%), and the smallest bias during the HVc (0.9 ± 1.1%). A similar pattern was maintained during Early Washout, defined as the mean SA during strides 6-30 of Washout. AIC scores also marginally favored the AB model over the SU model. However, although the AB model captured the effect of movement variability on the Initial Bias, the SU model more accurately predicted the very slow, and incomplete, return to baseline over the 750 stride Washout. Combined, these findings show that movement variability constrains locomotor use-dependent learning, and motivate development of an alternative model, one which can capture both the sensitivity of Initial Biases to practice variability as well as the decay-resistant component of use-dependent learning.

1-C-30 Do human-human physical hand interactions assist walking balance by mechanical support or haptic communication?

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Principles from human-human balance assistance may aid in the design of more effective and intuitive robotic assistance devices. Holding hands with another person while walking side-by-side can improve balance, but the mechanism of balance assistance is unknown. Our goal was to characterize the effect of hand contact with a partner during a balance-challenging walking task and examine how hand forces are used to assist balance. Specifically, we investigated whether interaction forces at the hand provide mechanical support, i.e. involve significant force, torque, and power; or haptic communication, i.e. convey information through touch. We measured whole-body kinematics (N=12 pairs) and hand forces (N=9 pairs) in healthy young adults. During a partnered beam-walking condition, one person walked on a narrow balance beam while assisted by partner walking by their side overground. A partnered overground walking condition was used as a control condition. In both conditions, each partner held one end of a custom handle on a six-axis force-torque sensor. Balance performance was compared between solo and partnered beam-walking conditions, and evaluated by the beam-walker's distance completed on the beam, lateral sway (standard deviation of lateral torso position), and angular momentum about the beam axis. Balance assistance in partnered beam-walking and overground walking was quantified by hand force magnitude, torque acting on the beam walker created by hand forces, and the angular power, all in the frontal plane about the beam axis or the ground midline. Finally, we tested whether the relationship between the torque and the beam-walker's angular kinematics could be characterized as a mass-spring-damper system. All balance performance metrics significantly improved ($p < 0.001$) during partnered beam-walking vs. solo beam-walking. On average, participants completed 2.5 ± 0.7 m during solo beam-walking and the entire beam length (3.7m) during partnered beam-walking. Lateral sway decreased by 66% and angular momentum decreased by 63% from solo to partnered beam-walking. Although force magnitude and RMS torque were small overall, they were significantly larger ($p < 0.05$) during partnered beam-walking vs. overground walking, force = 8.8 vs 5.4 N and torque = 3.3 vs. 2.2 Nm, respectively. However, RMS angular power did not differ significantly ($p = 0.49$) between partnered beam-walking vs. overground walking, 0.10 vs. 0.12 N*m/s, respectively. Torque on the beam-walker was moderately fit by a mass-spring-damper system (mean $R^2 = 0.30$). Given that the small forces in our study are within the range of those used in haptic communication during overground walking (10-30 N in Sawers 2017), that no significant power transfer occurred, and the limited similarity to a mass-spring-damper system, we conclude that hand interactions with a partner improve walking balance not through mechanical assistance but likely a form of haptic communication.

D – Integrative Control of Movement

1-D-31 Same action, different meaning: neural substrates of semantic goal representation

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Accurate control over everyday goal-directed actions is mediated by sensory-motor predictions of intended consequences and their comparison with actual outcomes. Such online comparisons of the expected and re-afferent, immediate, sensory feedback are conceptualized as internal forward models. Notably, voluntary actions are oriented not only towards immediate sensory outcomes, but also long-term conceptual goals and intentions for which the sensory consequence is sometimes absent or cannot be fully predicted. However, current predictive coding theories and the corroborating neural evidence address the processing of immediate sensory-motor goals while distal conceptual goals are yet to be incorporated and to date, the underlying processes that give rise to amodal introspective representations are unknown. Therefore, using behavioral measures and fMRI, we examined identical actions (either right or left-hand button presses) performed for two different semantic intentions ('yes'/'no' response to questions regarding visual stimuli). Importantly, actions were devoid of differences in the immediate sensory outcome. Our findings revealed voxel patterns differentiating the two semantic goals in the frontoparietal cortex and visual pathways including the bilateral LOC. Behavioral results obtained outside the scanner suggest that the results cannot be explained by kinetic differences such as force. To the best of our knowledge, this is the first evidence showing that semantic meaning is embedded in the neural representation of actions independent of immediate sensory outcome and kinetic differences.

1-D-32 Active exploration of the input-output properties of a novel tool improves system identification

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People are highly skilled at inferring the dynamics of a novel tool by simply viewing or manipulating it for a brief period of time. However, it remains unclear what features enable this capacity for system identification. Are people able to build a rich internal model of a physical system through passive observation of its dynamics? Or does it require active exploration of its input-output properties? We set out to test this question by systematically varying the amount of information available to infer a physical system's dynamics and its complexity. Here, participants were asked to predict the motion of a multilink arm following the collision with a point mass projectile. The projectile followed a linear path with a constant speed, and the animation froze when it contacted the (at rest) system. Different trajectories of the system were then displayed, and participants were asked to identify which trajectory was appropriate, given the laws of physics. Four groups of participants had differing amounts of information available to infer the system's dynamical properties: i) the Passive-Configuration group never observed the system move; ii) the Passive-Collision group saw a single animation of an example collision at the onset of the experiment; iii) the Passive-Dynamics group saw a full, 5-second animation of the system's kinematics (without a collision) before each trial; and iv) the Active-Interaction group was allowed to move the system to explore its dynamics for 5 seconds before each trial. The complexity of the system was varied within subject by changing the number of links in the multilink arm (i.e., degrees of freedom). Performance for each group was defined by d-prime (d') sensitivity, calculated as the difference between the standardized probability of correct trajectory identification minus that of false alarms. We found that the overall d' sensitivity was significant for both groups that received information about the physical system every trial (Passive-Dynamics and Active-Interaction), whereas the other two groups had equal probability of scoring either a hit or a false alarm. Notably, d' sensitivity for the Active-Interaction group was almost seven times greater than for the Passive-Dynamics group. Given that both groups saw a 5-second animation of the system every trial, this result shows a fundamental advantage of active exploration of input-output relationship over rich (but passive) observation. Furthermore, the Active-Interaction group was also the only group that modulated their predictions with the complexity of the system, which is evidence that they took into account the different degrees of freedom of each system in their internal simulation. These results show that system identification is tightly connected with active exploration and illustrate how the interaction with tools and their dynamics shapes how visual information is selected and analyzed for their internal representation.

1-D-33 Multisensory benefits when grasping under visual uncertainty

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Visually guided reach-to-grasp actions are often assisted by haptic information from the hand contralateral to the one performing the action (e.g., reaching for the lid while holding a jar). In normal visual conditions, the combination of visual and haptic inputs leads to better action performance than the separate unisensory inputs. Within this multisensory-motor integration process, haptics is more concerned with the control of the transport component, whereas vision is responsible for the control of grasp formation. But does the performance still benefit from multisensory integration when the visual information about the handheld object is highly uncertain? If so, what are the roles of haptic and visual cues? To test the impact of visual uncertainty on the multisensory integration process during grasping movements and to further disentangle the relative contribution of visual and haptic object size and position cues we ran two experiments. In Experiment 1, we asked participants to grasp objects of different sizes in central (normal visual uncertainty) or peripheral vision (45° eccentricity, high visual uncertainty) either with or without additional haptic information or with haptic information only. In Experiment 2, an additional condition was performed in which participants grasped a peripherally seen object while holding a post on which the object was placed (i.e., haptics was informative only about the object position). First, we replicated our previous finding that, in central vision, actions based on multisensory information are more efficient than actions guided by unisensory information. Second, we found that with increased visual uncertainty (only peripheral vision) grasping movements were slow and almost insensitive to changes in object size. In contrast, the simultaneous availability of peripheral vision and haptics led to faster movements and smaller grip apertures that better scaled with object sizes than in the peripheral vision only condition. Strikingly, this multisensory advantage was mainly driven by the availability of haptic positional cues. Complementing peripheral vision with only the haptic position cue was sufficient to dramatically reduce the grip aperture and produce movements as fast as when also the haptic size cue was provided. However, the scaling of the grip aperture was again insensitive to changes in object size. Taken together, our results show clear multisensory benefits even in conditions of degraded vision. Moreover, they reveal that, in multisensory reach-to-grasp actions, haptics plays a hitherto undetected role also in the control of grasp formation and not only in the control of the transport component.

1-D-34 Effort modulates the response to reward in reaching movements

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When the brain decides how to perform a movement, it considers both the effort required and the reward gained. With greater reward at stake, young adults will both react and move faster to acquire it sooner than they would a lesser reward. Older adults will also acquire a greater reward sooner but tend to rely on reacting faster rather than moving faster. Faster movements incur a greater energetic cost, and even more so in older adults. Perhaps older adults preferentially rely on reacting faster as a less costly strategy to obtaining reward sooner. Here, we simulated the increased effort costs of older adults by affixing physical mass to the arm, to probe how added effort modulates reward-related changes in movement vigor. Young adults ($n = 20$; 23 ± 4 yrs.) performed 10-cm radial, out-and-back reaches to rewarded and non-rewarded quadrants, under high and low effort conditions. In the high effort condition, reaches were performed with 8 lbs mass affixed to the robotic arm; no mass was added in the low effort condition. Each condition consisted of four blocks of 100 trials; in each block one quadrant was consistently rewarded with an audiovisual stimulus while the other quadrants were not. We asked whether the added effort would reduce the invigorating effect of reward on reach reaction time and peak velocity. In both effort conditions, rewarded trials exhibited faster reaction times ($p = 2.72e-05$) and greater peak velocities ($p < 2e-16$). Higher effort resulted in slowing of these kinematic measures ($p << 0.0001$). Though vigor increased for reward in both the low and high effort conditions, effort modified the strategy in which this reward was obtained. Higher effort costs shifted changes in vigor away from execution (peak velocity), and instead towards the preparation phase (reaction time). With low effort, peak velocity increased by 2.50 ± 0.184 cm/s towards a rewarded target as compared to its non-rewarded counterpart; when high effort was required, the increase in peak velocity was smaller, at 1.21 ± 0.184 cm/s (reward-effort interaction: $\beta = -1.29$ cm/s; $p = 3.16e-06$). Thus, the increase in velocity when responding to reward was mitigated by effort. This interaction was reversed for reaction time. When responding to rewarded targets, subjects reduced reaction time by 5.94 ± 1.413 ms in the low effort condition, compared to 8.22 ± 1.413 ms in the high effort condition. In the high effort condition, rather than react slower, subjects reacted at least as fast, if not faster, to reward (reward-effort interaction: $\beta = -2.28$ ms, $p > 0.05$). Our results indicate that more effortful movements shift reward responsiveness towards reaction time sensitivity, possibly because reducing reaction time incurs a lower energetic cost than reducing movement duration. Together, these results suggest that to obtain effortful reward, increases in movement vigor begin to favor the less costly movement preparation phase and shift away from movement execution.

1-D-35 A deep learning approach to decode reach-to-grasp movements from posterior parietal cortex of macaque

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Brain-Computer interfaces are helping patients with severe spinal lesions to volitionally control prosthetic limbs. To detect movement intentions of the patients, neural decoders translate brain signals into motion signals required to control effector devices. Decoding of bioelectrical neural signals is therefore a critical point in brain computer interfaces, requiring the development of high-performance, reliable and robust algorithms. These requirements are met in many fields by deep neural networks, adaptive algorithms whose performance scales with the amount of data provided, aligning with the increasing number of electrodes in implants. With the aim of testing reliability, accuracy and scalability of deep neural networks as neural decoders, we recorded 84 single neurons from posterior parietal cortex of two macaques. Neurons in the posterior parietal cortex modulate their activity depending on the characteristics of reaching and grasping tasks. We have recently shown that, using traditional machine learning algorithms, decoding of type of grips required to grasp objects is possible with fair accuracy (Filippini et al., 2017). In this study, we tested different neural networks (multi-layer perceptrons, convolutional and recursive neural networks), while decoding the intention to perform reach-to-grasp movement (binary classification) and up to 5 grips types (multi-class problem) from neural signals. To maximize the performance, the main hyper-parameters defining each architecture were tuned, searching for the optimal combination of the network depth, number of neurons for each layer, regularizers and dropout rate. The decoding approach based on a convolutional neural network scored promising results, with a F-Score higher than 0.6 (on average, precision of 0.5 and 0.46, recall of 0.88 and 0.84, respectively for monkeys 1 and 2) and AUC higher than 0.9 in the single-class case (detection of movement intention). In addition, this approach introduced half of the trainable parameters to fit respect to the other architectures, resulting in a more parsimonious approach that could be useful when decoding small datasets. It also showed a quasi-linear relationship with signal degradation (neuron dropping analysis), without unpredictable performance degradation. The neural networks applied in this study performed well while being robust, suggesting that these decoding solutions could establish a new state of the art in neuroprosthetic control.

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1-D-36 Differences in vertical perception between frontal and sagittal planes

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In aviation, decision making process depends on situation awareness built on multisensory perception. In lack of visual information, pilots could be tempted to rely on the vestibular system. Also, vestibular-induced spatial disorientation and illusions such as the leans, the graveyard spin and spiral, the Coriolis inversion, head up and head down illusions are significant causes of accidents. Innovative tests such has the HIT, cVEMP and oVemp tests have been recently developed for testing the utricular, saccular and canalar functions, which allows a detailed longitudinal follow up of the vestibular system in pilots. However, vestibular psychophysics, like vestibular thresholds, cannot be assessed using reflexive vestibular reflexes. Furthermore, in accidents involving disorientation, 85% are a consequence of unrecognized disorientation during complex flight scenarios. Hence, developing psychometric tests in realistic situations, i.e. using flight simulators, may greatly benefit to the longitudinal follow up of the training and the performances of pilots. As a first step in that direction, we used a helicopter flight simulator with a motion platform to probe pilot's sense of orientation in absence of vision, that is when vestibular information are likely to play a prominent role. Nine healthy individuals (only males, age=39±6, range=31-48 years), all of them professional helicopter pilots with no history of any vestibular impairment were included in the study. In a level-D full flight helicopter simulator, the cabin tilted 6 times in roll and 6 times in pitch (-15°, -10°, -5°, 5°, 10° and 15°) while the pilots had no visual cue. The order of the 12 trials was randomized with two additional trials among them where the cabin stayed in the horizontal plane but rotate in yaw (-10° and +10°). After the completion of each movement, the pilots were asked to put the cabin back in the horizontal plane (still without visual cue or time constraint). We measured the accuracy in recovering the horizontal plane achieved by each pilot for each tilt. We found that pilots were significantly more precise in roll (average roll: 1.15±0.67°) than in pitch (average pitch: 2.89±1.06°) (Wilcoxon signed-rank test: $p<0.01$). However, we did not find significant difference neither between left and right roll tilts ($p=0.51$) nor between forward and backward pitch tilts ($p=0.59$). Furthermore, we found that the performed accuracies were significantly biased with respect to the initial tilt. The greater the initial tilt was, the less precise the pilots were, although maintaining the direction of the tilt. This significant result was found in both roll (one-way repeated measures ANOVA: $p<0.01$) and pitch ($p<0.001$). However, the pitch trend was more prominent (slope=0.23 versus slope=0.068) than roll. This study is a first step in the determination of the perceptive-motor profile of professional pilots which could be of major use for their training and their longitudinal follow up.

1-D-37 Motor learning and sensorimotor integration in young adults with Attention-Deficit/Hyperactivity Disorder

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Background: Attention-Deficit/Hyperactivity Disorder (ADHD) is considered to be a neurodevelopmental disorder that exhibits unique neurological and behavioural characteristics 1, 2. Those with ADHD often have impairments in motor performance and coordination 3, 4. While behavioural impairments are present, there are noted alterations in the processing of somatosensory stimuli 5 and multisensory integration 6. However, it is unknown how motor learning may be implicated and whether there are neural markers pertinent to these differences, particularly in adults with ADHD. This work can provide insight to the role of altered neural processing in sensorimotor integration (SMI) on performance and the acquisition of novel motor skills in those with ADHD. Methods: Participants included those with ADHD (n=2) and neurotypical controls (n=12). This work utilized a novel motor tracing task, where participants used their right-thumb to trace a sinusoidal waveform that varied in frequency and amplitude. This motor task was completed in pre, acquisition, post, and retention blocks. Median nerve somatosensory-evoked potentials (SEPs) were collected pre and post. SEPs are named based on their polarity and latency and are reflective of neural processes and structures. For example, a negative SEP peak occurring 30ms post-stimulation is labelled N30; the N30 is reflective of sensory integration. SEPs were stimulated at two frequencies, 2.47Hz and 4.98Hz. SEPs were recorded centrally using 64-electrode whole-head electroencephalography (EEG) at a sampling frequency of 2048Hz. Results: When assessing performance via absolute percent error, the ADHD group had reduced error at pre, post, and retention tests when compared to controls. When normalizing percent error for post and retention performance to baseline values, performance post-motor learning is similar between groups (0.77±0.07 ADHD vs. 0.77±0.10 Controls), while controls continue to improve at retention (0.72±0.13 Retention vs. 0.77±0.10 Post) and the ADHD group plateaus (0.77±0.02 Retention vs. 0.77±0.07 Post). Controls had an increase in the N11 (1.02±0.23 ADHD vs. 1.11±0.40 Control), whereas both groups showed slight increases in the N13 (1.06±0.33 ADHD vs. 1.02±0.19 Control) SEP peak. The ADHD group had a reduced N30 SEP peak post-motor learning (0.85±0.03 ADHD vs. 1.02±0.14 Control). Discussion: This work is the first to utilize neurophysiological measures via SEPs in conjunction with a behavioural paradigm to assess SMI and motor learning in adults with ADHD. Preliminary results suggest that there are behavioural and neurophysiological differences in how those with ADHD acquire novel motor skills, including a reduced learning effect at retention. This may have important implications for strategies to promote learning in this population. Data collection was halted due to COVID-19, moving forward, increasing the sample size will help to further understand the mechanisms behind these preliminary findings.

1-D-38 Comparative reliability of corticospinal excitability estimates for the vastus lateralis during isometric knee extensions and squats

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INTRODUCTION: Transcranial magnetic stimulation (TMS) is increasingly used to examine changes in lower extremity corticospinal excitability (CSE) following exercise or rehabilitation interventions. Because CSE is task-specific, there is growing emphasis on the use of ecological tasks. Nevertheless, the comparative test-retest reliability of CSE measurements during established (e.g. knee extensions; KE) and more recent ecological (e.g. squats; SQT) lower extremity tasks has received less attention. The aim of this study was to compare the test-retest reliability of CSE, force, and muscle activity (EMG) during isometric SQT and KE. METHODS: 19 right-footed men (age: 25±5yrs) with similar age, weight and aerobic fitness performed SQT (N=7) or KE (N=12) on two consecutive days. Force and EMG were recorded during maximum voluntary isometric contractions (MVC). Corticospinal excitability was determined in the dominant leg during light (15%MVC) contractions based on stimulus-response-curves (SRC) derived from motor evoked potentials (MEPs). Test-retest reliability and absolute agreement were determined for force, EMG, the plateau of the SRC (MEPMAX) and the rising phase midpoint (V50). As a secondary analysis, all outcomes were compared between groups with mixed-methods ANCOVAs (2 Tasks × 2 Timepoints, covariate = body fat percentage). RESULTS: Compared with SQT, KE displayed better test-retest reliability and agreement for MEPMAX (KE ICC = 0.92, SQT ICC = 0.68) whereas V50, force, and EMG were similarly reliable (all ICC > 0.86). Force ($p < 0.01$) and MEPMAX ($p = 0.02$) were also greater during KE despite a similar V50 ($p = 0.11$). DISCUSSION: Differences in test-retest reliability, absolute agreement, and between-group comparisons highlight the need to carefully select lower limb TMS assessment tasks. Increased neuromechanic complexity may obfuscate reliability of lower limb corticospinal assessments, particularly at high stimulation intensities, encouraging future efforts to balance ecological validity with statistical sensitivity.

1-D-39 Repetition effects in action selection: dissociating hemispheric from effector specificity

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Action choices are influenced by future and recent past action states. For example, when performing two actions in succession, response times (RT) to initiate the second action are reduced when the same hand is used. These findings suggest the existence of effector-specific representations for action selection. However, given that each hand is primarily controlled by the contralateral hemisphere, the RT benefit might actually reflect body side/ hemispheric-specific rather than effector-specific repetition effects. Here, participants performed movements with either (i.e., left, right) hand or foot in one of two directions; direction instructions were specified anatomically ("inward, outward") or externally ("left, right"). Successive actions were initiated faster when the same effector was repeated (e.g., left hand - left hand), even when those actions involved different movement directions, whether specified anatomically or externally. Conversely, repeatedly using the same body side did not yield an RT benefit (e.g., left foot - left hand). Our finding, thus, lend support to the claim that repetition effects in action selection arise at the level of individual effectors.

1-D-40 Strategies of octopus arm control in the absence of visual feedback

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Without the structural limitations of a skeleton, the octopus' eight arms are free to bend in any direction anywhere down their length. The range of possible configurations for the octopus' limbs far exceeds that of skeletal animals, and provides them with seemingly infinite degrees of freedom. The octopus employs a complex, distributed nervous system within its arm and suckers to coordinate this extreme flexibility. The arms are also densely innervated with chemical and tactile sensory receptors, which feed into the distributed neural ganglia along the arms to form local sensorimotor control loops, creating an alternative configuration for the control of skilled movement. Understanding how interactions between local sensorimotor loops generate adaptive behavior in limbs with large degrees of freedom provides insight into the diversity of motor strategies that evolution has engineered, and may provide solutions for control problems faced by the field of robotics. Octopuses commonly forage at night and reach their arms into visually occluded spaces while searching for prey. To characterize the octopus' ability to forage using the local chemotactile control systems within its arms, we investigated the strategies the Pacific red octopus (Octopus rubescens) uses to find food while reaching a single arm into a visually occluded arena. This task space was developed using computer-aided design and 3D printed. Octopuses were then trained to reach into this space with the expectation of a food reward. By varying the location of the food item and tracking the arm using DeepLabCut markerless pose estimation software, we characterized movement patterns used by the arm as it foraged. Our results suggest that, absent visual feedback, the octopus relies on a contact-based arm control strategy that emerges from peripheral mechanisms of sucker coordination to simplify the control of its soft, highly flexible limbs.

E – Disorders of Motor Control

1-E-41 Horizontal saccade velocity trajectories in mild TBI

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Mild traumatic brain injury (mTBI) can result in significant problems affecting vision and oculomotor function (Armstrong, 2018), vergence eye movements (Magone et al., 2014; Suhr et al., 2015), saccades (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. 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. These results have identified eye velocity patterns 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 the underlying pathophysiology affecting the control of gaze in mTBI and suggest possibilities for vision therapy.

1-E-42 Age-related differences in shoulder muscle activity and coordination reveal less directional specificity in older adults

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Many older adults have difficulty with daily tasks. Age-related differences in shoulder muscle coordination may contribute to this difficulty. Older adults with rotator cuff tears have greater muscle activity than young adults, but the effect of age cannot be isolated. Studies that isolate age from pathology remain limited; none have measured the rotator cuff muscles despite them being the most common site of age-related shoulder pathology. Therefore, our objective was to determine if shoulder muscle activity, including the rotator cuff, differs with age in those without pathology. Identifying such differences would provide insight into the aging neuromuscular system and inform treatment

approaches. 32 right-handed adults with full shoulder motion and no shoulder pain or pathology participated. Younger (8F/6M, mean±SD 27.2±5.6 years), middle-aged (5F/5M, 51.8±2.7 years), and older adults (4F/4M, 71.5±9.5 years) were included. We recorded electromyography (EMG) from 15 shoulder muscles, including fine-wire recordings of 3 rotator cuff muscles. Participants were seated with their dominant arm casted to a 6 degrees-of-freedom load cell in 90° abduction. Using visual feedback, participants held 3D shoulder torque targets at 10% and 20% of their maximum strength in 26 directions. We analyzed the impact of age on the mean, rectified EMG at each target using a linear mixed effects model (continuous factor: age; fixed factors: muscle, target level, direction; random factor: participant). To examine coordination, we used non-negative matrix factorization to identify how muscles were coactivated. We quantified the impact of age on the structure of coordination patterns and their activation across targets. Shoulder muscle activity differed with age. The effect of age varied across muscles, but in all cases resulted in more uniform activity across torque directions in older adults. Muscles active during elevation had greater activity with age in nearly all directions (slope>0.06%MVC/year, $p<0.03$). In others the effect of age was localized to specific torque directions. Muscle activity increased or decreased with age in certain directions resulting in more uniform activity in older adults. Fewer coordination patterns could explain >90% of the muscle activity in older (2.9±0.8 patterns) compared to younger adults (3.5±0.5 patterns, $p<0.001$), suggesting reduced coordination complexity with age. Although coordination structure did not vary with age, age-related differences in how these patterns were activated mirrored the differences seen in individual muscles. More uniform activity across target directions is consistent with less directional specificity and may account for the shoulder weakness seen in older adults. Altered coordination may also contribute to age-related pathology via altered joint loading. Future studies are needed to determine how age-related differences develop over time and their relationship with pain, pathology, or dysfunction.

1-E-43 Why is performance in a tracking task in individuals with Parkinson's disease not that bad?

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When moving together, tracking another person or object (e.g., dance, tai-chi, or the mirror game), there are two broad control strategies we can consider - feedback or feedforward. In a feedback strategy, the person regularly corrects their movement based on observed error. To plan movements in a more feedforward manner, an ability to predict well the movements of the other is required. Even if the person can perfectly predict the other's movement, there are situations when a more feedback-based strategy is used, for example, when the person is unable to accurately plan their desired trajectories, perhaps due to their speed or difficulty. In a tracking task, we can identify signatures of these two strategies using kinematic markers. Specifically, a subject who uses a more feedback-based strategy will show more jitter in their movements, i.e., acceleration zero crossings. A subject who uses a more feedforward strategy will show smoother movement patterns, which we have previously described as co-confident (CC) regions. In older adults, we anticipate a greater use of feedback (compared to younger adults), due to a reduced ability to accurately plan movements. In people with Parkinson's disease (PD), due to a deficit in automaticity of movements, we would expect a greater use of feedforward movements, as automatic feedback movements are less available. In this study, we tested how people with PD perform during a tracking task, specifically the one-person mirror game. In this task, the participant needs to track, using a stylus on a graphics tablet, a target that moves left and right with sinusoidal trajectories, at different frequencies and movement amplitudes. We compared a group of people with PD to an age-matched control group, and a control group of young adults. We observed, similar to our previous findings, that participants had difficulty making slow, smooth movements, and this did not differ across groups. For relatively fast movements, the younger control group were better able than the other two groups to produce smooth movements. Surprisingly, differences in the amount of CC (our measure of smooth, low-error regions) were not observed between the older control and the PD groups. The PD group did perform significantly worse in position error - how well they tracked the target. However, the lack of difference in the CC measure is likely due to their reduced jitter frequency (i.e., acceleration zero-crossings). This corresponds to the predicted greater use of feedforward rather than feedback - they selected a strategy whereby they correct their movements at a lower frequency. Hence the similarity in CC seems to be the result of two opposing factors - while people with PD in general are less accurate in their movement production, this is offset by their tendency to use less feedback (i.e., lower jitter frequency). Such compensatory strategies appear to be beneficial for people with PD to maintain adequate motor performance.

1-E-45 Motor adaptation processes decline with age, but not with Parkinson's disease

Presenting Author: Pauline Hermans

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Motor learning deficits appear with aging and even more so in people with Parkinson's disease (PD). Here, we study motor adaptation to unravel the different processes involved in motor learning, making a distinction between explicit and implicit learning. Explicit learning refers to the use of cognitive strategies, such as aiming, to improve performance. Implicit learning is involved when automatically updating an internal model of a movement, thereby reducing error between the actual and expected performance outcome. Previous research in PD showed less savings or the ability to recall the adaptation, considered a largely explicit process. Twenty four patients with PD (MDS-UPDRS III motor score 24±11, ON-medication and between 43-78 years old), 24 age-matched controls (CT, 51-71 years old) and 30 young adults (YO, 18-30 years old) made center-out reaching movements to targets with their right hand, which was occluded from vision while holding the handle of the Kinarm End-Point Lab. Subjects learned to adapt to a 40° visuomotor rotation during two learning periods separated by a 30 min break, a retention period without visual feedback and a washout period. We interspersed cued trials with veridical feedback throughout the adaptation period to measure implicit adaptation. The outcome was the angle with which the hand deviated from a straight line towards the target (°, mean±SD). Performance on the last 60 trials with rotated feedback reflected perfect adaptation. Hand angle on the interspersed trials with veridical feedback during the learning periods reflected implicit adaptation level. The explicit adaptation level was calculated by subtracting the hand angle on implicit trials from the preceding rotation trial. Savings were defined as the difference between the hand angle in the first rotation trial from the second learning period and the one from the first learning period. PD-patients and age-matched controls reached similar adaptation levels in the first and second learning periods, but adapted less than the young controls (1st: YO 33.0±3.1°, CT 24.7±6.5°, PD 21.4±8.7°; 2nd: YO 32.6±3.2°, CT 25.7±6.9°, PD 22.7±10.6°). Similarly, implicit adaptation level was lower in PD and age-matched control than in younger adults in both learning periods (1st: YO 28.0±4.3°, CT 21.1±5.6°, PD

17.8±6.9°; 2nd: YO 29.6±4.4°, CT 23.5±6.9°, PD 19.6±9.8°). We found no significant difference in explicit adaptation (1st: YO 7.0±7.0°, CT 3.2±9.2°, PD 2.4±7.6°; 2nd: YO 8.6±8.5°, CT 3.8±10.2°, PD 5.6±8.9°) or savings (YO 8.7±17.2°, CT 4.7±15.5°, PD 5.2±12.6°). While we found that age affected measures of adaptation, even though not all differences were significant, there were no major differences between PD-patients and the age-matched controls. This indicates that early learning is intact, at least in PD. In contrast to previous literature, we did not find any deficits in savings, which holds a positive message for the rehabilitation potential in people with PD.

1-E-46 Novel phenotypic test to characterize vestibular dysfunction in rodents

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Phenotypic tests designed to identify vestibular, motor, and cerebellar deficits in rodents range in their sensitivity and utility. Swimming tests are of the most sensitive, as they eliminate compensatory proprioceptive input that the animal can use to compensate for other deficits. This proprioceptive information is available in other common behavioral tests, such as in the balance beam tests. The advantage to balance beam tests over swim tests which have made them more common in the field of vestibular testing is that they permit easy qualitative analysis of animal performance based on speed of crossing (Luong et. al, 2011). In contrast, swim tests are frequently analyzed using a qualitative method in which the animal's behaviour is subjectively scored by an experimenter (Mathur et. al, 2015). Though the scored results frequently show significant differences between wild-types and mutants, the subjectivity innate to this kind of analysis could lead to issues with inter-rater reliability as well as poor identification of the precise deficits caused by abnormalities. A previous attempt to mitigate this issue was done in guinea pigs, in which the trace of the animal's movement through water is analyzed for differences (Sawada, Kitahara, Yazawa, 1994). As an additional option that gives more insight into precise animal movement, we propose a novel instrumented swim test in which a miniature head motion sensor is affixed to the top of the animal's skull while it performs the swim task. Preliminary results reveal that the data collected from the affixed 3D accelerometer and 3D gyroscope correlate with subjectively scored results. In addition, we also identify other significant movement differences between mouse genotypes when swimming such as in their power spectra of head movement, indicating that the modified swim test could be useful in identifying specific deficits.

1-E-47 Proprioceptive dysfunction after chemotherapy is linked to self-reported movement dysfunction

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Background: Oxaliplatin (OX) is an effective treatment for colorectal cancer but can cause neurotoxicity that contributes to long-term movement impairments such as dexterity loss and falls in cancer survivors. These movement impairments are often assumed to result from sensory neuropathy caused by OX-induced degeneration of sensory nerves in distal limbs. However, our recent animal studies reveal that OX causes global signaling dysfunction in muscle proprioceptors independent of sensory nerve degeneration. Proprioceptors are distributed in all muscles and encode length and force needed for accurate motor control. Unlike sensory neuropathy that primarily alters distal sensory feedback, disruptions of proprioceptors may cause widespread proprioceptive deficits that could readily lead to deficits in multidirectional and multi-segmental controls. Yet, no studies have investigated the role of widespread proprioceptive dysfunction in human cancer survivors. This study aims to fill this gap by evaluating functional use of proximal proprioception in cancer survivors post-OX. We hypothesized cancer survivors would display impaired use of proprioception in proximal joints compared to healthy controls. Methods: We recruited 13 cancer survivors and 13 healthy controls. We assessed the use of proprioception for controlling upper limb position, force, and posture using target reaching, force matching, and postural stability tasks, respectively. Each task consisted of 6 directions to evaluate the spatial consequence of proprioceptive dysfunction. We fixed the dominant hand and wrist in an orthosis to emphasize elbow and shoulder use as these joints are proximal and less likely to have sensory neuropathy. All subjects completed tasks with and without visual feedback to differentiate contributions from proprioception and vision. Self-reported symptoms and functional limitations were documented using the QLQ-CIPN20 survey. We compared the task performance of the groups using linear mixed-effect models. Results: Cancer survivors tended to rely more on visual feedback than controls when completing the tasks ($p<0.05$). When removing visual feedback, their performance was less accurate and more variable compared to controls ($p< 0.05$). Among the tasks, the force matching task was most impaired in cancer survivors, and the deficits were significantly correlated with their perceived movement dysfunction ($r=0.87$, $p< 0.001$). In a subset of cancer survivors reported the highest movement dysfunction, their force matching tended to be more impaired in the directions that require substantial use of the shoulder muscles. Conclusion: The use of proprioception was impaired in cancer survivors post-OX. The link between force matching errors and perceived motor dysfunction suggests that deficits in the force aspect of proprioception may be a risk factor for movement impairments. These identified proprioceptive deficits present opportunities for future assessments and interventions.

1-E-48 A blended experimental and computational approach reveals abnormal contribution of muscle tone to joint hyper-resistance in children with spastic cerebral palsy

Presenting Author: Jente Willaert

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The pendulum test is a clinical test to measure joint hyper-resistance. During the test, the lower leg of a seated and relaxed patient is dropped from the horizontal position (Fowler et al. 2000) and knee kinematics are recorded while the lower leg swings under the influence of gravity. With increasing levels of spasticity, as measured by the Modified Ashworth Scale (MAS), the first swing excursion (FSE) decreases. Yet, FSE is highly variable between children with cerebral palsy (CP) with the same MAS. This might be due to different contributions of neural and non-neural factors to joint hyper-resistance (Van der Noort et al. 2017). However, distinguishing these contributions based on clinical tests alone is challenging. Here, we propose a blended experimental and computational approach to identify these different contributions. Based on our recent simulation work, we hypothesized that muscle short-range stiffness (SRS) and its interaction with baseline muscle activation explains the decreased FSE in children with CP (De Groote et al. 2017). SRS is a movement-history dependent increase in muscle force upon stretch that is proportional to baseline tone. We tested this hypothesis by performing the pendulum test in different conditions designed to alter the contribution of SRS, with and without pre-movement, in children with spastic CP and typically developing (TD) children. Since SRS is movement history-dependent, pre-movement of the leg before releasing it would reduce SRS and therefore increase the

FSE. Indeed, we found an increase in FSE of 8° in TD children ($p < 0.005$) and of 21° in children with CP ($p < 0.001$) when moving the leg instead of keeping it still (Willaert et al. 2020). The larger increase in FSE in children with CP might be explained by higher baseline activity. However, baseline cannot be reliably measured based on surface electromyography data. Therefore, we modeled the lower leg as a muscle-driven inverted pendulum. Modeled muscle mechanics couple an increase in baseline tone to an increase in SRS force, muscle stiffness and damping. We then solved for model parameters, baseline activity and passive stiffness, that optimized the fit between measured and simulated kinematics. First, we found a good fit between experimental and simulated data for a wide range of pendulum test kinematics. Further, we found larger baseline muscle activation in children that had lower FSE, demonstrating the important role of increased baseline muscle activity in joint hyper-resistance. Our results have important implications. First, performing the pendulum test in two conditions might allow clinicians to distinguish neural and non-neural contributions to joint hyper-resistance, which might influence treatment selection. Second, understanding the movement history dependence of joint hyper-resistance is important to assess its role during functional movements where movement history might differ from clinical tests.

1-E-49 Determining sensory feedback during shoulder abduction in hemiparetic stroke: A pilot study.

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Despite the development of many physical interventions to promote motor recovery after stroke, rehabilitation treatments are only partially effective. This is due to many remaining gaps and shortcomings in our understanding of neural mechanisms underlying sensorimotor impairments post-stroke that inform clinical practice. Advanced methods to assess information flow between brain areas are key to understanding how the sensorimotor system in the brain adapts and reorganizes following a hemiparetic stroke. To address this problem, we developed a new multi-modal brain imaging approach that combines high-density EEG, T1 MRI, and diffusion MRI. This approach allows tracking of neural signals between cortical sources through existing neural tracts. Experiment results from three able-bodied and five stroke participants indicate its feasibility. During the experiments, EEG signals were recorded from participants while electrically stimulating their index finger (twice of sensation threshold) at the paretic (individuals with stroke) or dominant (controls) hand, where the participants were asked to perform two different levels (20% and 40% of maximum) shoulder abduction (SABD). Only brain activity that is phase-locked to the finger stimulation is analyzed to examine the information flow of somatosensory information and how it is affected by SABD loads in stroke as compared to controls. The T1 and diffusion MRI were obtained from the same participants to extract the physical neural fiber bundles in a subject-specific brain network to determine neural information flows via these bundles. For able-bodied individuals, estimated cortical sources and dynamic information flow between them were only found at the sensorimotor areas contralateral to the stimulated finger from 50-100 ms after the stimulus. Conversely, in the hemiparetic stroke participants, the activation of brain activity started contralaterally to the stimulus side but then propagated to the ipsilateral hemisphere via the corpus callosum. The average laterality index (LI) of source activity for low (20% MVT, LI = - 0.10) vs. high (40% MVT, LI = - 0.25) level SABD in stroke indicates an increased shift of sensory processing towards the contralesional hemisphere with increasing SABD effort. For controls, the laterality index (LI = 0.89 for low-level SABD and LI = 0.90 for high-level SABD) does not change much and indicates contralateral dominance of sensory processing. The enhanced inter-hemispheric interaction (degree of inter-hemisphere interaction DIH = 0.48, DIH = 0.82) for stroke shows the inter-hemisphere information transfer, while for controls they are 0 for both low and high-level SABD. These results indicate that the hemispheric shift of somatosensory information flow is associated with magnitude of SABD loads in hemiparetic stroke. The proposed method provides a quantitative tool for the determination of the reorganization of the sensorimotor network after a stroke.

F – Adaptation & Plasticity in Motor Control

1-F-50 Adaptation as a competition between two distinct sensorimotor learning systems

Presenting Author: Scott Albert

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Current models suggest that sensorimotor adaptation is supported by two distinct systems: an explicit system that can be intentionally controlled, and an implicit system that relies on unconscious correction. There are many ways that explicit strategies can be altered, such as coaching and instruction, changes in awareness, and through the recall of past actions. But rarely is it considered how these changes in explicit strategy impact the process of implicit learning. Does enhancing the explicit system suppress implicit learning, or do these two systems remain independent during adaptation? Here we show that implicit and explicit learning processes share a critical resource, error, and thus are in direct competition with each other during visuomotor adaptation. When explicit strategies increase, they take errors away from the implicit system, thus suppressing implicit learning. This error competition rule has a profound impact on measuring implicit adaptation. Common ways of assessing implicit learning (e.g., quantifying its rate or total extent) not only reflect potential changes in the implicit system, but also changes in the explicit system. Our theory shows that changes in implicit learning can have multiple origins: either changes in the actual process of implicit adaptation, or changes in explicit strategy which indirectly alter an otherwise unchanged implicit learning system. Here we show that a simple model where implicit and explicit systems compete to reduce a common error, solves a number of interesting puzzles: (1) Why does enhancing explicit strategy via coaching suppress implicit learning? (2) Why does suppressing explicit strategy by mitigating awareness of a perturbation, enhance implicit learning? (3) Why do individuals that utilize large explicit strategies, simultaneously exhibit reductions in implicit adaptation? Through a series of new experiments as well as re-analysis of earlier literature, we demonstrate that these diverse observations may in fact have a common root cause: competition for error. Critically, this theory suggests that competition can go so far as to mask changes in the implicit system, making it seem as if the implicit system is unchanged when in fact it has been altered by past experience. In particular, we consider savings: the process by which the brain more rapidly compensates for a perturbation that it has experienced in the past. The competition rule suggests that the recent inability to detect savings in the implicit learning system may be due to competition with explicit strategy. Indeed, when we tested this idea by suppressing explicit strategy, substantial levels of implicit savings were unveiled during visuomotor adaptation. In summary, the competition framework provides a simple 'language' to describe common interactions between implicit and explicit adaptation, which may in fact be masking an unappreciated flexibility in the implicit learning system.

1-F-51 The effect of tactile augmentation on manipulation and grip force control during force field adaptation

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When exposed to a novel dynamic perturbation, 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. However, the relative contribution of kinesthetic and tactile information in force field adaptation is poorly understood. We studied the effect of augmented tactile information on adaptation to a force field. Five groups of participants performed smooth reaching movements, while a velocity-dependent force field and a tactor induced velocity-dependent tangential skin deformation were applied. Two groups experienced the skin stretch deformation in the same direction as the force field, each with a different level of stretch: high level (gain=100, maximal tactor movement of 2.5mm) and low level (gain=50, maximal tactor movement of 1.25mm). Additionally, two groups experienced skin stretch in the opposite direction to the force field (gain=-50,-100). A control group received only the velocity-dependent force field (gain=0). We also recorded the EMG signal from participants' muscles. We found that adding skin deformation did not affect the kinematics of the movement during adaptation. However, the tactile stimulation did affect the control of manipulation and grip force. To examine the effect on the manipulation forces, we calculated the adaptation coefficient as the slope of the regression between the two signals of manipulation and load forces. The results showed that adding skin stretch in the same direction as the force field (gain=50,100), and low-level skin stretch in the opposite direction (gain=-50) resulted in a smaller adaptation coefficient with respect to the control group, leading us to conclude that these conditions impaired the adaptation. Regarding the grip force control, we found an increase in the applied grip force for the two groups with skin stretch in the same direction as the force field (gain=50,100), in both the predictive and reactive components. However, during the adaptation process, the reactive component of the grip force decreased for the low-level group (gain=50), while for the high-level group (gain=100) both the predictive and reactive components increased throughout the adaptation. Modeling the adaptation process with a state space model showed that a possible mechanism accounting for our results is that the skin stretch caused a sensation of slippage, which affected the arm stiffness. Understanding the effect of augmented tactile information on the internal representations for manipulation and grip force control can shed light on the sensory processing of dynamic interaction with the environment, and is important for applications in which force feedback can be delivered using tactile devices.

1-F-52 How the consequence of movement error affects sensorimotor learning

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To safely navigate our environment, we must carefully consider the consequences of our actions. As maintaining balance is a primary objective of the nervous system, this requires consideration of any threats to stability and the consequences associated with falling. We propose that the potential injurious consequences of being inaccurate and losing balance may serve to augment the value of

movement errors experienced during adaptation and enhance sensorimotor learning. To test this hypothesis, we encouraged two groups (n=12 each) of participants to adapt to a novel visuomotor mapping induced by prism lenses while performing a precision walking task. In this task, participants stepped with their right foot onto the centre of a target positioned along the middle of the walking path. Participants performed this task with or without experiencing a slip perturbation when making foot-placement errors to a target. We designed this manipulation to simulate slipping during walking and to serve as a stability consequence for movement errors. We then probed how exposure to this stability consequence affected generalization and motor memory consolidation. We assessed generalization in two ways. First, during an interlimb-transfer test where participants used their left foot instead of their right foot to step to the target. Second, during an obstacle-avoidance task performed without the prism lenses where participants walked and stepped laterally over the middle of a 25cm high obstacle, first with their left leg (i.e., the leading leg), then their right leg (i.e., the trailing leg), before continuing to walk for several more steps. We used two-way (Group x Phase) mixed model ANOVAs to identify group differences. We found that while both groups demonstrated interlimb-transfer to the un-adapted left leg during the precision walking task, the stability consequence significantly enhanced this generalization (Group x Phase interaction: $F(1,22)=12.71$, $p=0.002$). Additionally, only the consequence group generalized learning to the leading leg (Group x Phase interaction: $F(1,22)=16.18$, $p=0.0006$) and trailing leg (Group x Phase interaction: $F(1,22)=10.98$, $p=0.003$) during the obstacle-avoidance task. To assess consolidation, we introduced an opposite direction visuomotor mapping following initial adaptation and evaluated relearning one week later. We found that the consequence group demonstrated significantly greater motor memory consolidation, reflected by a greater reduction in first adaptation trial error (i.e., initial recall) (Group x Phase interaction: $F(1,22)=18.18$, $p=0.0003$) and faster relearning (i.e., savings) (Group x Phase interaction: $F(1,22)=7.98$, $p=0.009$). Overall, our results demonstrate that experiencing a physical consequence when making errors enhances sensorimotor learning.

1-F-53 The age-related deterioration in dual-task performance is accompanied by a failure to upregulate brain activity

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The ability to perform simultaneous cognitive and motor tasks, such as talking while cooking, is important for everyday functioning. Although an age-related decline in dual-task ability is well established, most research focuses on lower limb tasks. Furthermore, less is known about the neural correlates of the age-related dual-task decline. Because older compared to younger adults already show higher brain activity during single motor tasks, it is possible that a ceiling level in terms of neural resources underlies the age-related decline in dual-task performance. To examine this hypothesis, the current study aimed to determine age-related differences in the neural correlates of dual-task performance. Healthy younger (N=12, age=20.9±1.5 yr) and older (N=12, age=69.7±2.9 yr) adults performed a visuomotor mirror star tracing task both without (single-task) and with a concurrent visuospatial memory task (dual-task) while concurrently electroencephalography (EEG) was measured. Before executing both task conditions, participants practiced the visuomotor task for approximately thirty to sixty minutes. Motor performance was measured in terms of both speed and accuracy. Tracing speed did not differ between single- and dual-task conditions in the two age groups. However, tracing accuracy during the dual- compared to the single-task condition decreased by 74.3% in older adults ($p<0.001$), while motor performance was not affected by the concurrent visuospatial memory task in younger adults (22.4% decrease in accuracy, $p=0.37$). Interestingly, there was a 33.9% decrease in frontal task-related power in the alpha frequency band (8-12 Hz) when performing the dual- compared to the single-task condition specifically in younger adults ($p<0.001$), while no changes in brain activity occurred in older adults (3.7% decrease, $p=0.58$). This upregulation of frontal alpha activity is presumably related to the increased attentional demand of the concurrent visuospatial task, even though there was no correlation between behavioral and neural measures. The absence of changes in brain activity in older adults together with the deterioration in tracing accuracy suggests that the age-related deterioration in dual-task performance was accompanied by a failure to upregulate brain activity to deal with increased task demands.

1-F-54 Sensitivity to error during visuomotor adaptation is similarly modulated by abrupt, gradual and random perturbation schedules

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It has been proposed that during sensorimotor adaptation the generation of sensory prediction errors engages two processes (fast and slow) that differ in retention and error sensitivity. Previous work from our lab has shown that repeated exposure to the same force-field perturbation results in greater error sensitivity for both processes. While it has been proposed that the motor system must store some component of prior training to speed up subsequent learning, it remains unclear what aspects of prior experience modulate error sensitivity. In the present study, we manipulated the initial training using different perturbation schedules and then observed what effect prior learning has on subsequent adaptation. It has recently been proposed that in the context of visuomotor adaptation, the fast and slow processes reflect explicit and implicit learning mechanisms, respectively. Based on this idea, we used two different adaptation schedules thought to differentially affect explicit and implicit learning, to test the idea that error sensitivity for fast and slow processes can be independently modulated. One group of participants was exposed to a gradual perturbation schedule during initial training. When a perturbation is gradually introduced, such that participants never experience large errors, learning is believed to be more implicit in nature. We predicted that when participants in this group were later tested on an abrupt perturbation, only the slow process would be affected by the initial training, compared to a control group who were initially trained using an abrupt perturbation. For a second group of participants, initial training was based on a structural learning paradigm, involving a series of brief exposures to large, random perturbations. This adaptation schedule is thought to be based on explicit learning mechanisms. For this group we predicted that when later tested on an abrupt perturbation, only the fast process would be affected by the initial training, as compared to the control group. Using a two-state model of adaptation, we estimated retention and error sensitivity parameters for the second session of each group and the first session of the control group. The model estimates function as a tool for understanding how the underlying processes of adaptation were affected by the prior training. Comparing the two sessions of the control group, we confirm that repetition of the same perturbation results in an increase in error sensitivity for both processes. By comparing the model estimates of participants in the gradual and structural learning groups to the first session of the control, we expected to see changes in error sensitivity that depended on the type of prior training participants experienced.

Interestingly, however, we found that error sensitivity of both the fast and slow processes was increased for both groups. We discuss the findings in the context of how fast and slow learning processes respond to a history of errors.

1-F-55 The necessity of a performance asymptote for overlearning to enhance retention
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Although overlearning (i.e., continued practice beyond the point at which performance stabilizes at asymptotic levels) is reported to enhance retention, it remains unclear if it is the asymptote per se that is required for such benefit to occur, or merely the increased number of trials that is associated with it. Shibata et al. (2017 Nat Neurosci) argued that practicing at asymptote increases neural inhibitory activity, thus protecting the newly acquired memory and enhancing retention. Interestingly, Alhussein et al. (2019 J Neurophysiol) manipulated the learning rate by having participants adapt to a gradual (no asymptote) or abrupt (asymptote) training session, and reported similar levels of retention. In this light, the objective of this project was to compare levels of immediate retention between conditions that differed with respect to the possibility for performance to stabilize at an asymptote, but that were matched in terms of the number of practice trials. In a fully within-subject and counterbalanced design, four conditions were carried out in which participants (preliminary n = 6; final n = 24) adapted to a gradually introduced 20° visual deviation while the presence (or absence) and duration of the performance asymptote were manipulated. When present, the performance asymptote at 20° was either Short (40 trials), Moderate (160 trials), or Long (320 trials). When absent, the visual deviation also gradually increased to 20° but then kept on continuously changing around 20° for 160 trials (Jagged). For each condition, immediate retention was assessed through reach aftereffects in the absence of corrective visual feedback. Preliminary results (n = 6) indicate that retention monotonously increased from the Short to the Moderate to the Long condition, indicating that retention is a function of the asymptote duration. However, the Jagged condition showed similar levels of retention as compared to the Moderate condition. One preliminary conclusion is that preventing performance from stabilizing at asymptote triggers a similar neural state that promotes memory stabilization.

1-F-56 Using online collection of hand tracking data in virtual reality: A proof of concept study with visuomotor adaptation of grip aperture
Presenting Author: Peter Holland
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Traditional motor learning experiments often require expensive specialist equipment and the presence of participants in the laboratory. Experiments also often take place in simple environments that little resemble the real-world. Virtual reality (VR) provides a chance to overcome these issues, with deeply immersive environments allowing naturalistic movements in 3D. In particular, the Oculus Quest VR headsets are relatively inexpensive and do not require a high-end PC, increasing their usability and uptake. Crucially, real-time marker-free hand tracking is present on these devices. This technology tracks the position and posture of the hands in real time using only the cameras on the device itself. This enables the presence of hands with individuated finger movements in VR. We have developed a way to collect the position of 20 markers on the hand alongside key experimental variables on each frame.

Importantly, data is recorded online and can be collected from any Quest device in the world with an internet connection, massively expanding the number and diversity of potential participants. A potential application of this technology is in post-stroke rehabilitation. 75% of stroke survivors suffer from long-term upper limb impairments. Recently, it has been shown that significant improvements of upper limb function are possible, even in the chronic stage of stroke. However, this requires a high-volume of rehabilitation, which is unfeasible in most healthcare systems. Developing at-home rehabilitation technologies is therefore critical to supplement in-clinic practices. Previously, augmentation of movement of the paretic arm has been shown to decrease learned non-use of the limb. Loss of the ability to fully open and close the hand following stroke can have a devastating impact on activities of daily living. We hypothesise that augmentation of hand function in VR may encourage use of the affected hand and provide real world clinical benefits. As a proof of concept for the use of these tools we designed and implemented a VR environment (Sub Escape). As in a traditional tracking task, participants were instructed to match a constantly changing and unpredictable target. The target represented a desired grip-aperture and participants had to open or close their hand to match the target in real time. In the baseline phase of the task the aperture of the virtual hand was yoked to that of the real hand. However, we then introduced a gain which leads to exaggerated movements in the virtual world. Participants successfully adapted to this change and also show de-adaptation when the relationship between virtual and real hand was restored to baseline levels. The introduction of marker-free hand tracking to Oculus Quest devices is potentially revolutionary for motor learning research and rehabilitation. We show here that we can collect data on the position and posture of the hands remotely in an adaptation experiment.

1-F-57 The dynamics of memory consolidation in visuomotor adaptation: Memory stabilization prevents decay

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Memories are considered to be consolidated when they are no longer susceptible to interference by new information. When learning is followed by a period of quiescence, memory traces stabilize, leading to long-term memory. Conversely, if learning is followed by exposure to conflicting information the process of consolidation is disrupted, leading to interference. Recently, we showed that anterograde interference impairs the ability to adapt to a visuomotor rotation within a 6 hs time window. Here, we used the same experimental protocol to examine the time course of motor memory consolidation and whether it relates to the rate of forgetting. To this aim, we first exposed four groups of subjects to learn two opposing 30-degree visuomotor rotations that were separated by either 5 min, 1 hs, 6 hs or 24 hs, while a control group was only exposed to the second rotation. All subjects returned 24 hs later to assess long-term memory retention. We found that even though all groups reached the same level of asymptotic performance during training (Kruskal-Wallis, $X2(89) = 7.22$, $p = 0.13$), memory retention differed across groups (Kruskal-Wallis, $X2(87) = 32.87$, $p < 0.001$). Retention was severely impaired in the 5 min and 1 h group (Dunn's test with Bonferroni correction, both different from control with $p < 0.001$), but recovered to control levels in the 6 hs and 24 hs groups (not different from control with $p > 0.88$). This result was strengthened by a set of control experiments that ruled out potential confounds related to differences in the amount of overlearning and forgetting across groups. Next, we asked whether the stabilization of the memory trace observed around 6 hs post training, would impact on the rate of decay. If so, memories encoded during training in the same experimental paradigm should decay during the first 6 hs post training but not thereafter. To test this hypothesis, we exposed 7 groups of subjects to a visuomotor rotation of the same magnitude and quantified memory retention at different time intervals from 1 min to 24 hs. As predicted, we found that memory decayed (One Way ANOVA, $F(147,6) = 26.3$, $p<0.001$) monotonically but reached an asymptote at 5.5 hs post training (One way ANOVA, followed by Tukey's test, 5.5 hs group did not differ from the 9 hs nor the 24 hs group with $p>0.99$). Altogether, our findings provide compelling behavioral evidence suggesting that visuomotor adaptation memories consolidate within a ~6 hs time window.

1-F-58 The role of effort in motor learning

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Understanding the process of learning and maintaining movement adaptations in changing environments provides important insights to movement control and is especially relevant for understanding movement disorders and enhancing rehabilitation. In the process of learning a new motor task, there are three rates of interest: 1) the learning rate, a factor of skill performance in new and changing environments, 2) the retention factor, reflecting the amount of adaptation retained over subsequent repetitions in the absence of feedback, and 3) the savings rate, a learning rate associated with relearning the task after washout (Krakauer 2009, Galea 2015). Previous research has shown that reward and punishment, monetarily valued or as points-based scores, can modulate the rate of learning, relearning, and forgetting (Nikooyan 2014, Galea 2015). Other evidence suggests that cognitive effort, induced through randomized task order during learning, may enhance motor learning (Frömer 2016). The role of physical effort, effort associated with completing the movement itself is less understood. In this study, we examine the effects of an error-encoding effort cost on learning rate, retention, and savings. Participants held the handle of a robotic arm and made 10 cm out-and-back reaching movements to one of eight possible targets positioned at 45-degree increments around the center of a home circle. They performed a visuomotor rotation (VMR) task, consisting of five phases: baseline, adaptation with a 30-degree visuomotor rotation , retention, washout, and savings in which participants were re-exposed to the 30-degree rotation. We adapted the traditional VMR task such that the robot consistently produced a damping force, in the opposite direction of hand motion. Participants were divided into two groups: an error-dependent effort cost where damping on the following trial increased with increasing error on the previous reach (N=5) and a constant effort group where the damping constant was 20 Ns/m regardless of the error of the previous reach (N=4). To quantify learning rates in the adaptation and savings phases, we fit a state-space model to individual subject data. Preliminary findings show both participants in both groups adapt to the VMR and exhibit savings. Average savings rates were 9.73 (± 8.69) [mean(± SD)] times higher than initial learning rates in the error-dependent damping condition, and 3.44 (± 2.10) times higher in the constant damping condition, with no statistical difference between groups ($p> 0.3$). Further data collection will help elucidate the role, if any, of effort in driving or inhibiting motor adaptation.

1-F-59 Training induced plasticity in sensory feedback following incomplete spinal cord injury

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Spinal cord injury not only disrupts motor commands descending from the brain but also causes malfunctions of the intrinsic circuitry of the spinal cord that arise from sensory feedback and supports coordinated movements. One component of this sensory feedback is a neural network arising from Golgi tendon organs, force receptors in the muscles, that link muscles throughout the limb. This network, together with feedback from muscle spindles, regulate the mechanical properties of the limb and contributes to the coordination of joints through inhibitory actions on motoneurons. Alterations in the organization of this network following incomplete spinal cord injury and subsequent rehabilitative training are being assessed at Georgia Tech as part of a larger study based at the University of Louisville that includes the effects of these manipulations on motor behavior and spinal cord histology. We have shown that the intermuscular force feedback network is reorganized and not simply amplified following lateral hemisection of the thoracic spinal cord in animal subjects. The strength of force feedback between muscles becomes highly imbalanced following injury so that the inhibition is greatly amplified in some directions and greatly reduced in others. Previous work has shown, in conditions mimicking downhill walking the inhibitory force feedback network is upregulated (Nichols et al., 2014). Based on this observation, we are investigating whether eccentric training (walking downhill) can return the network to more normal levels of inhibition and reestablish the patterns of feedback. In this blinded study, I have been successful in identifying the animals that received training on the basis of alterations in the inhibitory force feedback networks. We also are investigating the effects of eccentric training on length feedback. Previous work in our lab has shown a non-uniform upregulation of the stretch reflex in feline hindlimbs with thoracic lateral hemisections. Preliminarily, we see the stretch reflex across the hindlimb extensor muscles is the smallest in the eccentrically trained animals. Although we see some changes in the length feedback system, the force feedback system shows greater disparities following spinal cord injury and is imperative for restoring coordinated movements critical for locomotion.

1-F-60 Dissecting brain networks involved in sensory function using passive movements

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Somatosensory function involves position sense and movement sense, which arise from proprioceptive receptors located in the joint, the surrounding muscles and skin. Here, we make use of repetitive passive limb movements to isolate cortical processing of somatosensation thanks to frequency tagging. This technique based on "steady state evoked potentials" (Regan et al,1977) is based on the fact that the brain generates neural activity at a frequency that is similar to the frequency of the input signal. Here, we extend this technique to somatosensory processing by using repetitive passive limb movements in order to localize the different brain regions whose activity oscillates at the same frequency as the passive movements. To our knowledge, touch and proprioceptive feedback elicited using passive movements have only been explored in the fingers and lower extremity (Piitulainen et al, 2018). In our experiment, 25 healthy young adults performed passive movements on a robotic manipulandum. Following a 5 second rest (baseline), the robot pushed the arm passively at frequency F between two points placed at a distance D. In the first condition, we varied the frequency while keeping the distance constant (D= 2 cm and F= 1, 2 3 or 4Hz). In the second, we varied the distance but kept the frequency constant (F= 3 Hz and D= 0.5, 1, 1.5, 2 or 2.5 cm). Participants' brain activity was measured using a 128-channel high density Electroencephalography (EEG) system. In the left sensorimotor region, we compare the peak power at the frequency F between movement vs rest. Across all conditions, peak power measured at the frequency F in the left sensorimotor area was significantly higher than peak power during rest at the same frequency. For the constant distance condition, we performed a 2-way ANOVA with the frequencies (1, 2 3 and 4Hz) and period (passive movement vs baseline) as within subject factors. Peak power was higher during passive movements than during rest ($p=0.0023$, $\eta p2=0.51$). This difference was slightly larger in the conditions with higher frequencies (3 and 4Hz, main effect of frequency: $p=0.031$, $\eta p2=0.39$; frequency X period: $p=0.06$, $\eta p2=0.38$). For the constant frequency condition, we performed a 2-way ANOVA with the distances (0.5, 1, 1.5, 2, 2.5 cm) and the period (movement and baseline) as within subject factors. Peak power around 3Hz was higher during passive movement compared to baseline (main effect, $p<0.0001$, $\eta p2=0.12$). These values were slightly modulated with distance, being higher in the conditions with larger distances (2 and 2.5 cm, main effect of distance: $p=0.09$, $\eta p2=0.44$; distance X period: $p=0.0936$, $\eta p2=0.44$). Our results suggest that repetitive passive arm movements elicit steady-state evoked potential in the left motor region. The brain regions that exhibit a similar frequency response will be determined via source localization techniques. Our study represents a novel way to measure the neural correlates of somatosensory processing

1-F-61 Generalization of motor learning in psychological space

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To generate adaptive movements, we must generalize what we have previously learned to novel situations. The generalization of learned movements has typically been framed as a consequence of neural tuning functions that overlap for similar movement kinematics. However, as is true in many domains of human behavior, situations that require generalization can also be framed as inference problems. Here, we attempt to broaden the scope of theories about motor generalization, hypothesizing that part of the typical motor generalization function can be characterized as a consequence of top-down decisions regarding the degree to which an individual believes that two scenarios are similar and demand similar actions. Across five experiments, we tested this idea by measuring people's subjective similarity judgments over both traditional dimensions believed to dictate motor generalization (i.e., movement direction) and novel abstract dimensions (i.e., target shape) in a standard visuomotor rotation task. We found that subjective judgments about different kinematic contexts could explain a significant portion of variance in the generalization of learned sensorimotor behaviors (Experiment 1). Second, we found that the correlation between subjective similarity and motor generalization was above and beyond what could be explained by just perceptual constraints (Experiment 2) or kinematics alone (Experiment 3). Moreover, explicit instructions about the "consequential" dimension of movement contexts determined how people generalized (Experiment 4). Lastly, we confirmed that the above effects were driven by a top-down, cognitive component of motor learning, rather than an implicit, procedural component (Experiment 5). Taken together, our results reveal an important role for cognitive inferences in shaping motor behavior. This study has implications for understanding the neural representations involved in motor learning and may help predict why and when motor generalization behavior diverges from conventional models of sensorimotor adaptation.

1-F-62 Direct measures of implicit learning hit ceiling within 1-4 trials of training regardless of feedback

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People can quickly adapt their movements to various perturbations, which is usually attributed to explicit components. However it is unknown how quickly implicit components of learning emerge, as this has never been measured directly but has merely been inferred as the residual aspect of explicit learning. Here, we will discuss a series of experiments where we directly measure implicit components of learning, like reach aftereffects and changes in estimates of hand location, following every single training trial when reaching with a 30° visuomotor rotation. In stark contrast to the assumption that the implicit stage of learning is slow, we find that these direct measures of implicit learning asymptote almost immediately. In our first study, reach aftereffects and changes in hand localization hit their usual maximum magnitude within respectively three and one training trials. In our second study we test if and by how much this rapid implicit measure of learning can be slowed. We test both terminal cursor feedback as well as the absence of movement during training ("passive exposure"), so that there are no sensory prediction errors guiding adaptation. But hand localization shifts still saturate within 3-4 trials. Even in our third study, where we change the perturbation size and direction every 12 trials, we see immediate changes in reported hand location. In short, while updated estimates of hand position and reach aftereffects do not reflect explicit strategies to counter a perturbation, they change very quickly and robustly. Our results also challenge the untested assumption that the time course of implicit learning can merely be inferred from that of explicit learning. These two processes likely occur simultaneously and mostly independently.

1-F-63 Gradual exposure to Coriolis forces induces adaptive changes in sensorimotor control but not in the representation of peripersonal space

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The space surrounding the body is crucial for the organisation of voluntary motor actions directed at nearby objects. This space seems to be functionally represented in the brain in particular in relation with motor functions, and is known as peripersonal space. However, despite a large number of studies, how the peripersonal space is represented and changes according to new action capacities remains unclear. It was recently shown that the representation of peripersonal space contracted following abrupt exposure to a new force field, suggesting a conservative spatial strategy triggered by consciously perceived motor errors. In the present study, we assessed the impact of a gradually-increased force perturbation, produced by a rotating platform, on the representation of peripersonal space on 16 young adults. We hypothesized that such gradual exposure would produce sensorimotor adaptation to not-consciously perceived motor errors, but that reachability judgments, used as a proxy of peripersonal space representation, would not be affected. Results showed a systematic after-effect on reaching movements, similar to the motor changes usually observed with an abrupt change of force field, but no significant change in the representation of peripersonal space. Overall, the findings suggest that the conscious experience of motor errors may represent a key component of plasticity of peripersonal space representation.

1-F-64 Thigh musculature motor unit characteristics associated with anterior cruciate ligament injury and arthrogenic muscle inhibition

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Introduction: Arthrogenic muscle inhibition (AMI), characterized as a reflex inhibition of joint musculature after joint injury, is responsible for quadriceps atrophy following knee injury. The exact mechanisms of AMI after anterior cruciate ligament (ACL) injury remain unclear. Decreased volitional force output associated with AMI may be caused by altered afferents which could reduce efferents from motor neurons, likely characterized by lower MU firing frequency, action potential, and recruitment threshold of the motor units (MUs). This study compared MU behavior in ACL injured subjects before and after ACL reconstruction (ACLR) compared with Controls. Methods: 56 subjects (31 ACL injured) participated in the study (32 female; age: 19.0±3.1 yrs; height: 173.9±8.6 cm; weight: 72.9±15.0 kg). Subjects underwent longitudinal data acquisition at intervals of pre-surgery, 6 months, and 12 months post-ACLR. Subjects sat on a dynamometry chair in a self-selected, relaxed position. Surface EMG was recorded with 5-pin array dEMG sensors (Delsys; Natick, MA) at 20 kHz. Standard EMG preparation was performed with electrodes placed on vastus medialis (VM) and vastus lateralis (VL) according to SENIAM standards. EMG signals from four pairs of the sensor electrodes were differentially amplified and filtered with a bandwidth of 20-450 Hz. Three maximal voluntary isometric contraction (MVIC) trials were conducted, and the peak force was determined to establish 10, 25, 35, and 50% MVIC. In random order, subjects followed a trapezoidal shape isometric contraction with %MVIC held for 10 seconds. Following data acquisition, post-processing decomposition of the EMG occurred with Delsys dEMG Analysis software. MU data of average firing rate, MU amplitude, and recruitment threshold were extracted and analyzed with JMP 14 (SAS; Cary, NC) via least squares linear regression. Results: Quadriceps MU average rate coding by recruitment threshold (R2=0.09) demonstrated that all time points of ACL injured had lower rate coding across recruitment levels for the VL ($p<0.001$) compared to controls, and for the VM at ACL pre-surgery ($p<0.001$). The VM recovered MU average rate coding by 6 and 12 months post-ACLR. Quariceps MU peak-to-peak amplitude (a surrogate of MU size) by recruitment threshold (R2=0.40) demonstrated that all time points of ACL injured had lower MUAP across recruitment ($p<0.001$) compared to controls with the sole exception of the VM of the ACLR 12mo group. Conclusions: Quadriceps MU activity are significantly altered after ACL injury, post-ACLR, and throughout rehabilitation compared to healthy controls. Rehabilitation and targeted intervention programs should monitor MU activity to assess altered motor activity and motor control schemes that may not be evident in clinical and functional examinations, but could contribute to lack of motor control and increased risk of second ACL injury.

1-F-65 Preliminary evidence for short-term retention of increased paretic propulsion after intermittent exosuit assistance in people post-stroke with moderate propulsion deficit

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Stroke is a leading cause of disability, often causing slow and asymmetric gait due to reduced paretic propulsion. Unilateral soft ankle exosuits for stroke survivors can improve paretic propulsion when actively applying plantarflexion forces to the paretic ankle. Yet, the underlying gait adaptations during active assistance and the translation of these changes to post-active gait remains understudied. Intermittent assistance (IA) is a paradigm wherein the exosuit serially switches between active and unassisted modes during gait, thereby capturing short-term retention of learned motor patterns, which can provide insight into the rehabilitation potential of a robotic intervention as well as user-specific response. The immediate release of cable tension while walking in a soft exosuit enables abrupt switching to the unassisted, transparent mode, a challenge with rigid robots given their inertial properties. Here, we posited that applying IA with a soft exosuit would result in short-term retention of increased paretic propulsion during post-active gait with respect to baseline. Four chronic post-stroke subjects (S1-4; 49.5±12yr, 4M) walked at their comfortable walking speeds on an instrumented treadmill for one baseline (4min) and three IA (6min) bouts. Each IA bout comprised alternating 2-min assisted and 1-min unassisted sections. Average unassisted peak propulsion (Pmax) was compared between the baseline and final IA bouts. Secondary analyses of baseline paretic propulsion symmetry (Pp) and the correlation between Pmax and peak biological ankle torque (Tmax) were conducted to probe user-specific factors. S1 and S2 increased Pmax relative to baseline by 1.2%BW and 3.2%BW respectively ($p<.0001$), while S3 and S4 showed no significant changes. Retention in S1 and S2 exceed the within-day minimum detectable change for Pmax, 0.8%BW, and are thus clinically relevant. In a follow-up test with S2, the subject walked in the unassisted mode on a time-matched schedule, and observed no change in Pmax, suggesting changes seen with IA are not due to walking practice alone. Secondary analyses of Pp showed that S1 (Pp=0.26) and S2 (Pp=0.29) had moderate propulsion impairment, while S3 (Pp=0.40) and S4 (Pp=0.17) were mildly and severely impaired, respectively. Moreover, adjusted correlations between unassisted Pmax and Tmax were stronger in S1 ($R^2=0.44$, $p<.0001$) and S2 ($R^2=0.41$, $p<.0001$), than S3 ($R^2=-0.01$, $p=0.9239$) and S4 ($R^2=0.11$, $p=0.0014$). This suggests that subjects with moderate propulsion deficits (Pp~0.27), who use ankle torque to modulate Pmax during IA may best retain increased propulsion during post-active gait. These initial data show that IA can measure short-term retention in post-active paretic limb kinetics and variation in user adaptations. Future work will increase sample size to evaluate the use of IA to identify subjects appropriate for exosuit-based gait rehabilitation for improving paretic propulsion and ultimately gait function.

1-F-66 Sensorimotor and cognitive changes as a result of long duration spaceflight

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Astronauts returning from spaceflight can show transient declines in mobility and balance performance. These vestibularly-mediated behaviors have been investigated thoroughly, yet investigation of the effects of spaceflight on other sensorimotor behaviors is sparse. Here, we aimed to understand the effects of spaceflight and microgravity on a variety of sensorimotor and cognitive tasks both during and following ISS missions. We obtained mobility (Functional Mobility Test), balance (Computerized Dynamic Posturography), bimanual coordination (Purdue pegboard), motor-cognitive dual tasking and visuomotor adaptation measures, in addition to a variety of cognitive measures (Digit Symbol Substitution Test, Cube Rotation, Card Rotation, Rod and Frame Test) before, during and after astronauts (n=15) underwent 6+ month missions to the International Space Station. Functional neuroimaging data were also gathered during the visuomotor adaptation task before and following spaceflight. We used linear mixed effect models to analyze performance changes due to the microgravity environment, behavioral adaptations aboard the ISS and recovery from microgravity. We identified declines in mobility and balance from pre to postflight, suggesting possible disruption and/or downweighting of vestibular inputs; these behaviors recovered to baseline levels within 30 days postflight. Bimanual coordination declines were identified pre to postflight suggesting possible upweighting of tactile inputs during spaceflight; recovery to baseline levels was also evident within 30 days postflight. There were no performance changes in dual task cost during or following long duration spaceflight. Cube rotation response time significantly improved pre to postflight and showed significant improvements from preflight to their arrival aboard the ISS where the astronaut is tethered into the testing setup with their feet attached to the "floor". Free-floating performance on the ISS did not improve, suggesting that tactile inputs to the foot sole aided orientation. Analysis of the visuomotor adaptation and neuroimaging data is ongoing. Overall, these results indicate sensory reweighting due to the microgravity environment of spaceflight. The absence of gravity and decreased use of the legs coupled with an increased reliance on hands and arms for propulsion around the ISS likely promotes central nervous system sensory re-weighting to favor tactile inputs. It may also be that there is a shift from exocentric (gravity) spatial references towards an egocentric spatial reference. Upon return to Earth, adaptions become maladaptive, resulting in transient sensorimotor performance declines. Cognitive changes are likely due to increased tactile feedback that would provide additional orientation cues to assist mental rotation performance.

1-F-67 Isolating explicit aiming from sensorimotor adaptation

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Recent work has shown that visuomotor adaptation comprises multiple learning processes which include explicit and implicit components. Here, we present a novel task designed to isolate explicit aiming from motor noise and implicit sensorimotor adaptation. Our participants have unlimited time to aim and fire a cannon at distal targets. The cannonball impacts at a fixed radial distance. Angular errors are introduced to the cannonball's flight with Gaussian noise (3° STD) and a fixed angular rotation during learning epochs. This task emulates traditional visuomotor rotations, but with full control over the relationship between explicit aim and errors. We eliminate implicit motor learning by randomizing the cannon's initial aim angle so the ideal change in aim for each trial requires a unique series of key presses that is counter-balanced in direction (CW or CCW key) over trials. Participants (n=98) aimed the cannon at a single target in a series of six learning blocks (separated by baseline and washout phases) where feedback was rotated by ±15/30/45° or ±45/60/90°. Participants rapidly corrected for the perturbations within 3.1 ± 0.2 trials. When the perturbation was removed, they returned to aiming to the target within 2.3 ± 0.1 trials. We further explored this explicit learning by exposing participants (n=30/rotation size) to ±15/30/45/60/90° rotations at 8 targets spaced in 45° increments around 360°. Participants compensated for the rotation within 1.3 ± 0.3 target cycles and returned to aiming directly at the target in washout within 0.5 ± 0.1 target cycles. In both experiments, compensatory aiming largely changed in a single step, jumping from direct target aiming to a new ideal aim point that compensated for the rotation. This change in aim was consistent with a sudden "aha" from insight learning, rather than a trial-and-error pattern of reinforcement learning or the graded sign-opposite adjustment of error-based supervised learning. In a further set of experiments with either one or eight targets, we simulated implicit adaptation in response to errors with a single-process generalizing state-space model that adapted the mapping between cannon aim angle and feedback. Participants (n=151) were exposed to ±15/30/45/60/90° rotations, and they rapidly changed aim to reinstate good performance. However, as the simulated implicit adaptation also compensated for error, participants continuously decreased the magnitude of their re-aiming over the learning block in the same manner as traditional reaching tasks (Bond & Taylor, 2015). Participants also aimed in the opposite direction to compensate for the "implicit" aftereffect in washout trials. Our results approximate explicit aiming in reach adaptation sufficiently well to serve as a model task for this form of learning. Our task offers a powerful tool for insight into explicit aiming in visuomotor adaptation because of its full experimental control over simulated motor noise and implicit adaptation.

1-F-68 Reflex gains reflect evidence accumulation and changes of mind

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Decision making and motor control appear inseparable. The brain's decision processes provide a continuous flow of information to the motor system, allowing it to prepare for eventual action and outcome following the accumulated evidence of an evolving decision. Indeed, recent work has shown that reflex gains of muscles are tuned to the process of decision formation (Selen, Shadlen, & Wolpert, 2012). Continuous flow also implies that the information stream is not only sampled before the action, but also during the action, which could lead to a revision of the action, called a change of mind (CoM). In support, when participants are asked to indicate the direction of a random dot motion (RDM) stimulus by reaching towards one of two targets, they occasionally change the trajectory midway to indicate the other choice (Burk, Ingram, Franklin, Shadlen, & Wolpert, 2014; Resulaj, Kiani, Wolpert, & Shadlen, 2009). To explain these findings, Resulaj et al. extended a drift diffusion model by adding new bounds in the post-decision period to change or reaffirm the initial decision. In this study we ask whether the preparatory state, in terms of the reflex response, differs between CoM and non-CoM trials and whether this matches the predictions from Resulaj et al's model. Participants (n=16) viewed an RDM stimulus and indicated the perceived motion direction by making a goal directed reaching movement with a robotic manipulandum. The RDM stimulus was extinguished after a random viewing duration and the robotic manipulandum quickly stretched the pectoralis muscle at the same time, which was the imperative to indicate the perceived motion direction. The goal directed reaches allowed for revising the initial choice based on information that had not yet been processed at movement onset. Using EMG, we quantified the reflex gains of the pectoralis and deltoid muscle. As expected, our subjects showed a significant number of CoM trials, that improved performance (Resulaj et al., 2009). Furthermore, reflex gains did scale with both the coherence level and viewing duration of the dots (Selen et al., 2012). Currently we explore whether reflex gains in CoM trials systematically deviate from the reflex gains in corresponding (in terms of viewing duration and coherence) non-CoM trials. We hypothesize that reflex gains will be smaller in CoM trials, as the decision variable in CoM trials is supposed to have drifted less far from its neutral value. References: Burk, D., Ingram, J. N., Franklin, D. W., Shadlen, M. N., & Wolpert, D. M. (2014). Motor effort alters changes of mind in sensorimotor decision making. PLoS One, 9(3), e92681. doi:10.1371/journal.pone.0092681 Resulaj, A., Kiani, R., Wolpert, D. M., & Shadlen, M. N. (2009). Changes of mind in decision-making. Nature, 461(7261), 263-266. doi:10.1038/nature08275

Selen, L. P., Shadlen, M. N., & Wolpert, D. M. (2012). Deliberation in the motor system: reflex gains track evolving evidence leading to a decision. J Neurosci,

1-F-69 Implicit adaptation is attenuated by temporal inconsistencies in sensory prediction errors

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Implicit adaptation is attenuated when feedback is provided at the end of the movement (endpoint feedback), compared to when feedback is provided throughout the movement (online feedback). There are many reasons why endpoint feedback may be less effective: It is static, of limited duration, and provides information at a single spatial position. A more subtle difference is that endpoint feedback is more variable in timing given that its appearance will depend on movement velocity. Studies of eyeblink conditioning have underscored the importance of consistent timing for optimizing learning (Dews, 1970). To explore this hypothesis, we conducted a visuomotor adaptation experiment in which we manipulated the temporal consistency of the feedback. In all conditions, participants reached to a target and were provided with clamped visual feedback, a cursor that was offset by 15° relative to the target. Despite instructions to ignore this task-irrelevant cursor, participants show signatures of motor adaptation with the heading direction of the hand gradually shifting across trials in the opposite direction of the feedback until reaching an asymptotic value. The feedback cursor was always presented at the radial distance of the target. As reference points, we included an online group in which the cursor was always visible until the radial distance of the hand movement reached the target amplitude and an endpoint feedback group in which the feedback was only presented for a single refresh cycle, appearing when the hand reached the target amplitude. For this group, the timing of the feedback is variable across trials given natural variation in hand velocity (mean standard deviation = 1.4 cycles). We compared these "classic" conditions with three fixed-timing conditions in which the feedback was presented on the first, second, or third refresh cycles after movement onset, with the timing varied across groups. Note that in these conditions, the spatial position of the cursor is no longer contingent on the radial position of the hand. We included one additional control condition in which the feedback timing was randomly selected across trials to be on the first, second, or third frame (variable timing). Consistent with previous studies, endpoint feedback resulted in a slower rate and lower asymptotic level of adaptation compared to online feedback. Strikingly, all three of the groups with fixed-timing exhibited similar adaptation as that found with online feedback, indicating the absolute timing of feedback had little effect on adaptation. Importantly, adaptation for the variable timing group was similar to that observed in the endpoint condition and less than that observed for the fixed-timing groups despite the cursor appearing in the same temporal window as for the fixed-timing groups. Together, these results point to a potentially important role of consistency in the timing of the error signal in driving implicit sensorimotor adaptation.

1-F-70 Precision of perceived hand position decreases during motor adaptation: Initial results

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Internal estimates based on predicted consequences of motor commands are thought to improve perceptual precision over and above purely sensory information. Invalidation of such internal predictive models (i.e. an increase of estimation uncertainty), in turn, should decrease perceptual precision. Here, we test this idea, together with the temporal dynamics of the precision of human position sense during visuomotor adaptation. Healthy young volunteers (n=21) repeatedly adapted to a 45° clockwise or counter-clockwise visuomotor rotation for 2-4 reaches, using an instructed fully compensatory strategy, followed by 2-4 washout trials. After 2, 3 or 4 trials during rotation and washout, participants localized their unseen hand with the last movement being performed in the absence of visual feedback. This yielded an estimate of perceptual precision early during implicit motor adaptation. We found implicit motor adaptation as indicated by reach after effects in washout, and by a localization bias as early as after a single rotation trial. Importantly, we also observed an increase in inter-quartile-range of angular localization errors in rotation blocks compared to washout blocks as evidence of a decrease in perceptual precision. Interquartile range additionally increased from the second to the fourth rotated trial. These preliminary findings of our ongoing study allow for two possible explanations for the observed decrease in precision of perceived hand position. First, sensory prediction error may have invalidated an internal predictive model whose state estimate contributes to position sense, hence increasing uncertainty in localization. Second, a mismatch of visual and proprioceptive information may have increased uncertainty of proprioceptive information. We are currently investigating these alternatives. In either case, the temporal dynamics of perceptual precision during sensorimotor learning have implications for the time-course of error-based learning mechanisms, and their interactions.

1-F-81 Interhemispheric parietal-frontal connectivity predicts the ability to acquire a non-dominant hand precision skill

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After chronic impairment of the right dominant hand, some individuals are able to compensate with increased performance with the intact left non-dominant hand. This process may depend on the non-dominant (right) hemisphere's ability to access dominant (left) hemisphere mechanisms. To predict or modulate patients' ability to compensate with the left hand, we must understand the neural mechanisms and connections that underpin this process. We studied 17 right-handed healthy adults who underwent resting state functional connectivity (FC) MRI scans before 10 days of training on a left hand precision drawing task. We sought to identify right-hemisphere areas where FC from left hemisphere seeds (primary motor cortex, intraparietal sulcus, inferior parietal lobule) would predict left hand skill learning or magnitude. We found that left hand skill learning was predicted by convergent FC from left primary motor cortex and left intraparietal sulcus onto the same small region (0.31 cm^3) in the right superior parietal lobule. Therefore, when an individual learns to perform well with the left hand, the right superior parietal lobule may play a key role in integrating left-hemisphere mechanisms that typically control the right hand. Our study provides the first model of how interhemispheric functional connections in the human brain may support compensation after chronic injury to the right hand.

G – Theoretical & Computational Motor Control

1-G-71 Low-dimensional neural manifolds describing natural behaviors

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The activity of populations of neurons across many brain areas is constrained to low-dimensional sub-regions of the neural space known as neural manifolds. Recent studies of the primary motor cortex (M1) suggest that it is the activity on the low-dimensional neural manifold rather than the activity of individual neurons that underlies the computations required for planning and executing motor behavior. However, neural manifolds have only been identified for neural recordings obtained in constrained laboratory settings; the relation between M1 activity during natural tasks of relevance to the activities of daily living and that during repetitive laboratory tasks remains unknown. Is the underlying simplicity suggested by the low dimensionality of M1 manifolds simply a byproduct of the constrained laboratory tasks? If so, is the dimensionality of M1 manifolds corresponding to natural behaviors such as grooming, foraging, or feeding, higher than that of laboratory tasks? Recent theoretical neuroscience studies have notably shown that the dimensionality of the neural manifold poses constraints on the number of neurons that need to be sampled in order to construct accurate brain-to-behavior decoders: the higher the dimensionality of the neural manifold, the more neurons need to be sampled to faithfully represent the behavior. Therefore, establishing the dimensionality of the neural manifold corresponding to natural behaviors is crucial to the design of brain-machine interfaces, a rehabilitative technology that converts neural signals into control commands to restore movement to paralyzed patients. We found that the dimensionality of neural manifolds associated with unconstrained natural behaviors ranged between 3 and 14, comparable to that of manifolds associated with laboratory tasks. The low dimensionality found for both natural and laboratory behaviors suggests that neural decoders for individual behaviors can be based on a low-dimensional representation of neural activity. Our results suggest that it may be possible to construct generalized decoders that can operate across distinct low-dimensional manifolds, each associated with a specific behavior.

1-G-72 Tongue motor control: deriving articulator trajectories and muscle activation patterns from an optimization principle

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Speech motor control is known to be highly resistant to perturbations of various origins. In particular several studies have demonstrated the capacity of speech motor control system to deal with steady state perturbations such as bite-block, lip-tube, or modified palatal vault, using the excess degrees of freedom of the relations between motor commands and articulatory positions or between articulatory positions and spectral characteristics of speech sounds. Efficient adaptations to repeated perturbations of the auditory-feedback, of the jaw movements, or of vocal tract morphology have also been shown. This flexibility echoes what is observed for upper limb motion and suggest the operation of a similar control principle. In this study, we explored the predictions of optimal feedback control theory applied to tongue motion. We assumed that the CNS aims to minimize both neuromotor effort and motor error. We also assumed that it estimates the current state of the articulator system through the combination of delayed and noisy sensory feedbacks and the predictions of an internal model of the dynamics of the speech production system. In more detail, we used a biomechanical model derived from two-dimensional finite element modeling of the tongue. The first three formants of the voice were calculated from the vocal-tract shape with a harmonic model of the vocal tract. For simplicity, functions of tongue position and velocity were considered as proprioceptive input. We assumed that motor commands and sensory signals were corrupted by multiplicative noise. Feedback updated the state of the system through an extended Kalman filter. We essentially explored the generation of movements from a rest (e.g. schwa-like) tongue position to vowels like [i], [a] or [ɔ]. Optimization predicted complete muscular activation and kinematic patterns in time. Movements of flesh points were roughly sigmoidal, in accordance with reported articulatory recordings. Muscle activation was consistent with the findings of tongue EMG studies; tongue being a muscular hydrostat and not an articulated rigid body, muscle dynamics were specific: most movements involved a long initial bell-shaped activation of agonists followed by a final short braking antagonist burst. Interestingly, trajectories in acoustic space were sometimes markedly curved (esp. in F1-F2 space). Variability in final acoustic production emerged as a consequence of sensory and motor noise, for a fixed goal and starting posture, providing an estimate of the sensorimotor contribution to phonemic variability. Last, we tested the effect of a sudden acoustic perturbation Specific experimental work using these artificial speech task will have to be undertaken to validate the kinematic and acoustic predictions of this model.

1-G-73 A model for the self-organization of spinal circuitry through learning

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We are testing the feasibility of self-organization in the spinal cord based on musculoskeletal mechanics and behavioral experience. We have designed an artificial model creature (Oropod) with the simplest musculoskeletal system and sensor population that we thought might exhibit an interesting range of behaviors. The Oropod consists of a unidimensional sensorimotor plant with two arms, each operated by an antagonistic pair of muscles with length-dependent force output and equipped with proprioceptors for muscle length, velocity and force and tactile receptors for contact. Its nervous system is composed of simplified, non-spiking neurons that mimic Hodgkin-Huxley biophysics for synaptic integration. We configured it with spontaneously active beta motoneurons, innervating both extrafusal and intrafusal muscle fibers. The beta motoneurons are driven to mimic the spontaneous twitches and waves of muscle activation that have been observed during embryogenesis. We discovered that a simple, Hebbian rule for synaptic plasticity accounts for the development of the selective monosynaptic projections of spindle primary afferents to homonymous motoneurons, the first components of the system to appear during fetal development. Beta innervation avoids the need for the unphysiological anti-Hebbian growth rules that others have used to account for development of spinal circuitry, thus suggesting a function for the ubiquitous but enigmatic beta innervation in mammals. Further application of this Hebbian rule to populations of excitatory and inhibitory spinal interneurons results in plausible patterns of spinal circuitry. The next step is to test whether descending command systems can learn to accomplish useful tasks via this self-organizing spinal circuitry. Such capability was demonstrated previously in models consisting of the well-described adult mammalian spinal circuitry connected to anthropomorphic musculoskeletal models (Tsianos, Goodner & Loeb, 2014, J. Neural Engng.). These are the first steps toward identifying how the CNS utilizes adaptive mechanisms in hierarchically self-organizing subsystems to facilitate learning and performance of voluntary behaviors and haptic perception. Funding: EU H2020 FET project #829186 'ph-coding'

1-G-74 Predictive attenuation of touch and tactile gating are distinct perceptual phenomena

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In recent decades, research on somatosensory perception has led to two important observations. First, self-generated touches that are predicted by voluntary movements become attenuated compared to externally generated touches of the same intensity (attenuation). Second, externally generated touches feel weaker and are more difficult to detect during movement compared to rest (gating). Researchers today often consider gating and attenuation to be the same suppression process; however, this assumption is unwarranted because, despite more than forty years of research, no study has combined them in a single paradigm. We quantified how people perceive self-generated and externally generated touches during movement and rest. We demonstrate that whereas voluntary movement gates the precision of both self-generated and externally generated touch, the amplitude of self-generated touch is selectively attenuated compared to externally generated touch. We further show that attenuation and gating neither interact nor correlate, and we conclude that they represent distinct perceptual phenomena.

1-G-75 Spatio-temporal modularity in choreographed and improvised dance across skill level and task

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Background In order to simplify the production of complex movements, our sensorimotor system might rely on a discrete number of elementary building blocks, which can be rearranged and combined to construct motion, so called movement primitives. So far, few studies have investigated such modular organization of motor skills in complex, unconstrained full-body movements in individuals with differing skill levels. The current study aims to answer the following questions: if there is an association between experience and spatio-temporal modularity (number of modules and temporal segments), how stable is the association across tasks and does it generalize to unconstrained, improvised movements? Methods In order to answer these questions, kinematic data of 21 dancers with differing experience (2 to 18 years) were captured during improvised dancing as well as during a predetermined choreography with different qualities of expression (neutral, slow, quick, free and constrained). The kinematic data were captured with 28 cameras of a Vicon motion analysis system. The Plug in Gait marker set consisting of 39 markers was used. A hierarchical kinematic body model was fitted to the 3D marker positions to calculate joint angle trajectories. A temporal model was used as the generative model for the joint angle trajectories. In addition to the optimal number of primitives, the appropriate number of temporal segments (bins) was determined with Bayesian model selection. The model evidence was estimated via Laplace approximation. A Bayesian hierarchical regression model was implemented to determine the association between experience and bins as well as experience and primitives. Results Preliminary results of the hierarchical regression analysis based on the data of 11 subjects show a negative association between experience and number of bins (slope $\mu = -0.25$; ci = [-0.468, -0.029]) and a positive association between experience and number of primitives (slope μ = 0.10; ci = [0.002, 0.206]). On a condition level, the association with bins remains for all conditions, except for the improvisation and slow condition. For the number of primitives, the association only remains for the conditions slow and neutral. Discussion Preliminary results indicate that with increasing skill level the pool of primitives increases. This suggested increase in movement repertoire might enable broader movement segments, supporting previous evidence from taekwondo movements (Endres, Christensen, Omlor & Giese, 2011). However, this general finding does not seem to be stable across tasks and generalization to improvised dancing is limited. References Endres, D., Christensen, A., Omlor, L. and Giese, M.A. (2011). Emulating human observers with bayesian binning: Segmentation of action streams. ACM Transactions on Applied Perception, 8(3):1-12.

1-G-76 Multilateration is a fundamental computation for localizing touch

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Perhaps the most recognizable 'sensory map' in all of neuroscience is the spatially distorted somatosensory homunculus. While it gives the impression of a straightforward link between cortical territory and body part, this simplicity belies the true complexity of the spatial coding of touch. There is in fact no one-to-one link between the homunculus and coordinates of the actual body. Any isolated activation is spatially ambiguous without a neural decoder that can read its position within the entire map, but how this is computed by neural networks is unknown. Tactile localization is a long-standing unsolved mystery in sensorimotor integration, one we aimed to solve in the present study. Similar spatial ambiguities were faced by surveyors hundreds of years ago as they tried to make accurate spatial maps of countries. How could one ever know the location of the parts (i.e., landmarks) without knowing the whole coordinate system (i.e., the entire territory)? The solution lies in the simple computation of multilateration: given a precisely known distance between two baseline landmarks, the location of a third landmark could be computed from its distance from the other two. We propose that, like a surveyor, the human brain also employs multilateration to localize an object on the body. To do so, this 'neural surveyor' uses simple arithmetic to calculate the relative distance between the afferent input and the joints (the baseline landmarks). In the present study, we provide multiple lines of evidence that the brain may use multilateration to localize touch on the limb. We first developed a Bayesian formulation of multilateration in the nervous system. We then developed a simple feedforward neural network model that implements this computation and optimally decodes where the body is touched. This network consisted of an encoding layer (i.e., the low-level homunculus), a decoding layer that performs the distance-based computations, and a Bayesian decoder that derives a location estimate in body-centered coordinates. The tuning of the units in both layers captured fundamental properties of somatosensory cortical neurons. Simulations revealed that multilateration produced a unique pattern of localization variability that was not identified in other forms of computation, demonstrating that reflects the computational signature of multilateration. Finally, we detect this pattern in actual psychophysical experiments, suggesting that the computation of multilateration is a candidate mechanism underlying tactile localization. These results suggest that multilateration provides the homunculus-to-body mapping necessary for localizing touch.

1-G-77 Manipulating a whip - learning to control dynamically complex objects

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One of the paradoxes of human motor neuroscience is that human sensory-motor abilities vastly out-perform modern robot technology, despite the slow neuromuscular system. A possible resolution of this paradox is that humans rely heavily on prediction based on some form of internal model. Neural and behavioral evidence supports the existence of such models, yet the exact nature of the model itself still remains to be clarified. We hypothesize that the internal model used for motor control is based on (at least) three distinct classes of motor primitives: submovements and oscillations, which provide a basis for unconstrained movements, and mechanical impedance, which facilitates physical interaction. Encoding movements with combinations of these motor primitives may be an essential simplification required to enable dexterous manipulation of complex objects. To test this hypothesis, we examined how humans learn to manipulate one of the most exotic and complex tools which they can handle: a whip. In simulation, we tested whether a distant target could be reached with a whip by using a controller composed of motor primitives. The motor learning process to reach a distant target with a whip was framed as an optimization problem, where the goal was to find an optimal set of parameters that could minimize the distance between the tip of the whip and the target. Multiple target locations were tested, with the upper-limb and whip modelled as a chain of 54 DOF, yielding a 108-dimensional state-space representation. We discovered that, regardless of the target location, this approach was able to manage this daunting complexity, and optimization succeeded to identify the optimal movement parameters that could reach a target with a whip. A detailed model of the whip dynamics was not needed for this approach, which thereby dramatically simplified the learning process. This may be a key simplification which humans use to learn complex motor skills, since only a small set of parameters may need to be determined and retained without the need to internalize the detailed dynamic properties of the object being manipulated. Experimental studies also observed that humans appear to employ a small number of primitive actions to hit a target with a whip. However, there were differences between simulation and experiment: in simulation, the task was accomplished with a single submovement planned in joint-space coordinates; experimental studies showed two submovements in end-effector coordinates. Nevertheless, these investigations support our hypothesis that an internal representation encoded in terms of primitive actions may be a key strategy underlying successful mastery of dynamically complex objects.

1-G-78 Building a generalizable brain-computer interface via fast exploration of Kalman parameter space

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Brain computer interfaces (BCIs) are being used to restore some motor function to people with movement disorders arising from neurodegenerative disease, stroke, or spinal cord injury. BCIs use a subject's neural activity to directly control an assistive device, such as a robotic arm or a computer cursor, bypassing the impaired motor system. A crucial challenge to clinical viability is the lack of generalizability across activities of today's systems. That is current BCI systems do not typically perform well on novel tasks that were not included in the calibration of the decoder. Here we propose a strategy

to provide a generalizable BCI without requiring an extensive calibration session. At the core of every BCI system is the decode algorithm, which translates the user's neural activity into control of the external device. The current state-of-the-art decoders are variations of the Kalman filter, which provides a linear mapping of neural activity to movement execution. The parameters of the Kalman filter are typically calibrated using a fast, repetitive task. Current BCIs perform poorly on tasks that differ from those included in the calibration session. In light of this, we designed a two-fold strategy to building a generalizable decoder: 1) We developed an adaptive decoder that modifies the parameters of a Kalman filter to reduce the error between decoded and intended kinematics. Importantly, the loss function of our adaptive decoder depends only on the observed neural firing rate; that is, it does not require kinematics or other information about the task. This is important because, in an online BCI use scenario, we do not have access to all of a user's intended kinematics. 2) As we adapt the Kalman parameters to minimize decoding error, we learn the association between neural activity and the space of Kalman parameters generated by the adaptive decoder. We model this association using nonlinear methods such as cubic splines. Finally, we merge the spline fit with the adaptive Kalman filter to create a hybrid "SplineKalman" decoder. The SplineKalman updates its parameters every 100ms using only neural firing rate. Reaching data was collected from two Rhesus monkeys with 96-electrode arrays implanted in primary motor cortex (M1). The monkeys performed a center-out reaching task, followed by a novel kinematic task which required generating significantly smaller velocities and continuous movements for 6 seconds. Then, offline, we calibrated a Kalman filter using only the center-out reaching data and tested the decoders on the novel kinematic task. Our SplineKalman decoder outperforms traditional decoders at generalizing to a task with distinct kinematics. Importantly, the SplineKalman decoder does not require training on a multitude of tasks with different kinematics in order to perform well. All of the results presented here are based on offline analyses but could be extended to online BCI control.

1-G-79 Effect of reward and effort on the opportunity cost of time and movement vigor

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Imagine yourself reaching for your car door. What determines how fast you reach? Current theories of motor control assume that the value of the immediate outcome of the movement (getting the car door open), and the effort of the movement, will be the primary factors that influence your reach vigor. However, the way we move is also affected by our internal state, which in turn is influenced by our recent experiences. Imagine reaching in two different contexts, say, after a pleasant visit at your friend's vs. after a dreaded trip to the dentist. Would these experiences differentially affect how you move? That is, does your internal state, as determined by your history of reward and effort, affect your movement vigor? We sought to answer this question using a generalized model for vigor that builds on an optimal foraging framework--the marginal value theorem (Charnov 1976,Yoon et al. 2018). The essence of this model is that the brain performs foraging actions--harvesting at and moving between reward sites--in a way that maximizes the average rate of capture. In a high-quality environment, i.e., one where opportunity cost is high, shorter durations should be preferred as opposed to a poor environment in which the brain should prefer to harvest longer and move slower. We tested this prediction in two experiments in which we controlled the history of reward and effort and measured how they influenced reach vigor. Subjects held a robotic manipulandum and reached to a 'patch' to harvest reward at a decaying rate, and then decided to leave the patch for another. In Exp. 1 (n=14), patches were placed in two environments that differed in the amount of reward per patch, resulting in high and low reward rates. In Exp. 2 (n=18), the patches were placed in two environments that differed in the amount of effort required to reach between patches, resulting in high and low effort rates. Within each environment we placed 'probe trials' with constant reward in Exp.1 and constant effort in Exp.2. Probe trials ensured that while the history of reward and effort varied by environment, the immediate reward and effort was constant throughout. The theory's prediction was that in a poor environment, people would not only harvest for longer, but also expend less energy reaching, thereby moving slower. Remarkably, in both experiments, in the poor environment subjects reached with reduced speeds between probe patches ($p<0.001$, $p<0.01$, respectively). In the reward experiment, in the poor environment subjects spent a longer time harvesting in patches of equivalent reward (probe patches) ($p<0.001$). Thus, following a history of high reward or low effort, the brain was more willing to expend energy to move, reaching with greater vigor, and was less willing to spend time harvesting, abandoning the reward site sooner. These findings demonstrate that decision-making and motor control are both influenced by an opportunity cost that depends on the history of reward and effort.

1-G-80 Contextual cues can form separate motor memories in a novel action-outcome association task

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There has been considerable interest in determining if contextual cues can be used to consolidate and retrieve multiple motor memories. The results from sensorimotor adaptation tasks are mixed: Movement-related contextual-cues (e.g., direction of movement) can afford storage of two opposing mappings, while arbitrary external contextual-cues (e.g., color) cannot prevent catastrophic interference. However, we appear capable of storing multiple mappings when using a variety of digital devices despite having similar movements (e.g., video games use the same controller to play a racing game and a first-person shooter). We propose that studies focusing on context-dependent, dual-learning in sensorimotor adaptation tasks generally pressure the recalibration of a single, existing motor memory. However, arbitrary external contextual-cues may support the formation of two distinct motor memories when they are being formed de novo. To test this idea, we explored the role of external contextual-cues in a task that requires the learning of novel action-outcome mappings. Here, participants trained to move a virtual cursor between varying start and target locations with two arbitrary and unintuitive mappings between movements of the cursor and responses on a keyboard. Each mapping was linked to a set of external contextual cues, such as cursor identity and background scene, and the different cue-to-mappings were fully interleaved during training. We find that participants were readily able to learn both mappings, unlike findings from sensorimotor adaptation tasks. A critical question is what kind of action-outcome association has been formed within each context. This can be answered with a test of generalization to untrained start-target pairs. We find that participants demonstrate robust generalization to novel conditions in each context without a cost of an increase in preparation time, suggestive of the formation of two, separate motor memories. Participant's behavior could be captured by a simple RL model that learns the value of the keys in states relative to the target location and a Bayesian mechanism that can link the contextual cue with appropriate key values. These findings suggest that contextual cues may play an important role in the consolidation and retrieval of newly learned motor skills, offering an account of why previous sensorimotor adaptation studies may have failed to find contextual dependency -- they may be unable to cue separate recalibrations of an existing memory.

Poster Session 2

A – Control of Eye and Head Movement

2-A-1 Population coding of naturalistic self-motion in vestibular nucleus

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The vestibular system provides information about head motion in space and contributes to self-motion perception as well as stabilization of gaze and posture. The physiology of the vestibular system has been characterized mainly by studying single-unit recordings. Thus, our understanding of how neural responses relate to self-motion perception and reflexes is limited because behaviors, in general, arise from the collective activities of the neural population rather than single cells. While two studies have examined coding by neural populations in the vestibular system (specifically in vestibular nuclei (VN)), the stimuli used were artificial and had low amplitude and frequencies. Natural stimuli, on the other hand, can reach high amplitudes and contain a range of frequencies, which can have a significant impact on population coding as observed in other systems. Accordingly, we investigated population coding of natural self-motion in VN by simultaneously recording from multiple vestibular only (VO) neurons during natural head motion. We found that the activities of neurons were correlated during artificial and naturalistic head motion; In particular, noise correlations were significant during both stimuli conditions and had the same sign as signal correlations. Theoretical and experimental studies have shown that this correlation structure (i.e. the relationship between signal and noise correlations) is redundant and reduces information in large neural populations. Moreover, we found that correlation structure depends on the stimulus features and is plastic. In particular, we observed that noise correlations decrease with the amplitude of the stimulus. To understand the implication of correlation plasticity on population coding in large populations, we used a mathematical model that includes the known filtering characteristics of VO neurons as well as static nonlinearities, the structure of correlation, and its plasticity in neural populations with a varying number of cells in the population. In agreement with our data, the model predicted that information decease in VO populations with size and, thus the population coding is redundant. Furthermore, the correlations of plasticity observed in VO populations mitigated the detrimental effect of correlations in VO populations when natural stimuli were used. These findings suggest that correlation structure, and accordingly, population coding of natural self-motion in VN has adapted to characteristics of natural stimuli which is essential to developing neural prosthetics in patients with vestibular deficits.

2-A-2 Dynamic contrast sensitivity during human locomotion: The effect of locomotor phase and retinal image velocity

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During locomotion, high-acuity vision is maintained by reflexive head and eye movements that stabilize visual targets on the retina, but this stabilization is not perfect. Nevertheless, dynamic visual acuity is reported to be as good as static visual acuity, suggesting that visual mechanisms work to mitigate possible adverse consequences of retinal image motion. Here we investigate these mechanisms by measuring and comparing contrast sensitivity (CS) during walking and standing. High spatial frequency (11 cycle per degree) Gabor targets subtending ~ 5 deg of visual angle were presented to human observers on a projection screen at a viewing distance of ~175 cm using a high-frame rate (1440 Hz) projector. The target was presented centrally against a gray background and no fixation point was present. Targets were presented for ~24 ms and the participants responded whether the target was tilted leftwards or rightwards. A single contrast was used for the Gabor target and this contrast was determined based on pilot testing to result in ~80% correct responses; this single contrast level was constant for each participant but was adapted to suit the performance of each participant. Participants completed a total of 1000 trials while standing still and another 400 trials while walking at ~3.1 mph on a treadmill. Head, eye, and ankle movements were recorded via motion capture (Optitrack) and eye tracking (EyeLink) systems. Trials were then binned according to locomotor phase and eye-in-space velocity to examine how these factors impact performance as gauged by the percentage of correct trials in each bin. We also compared performance between standing and walking. Results suggest that performance was actually improved during walking relative to standing. Performance was also better when retinal image velocity was slower. Some participants exhibited an effect of the locomotor phase, but this was inconsistent across subjects. Acknowledgements: Research was supported by NIGMS of NIH under grant number P20 GM103650.

2-A-3 Biomimetic stimulation improves accuracy of prosthesis-evoked vestibulo-ocular reflex (VOR) responses

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Even the simplest sensorimotor transformations require precise neural dynamics in order to produce accurate and well-timed behaviors. As such, recent developments of sensory prostheses have focused on biomimetic designs to better interface with the rest of the nervous system. However, progress is limited due to the complex sensor physiology and the non-specific stimulation. One recent effort not bound by these limitations is the vestibular prosthesis, which senses head rotation and transforms the movement into vestibular afferent stimulation, substituting for the damaged periphery. Due to the system's simple structure, well-studied physiology, and clear behavioral readout, the vestibular prosthesis is then the ideal tool to investigate how biomimetic designs can affect prosthesis performance, in addition to how neural dynamics can influence sensorimotor transformations. We asked whether representing the natural dynamics of vestibular afferents in the mapping between head motion and afferent stimulation would result in better performance. To test this proposal, we compared vestibulo-ocular reflex (VOR) responses evoked by the mapping without natural dynamics (static mapping) to those evoked by two newly implemented mappings mimicking the high-pass dynamics of vestibular afferents. Testing was done in two monkeys with profound bilateral vestibular loss that had been implanted with a prosthesis. VOR eye movements were first quantified in response to sinusoidal stimulation that spanned the natural frequency range (0.2 - 20 Hz). We found that afferent-like high-pass mappings evoked more robust VORs with more precise timing. On the contrary, the standard static mapping showed a gain decline and increasingly lagging timing at high frequencies (5 - 20 Hz). In addition, to directly investigate the effects of neural dynamics on VOR performance, we implemented a mapping with high-pass dynamics exceeding the natural range. This mapping showed too much compensation and produced an undesirable phase advance. Similar trends were also observed with VOR eye movements in response to transient and naturalistic stimulations. Overall, the mapping that mimicked the afferent subclass known to provide primary contribution to the VOR yielded optimal performance, suggesting that endogenous afferent dynamics are well matched to produce accurate VOR responses. Our results confirm that the implementation of biomimetic mappings in vestibular prostheses can help optimize functional outcomes for patients, underscore the critical role that afferent dynamics play in accurate sensorimotor transformations, and advocate for a more biomimetic design of sensory prostheses.

B – Fundamentals of Motor Control

2-B-4 Overcoming a virtual surgery by learning new muscle synergies: Effect of practice duration

Presenting Author: Denise Berger
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Humans have a remarkable capacity to learn new motor skills, a process that involves the generation of new muscle activity pattern. Understanding how the CNS controls movements and learns motor skills represents a fundamental challenge in neuroscience. Muscle synergies, coordinated activation of muscle groups, may simplify motor control by allowing the generation of muscle patterns through the optimization of a small number of parameters. Learning new motor skills may be achieved through the acquisition of novel muscle synergies. Reaching tasks in a virtual environment (VE) using myoelectric control to move a cursor while generating isometric force, as the mapping between muscle activity and cursor movement is known precisely, provide the opportunity to test hypotheses about both muscle pattern organization and their reorganization during learning. In particular, muscle-to-force remappings (virtual surgeries) that either cannot be compensated by recombining existing subject-specific muscle synergies (incompatible surgeries) or that can be compensated by recombining existing muscle synergies (compatible surgeries) allow to directly test the synergistic organization and to investigate muscle synergy learning. We have previously shown (Berger et al., 2013) that after incompatible surgeries participants explored new muscle patterns, but typically failed to overcome the perturbation. We hypothesize that, as with learning complex skills such as musical instrument playing, with enough practice it is also possible to learn to successfully perform an isometric reaching task after an incompatible surgery. To test this hypothesis, we investigated whether longer space exploration than in our previous protocols, i.e., by allowing trial durations of up to 15 s rather than 2 s, affects the ability to overcome incompatible virtual surgeries. We found that, when sufficient time for task space exploration is available, adaptation to incompatible surgeries is slower that adaptation to compatible surgeries, as predicted by a neural organization of muscle synergies. However, with longer exploration, trial success improves with practice. Remarkably, improvements in movement direction after incompatible surgeries occur faster for corrective movements than for the initial movement, suggesting that learning of new muscle synergies if more effective when used for feedback control. Moreover, reaction time after incompatible virtual surgeries was significantly higher than after compatible virtual surgeries, suggesting an increased explicit component on the movement planning after the incompatible virtual surgery.

Taken together, these results indicate that exploration is important for motor skill learning and suggest that human participants, with sufficient training, can learn new muscle synergies.

2-B-5 Mechanisms of network interactions for flexible cortico-basal ganglia-mediated action control

Presenting Author: Petra Fischer

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In spite of tremendous progress in describing how neuronal activity unfolds before and during movements, the mechanisms that trigger the switch from movement preparation to execution, regulate movement vigour and enable movement inhibition remain unknown. In humans, finely tuned gamma synchronization (60-90 Hz) rapidly appears at movement onset in a motor control network involving primary motor cortex, the basal ganglia and motor thalamus. Yet the functional consequences of brief movement-related synchronization are still unclear. Distinct synchronization phenomena, including synchronization in the beta range (13-30 Hz), have also been linked to different forms of motor inhibition, including relaxing antagonist muscles, rapid movement interruption and stabilizing network dynamics for sustained contractions. I will introduce detailed hypotheses about how intra- and inter-site synchronization could interact with firing rate changes in different parts of the network to enable flexible action control. First, gating of movements may be mediated by a shift in spike timing of cortical cells such that their activity converging in BG sites depolarizes recipient cells more strongly to trigger the firing cascade that causes muscle activation. Second, movement invigoration may depend on coincident activation and temporally clustered inhibition of the relevant ensembles to maximize their impact downstream, generating brief synchronized pauses in basal ganglia output nuclei that may promote post-inhibitory thalamic activity to boost thalamo-cortical firing rates. Third, incidental co-activation of non-target effector ensembles that are loosely connected to the target-effector ensembles may be avoided by staggering bouts of rhythmic activity, such that incoming non-target-related surround activity would be delayed and thus suppressed by strong local inhibition (potentially occurring at multiple levels of the network). Fourth, rapid suppression of ongoing movements may be enabled by rapid phase- or frequency-shifts within one of the coupled oscillator networks that are present throughout the cortico-basal ganglia-thalamo-cortical network to allow an efficient activity reset. The proposed cause-and-effect relationships will hopefully help inform hypotheses about the mechanisms of movement-related cortico-basal ganglia-thalamo-cortical communication. To which extent findings obtained in humans also apply to other species, ultimately allowing more fine-grained investigations, is yet to be shown. Confirming or revising the proposed hypotheses could transform our understanding of the neuronal basis of flexible movement control.

2-B-6 Sensorimotor predictions lead to sensation-specific tactile suppression

Presenting Author: Elena Fuehrer

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Tactile sensations on a moving body part that occur while a movement is being planned or executed are perceived as less intense than the same sensations occurring at rest. This phenomenon has been explained by predictive mechanisms. Based on efference copy signals, internal forward models are assumed to predict the sensory consequences of a movement, and the predicted sensory consequences are suppressed. Previous research shows that both the predictability of movement-relevant object features, and the movement-relevancy of somatosensory information modulate such suppression of tactile sensations. We examined whether tactile suppression is specific to the nature of the predicted sensory consequences, or whether it results from a general cancellation process. Participants were instructed to move the tips of their index fingers across textured objects at a designated speed. Depending on the spatial period of the texture, these movements caused participants to experience either a low (40 Hz) or a high (240 Hz) frequency vibration at their fingertips. Objects were presented in a blocked manner, so the sensory movement consequence i.e., the vibration frequency, was predictable (either low or high, depending on the block). To quantify tactile suppression, participants had to detect additional vibrotactile probes of varying intensities that were applied at the base of the moving index finger around movement onset. These vibrotactile probes also had either a low (40 Hz) or a high (240 Hz) frequency, matching (congruent) or mismatching (incongruent) the predicted sensory consequences of the movements. Compared to measurements taken on the same participants at rest, and in line with previous work, detection thresholds of the vibrotactile probes were elevated during movement, clearly indicating tactile suppression. Meanwhile, detection precision was not hampered during movement. Interestingly, congruent probes matching the predicted movement consequence received greater suppression overall than incongruent probes, but this was systematic for the low frequency probes only, with a clear effect and a trend for the low and high frequency probes respectively. These results show a modulation of how external vibrotactile probes are suppressed depending on the predicted movement consequence. Altogether, our findings indicate that sensorimotor predictions can lead to sensation-specific tactile suppression and argue against a mere general cancellation process.

2-B-7 The influence of cardiovascular activation on reach-to-grasp movements in virtual reality

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The brain's model of the body's internal state (interoception) has been largely overlooked in prior work on motor control, especially in precision tasks like reach-to-grasp, which require a high level of movement coordination. Previous studies have shown that performance on ballistic movement tasks (e.g., move arm as fast possible) improves with increased cardiovascular activation, whereas more complex movement tasks (e.g., accurate pointing) show a non-linear (often quadratic or "U-shaped") relationship between performance and cardiovascular activation. Actions that require complex coordination, involving precise control, such as reach-to-grasp movements, have yet to be examined under different levels of cardiovascular activation (and variable interoceptive state). Accordingly, this study investigated the relationship between exercise-induced cardiovascular activation and reach-to-grasp performance. Five participants, two males (23.4 ±8.9, mean ±sd, years old), reached-grasped-and-lifted a virtual objects of 5.4×2.5×8 cm (w, d, h), located at 30 cm from starting position projected in a head-mounted display-based virtual environment (VE). Reach-to-grasp movements were performed immediately after cessation of cycling at 60% and 80% of the individual's heart rate reserve (HRR). Each cycling intensity was repeated three times resulting in 135 trials per activation level per participants. We observed a quadratic relationship between current cardiovascular activation and kinematic features of movement time (R^2=0.42 at 60% HRR, 0.37 at 80% HRR) and peak transport velocity (R^2=0.62, 0.41). We

also saw a weaker quadratic relationship between cardiovascular activation and temporal coordination features of time to peak transport and time to peak aperture ($R2 = 0.15, 0.18$). These preliminary data suggest that nature of relationship between performance and cardiovascular activation may differ for different features of the reach-to-grasp movement. These data have implications for the understanding of reach-to-grasp performance as it relates to both sport and pathology.

2-B-8 Grasp planning for object manipulation without simulation of the object manipulation action

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When we grasp objects, our grasps typically facilitate the planned object manipulations. For example, people grasp a to-be-rotated knob with a clockwise rotated grasp for counterclockwise rotation of the knob and vice versa. We examined whether grasp selection for object manipulation is based on the simulation of the object manipulation action, that is, the anticipated body movements that are required to realize the intended object manipulation. We conducted five experiments, in which participants adapted to different relationships between object manipulation actions and object movements, the representation of which is an essential prerequisite for simulation-based motor planning. The effect of the adaptation on grasp selection was assessed in test phases before and after the adaptation phases. In three experiments, adaptation to different relationships between object manipulation actions and the resulting object movements did not significantly affect grasp selections, suggesting that grasps for object manipulation are planned without simulating the object manipulation action. A fourth experiments asserted that our manipulations sufficed to reliably change grasp selections for object manipulations. A final experiment showed that participants picked up information about the relationship between object manipulation actions and object movement during the adaptation phases. However, whereas it affected planning of the extent of hand rotations during the object manipulation, it did not always affect grasp selections. In sum, our data show that grasp planning was not based on simulations of the body movements associated with the currently planned object manipulation.

2-B-9 Learning weight-color associations during object manipulation. The role of task complexity and explicit learning

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During grasping and lifting everyday objects, we adjust our grip forces according to the object's weight in a feedforward manner before direct weight information is available after lift-off. If relevant size or material information is not available, we may need to decode this predictive knowledge from learned object features such as shape, color or labels. Here we study the learning of a color-weight association under different task complexities implemented by different numbers of associations. In addition, we analyzed whether the learned feedforward control is subjected to explicit knowledge. Two groups of 12 subjects either lifted 3 boxes with 3 different weights (0.3 kg, 0.6 kg, 0.9 kg) coded by 3 colors or 2 boxes with 2 weights (0.3 kg, 0.6 kg) and 2 colors. Apart from the different colors, the objects looked identically. Each weight was presented 30 times with the order of weights (and colors) pseudorandomized. Three more trials for each weight after a 10 minutes break served as retention measurement. Participants grasped the objects at a handle equipped with a force sensor. We quantified grip force anticipation by measuring the peak grip force rate (pGFR) during force increase before lift-off, an established measure for predictive control during object lifting. After the retention measurement, we asked participants to estimate the weight of the different objects. For both groups pGFR did not differ for the 2 or 3 objects during the first 3 lifts of the 2 or 3 objects. In the following lifts color-weight associations developed as obvious from higher pGFRs for heavier objects. This was the case for the 0.6 kg versus the 0.3 kg object in both groups (2 Weights Group: p=0.005, 3 Weights Group: p = 0.002), but not for the 0.9 kg versus 0.6 kg object in the 3 Weights Group (P = 0.102). During retention the difference in the pGFRs for the 0.3 kg and the 0.6 kg object was less clear in the 2 Weights Group (p=0.069), while it remained significant in the 3 Weights Group (p=0.005). All subjects estimated the 0.6 kg object heavier than the 0.3 kg. The ratio however varied substantially between 2 and 10 and did not correlate with the ratio or the differences in pGFRs (>0.1). Color-weight associations during object lifting can be learned within few lifts. Decrements may however be obvious in retention measurements indicating the need for frequent practices for a firm memory establishment. Increasing task complexity by increasing the number of to-be-learned associations does surprising not lead to a general decrement of performance. Rather, one of the two contrast is learned with the same precisions as with only two objects, while the second contrast is largely neglected. Thus, facing higher number of associations, the system seems to decide to optimize the processing of a subset and probably delaying the learning of the rest. Explicit knowledge does not seem to play a major role in the individual learning of the forces-weights associations.

2-B-10 Disentangling inhibition of discrete and continuous movements on the basis of behavioral latencies and midfrontal neural dynamics.

Presenting Author: Mario Hervault
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People are able to adapt their behavior to changing environmental contingencies by rapidly inhibiting their actions. Inhibition of action is often studied by the "stop-signal paradigm" in which the time needed to cancel a prepared discrete response is estimated as a stop-signal reaction time (SSRT). This estimation is based on the "horse-race model" assuming that successful inhibition relies on the outcome of a race between independent GO and STOP processes. Still, less is known about situations calling for the cessation of an ongoing continuous movement, in which this race model cannot be used. In two different variants of the paradigm, we asked participants to cancel a prepared discrete movement or to stop an ongoing continuous movement, in reaction to a stop signal. In a first study, we elaborated a novel methodology to measure the SSRT of an ongoing movement, based on the deviation of the ongoing trajectory in the phase space relative to movements without a stop signal. The absence of correlation between the inhibition latencies (SSRT) in the two tasks argued in favor of dissimilarities in the inhibitory processes involved in cancelling and stopping action. In addition, generalized linear models showed a significant influence of the motion parameters on the inhibition of ongoing rhythmic movements. In a second study, midfrontal time-domain and oscillatory (Delta/Theta) power dynamics from electroencephalographic data provided evidence for distinct processes of action inhibition. These findings do not support a conceptualization of action inhibition as a unitary construct but rather suggest that the differential engagement of N2 and P3 ERP components as a function of the action type pertains to functionally independent inhibition processes.

2-B-11 Unexpected "freezing behavior" in freely moving rats by optical stimulation of the midbrain locomotor region causes decrease in firing rate of spinal neurons

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Understanding the complex mechanisms behind the movement in mammals is one of the main goals for both motor research and developing therapeutics. It is well-known that the mesencephalic locomotor region (MLR) plays an important role in initiating and regulating movement. Nevertheless, the elements of how MLR is controlling spinal locomotor circuits are still not fully understood. Here, we stimulate the MLR using a photosensitive genetically expressed sodium channel (ChrimsonR), using CamKIIa as a promotor in an AAV virus in wild type Wistar adult rats. Contrary to the anticipated locomotor response, the stimulation unexpectedly induced a strong arrest of movement where the whole body of the rat "completely froze". Measurements of motion were performed using accelerometers connected to an optical fiber on the head. A recent study reported a similar "freezing behavior" using the same genetic promotor in MLR (Carvalho et al 2020). To further investigate the effect of "freezing" on the spinal locomotor circuitry we implanted multielectrode arrays with 128 channels in the lumbar spinal cord of the rat. Optical stimulation of MLR reduced the neuronal spiking activity in spinal neurons. The neurons inducing the "freezing behavior" were histologically identified in the pedunculopontine nucleus and the cell type is likely glutamatergic based on the prior experience with the CamKIIa promotor, yet the characterization is ongoing.

2-B-12 On the perception of movement vigor

Presenting Author: Ombeline Labaune
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It is common to get the impression that someone moves rather slowly or quickly in everyday life. However, the basis of such a judgment remains largely unknown. Vigor refers to the overall quickness of movement and is often defined quantitatively through the amplitude-speed (or amplitude-duration) relationships that characterize point-to-point movements. In natural behavior both the preferred speed and duration increase with amplitude, which we call here the "vigor law" due to its demonstrated robustness across effectors and individuals. While vigor has been investigated extensively in action, little is known about its counterpart in perception. We thus conducted a series of five experiments to investigate this issue. In Exp1, 2 and 3, participants had to look at dots moving on a screen, representing horizontal reaching movements varying through amplitudes and speeds (and hence durations). They had to judge if movements were fast or slow. Results in these experiments showed that the speed and duration of movements perceived as neither fast nor slow (i.e. medium) robustly increased with amplitude. Thus, the vigor law seems to hold when observers judge movements of others. However, no significant correlation was found between the perceived and the performed vigor which was concurrently evaluated. In Exp4, a dynamic visual illusion was used to go beyond these results. Participants had to judge if movements of dots (of various amplitudes) were faster or slower than a reference movement (RM). Three conditions were considered: (1) movements always had the same speed than RM with durations varying across amplitudes; (2) movements always had the same duration than RM with speed varying across amplitudes; (3) movements had different speeds and durations than RM but complied with the vigor law (derived from reaching movements of several participants from

previous experiments). Results showed that, in (1) participants judged movements faster for smaller amplitudes (corresponding to shorter durations) and slower for larger amplitudes (corresponding to longer durations), suggesting that participants could assess the quickness of motion from its duration. However, we got exactly the reverse trend in (2) for an assessment based on motion speed. Interestingly, when movements followed the vigor law in (3), participants hesitated more and judged movements as neither faster nor slower than RM regardless of amplitude. This suggests that the vigor law could define what is perceived as a neither too slow nor too fast movement. Exp5 followed the same protocol than Exp4 except that all stimuli were based on the own participant's movements (evaluated before). Results were not improved by this protocol. Overall, our findings suggest that the judgment of movement quickness is not simply based on thresholds put on physical quantities such as speed or duration but on the integration of a vigor law, and that the judgment is rather "externally-based" than "internally-based".

2-B-13 Revealing cell types in vivo via dimensionality reduction and graph clustering of spike waveforms

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Anatomical, physiological, and transcriptomic studies suggest a diverse range of neuronal cell types. However, current in vivo methods--such as clustering on waveform features--only differentiate between broad- (BS) and narrow-spiking (NS) neurons. This gap between 'known' and 'observable' diversity in vivo limits our understanding of how cell types shape behavior. Here, we developed a new method (WaveMAP) combining non-linear dimensionality reduction (UMAP) with graph clustering on spike waveforms and show that it better reveals candidate cell classes in vivo. We applied WaveMAP to extracellular waveforms recorded with U-probes from macaque dorsal premotor cortex (PMd) during a decision-making task. WaveMAP revealed BS and NS classes are comprised of at least three and five sub-classes of neurons respectively. These sub-classes had distinct physiological, functional, and laminar distribution properties. First, BS neuron sub-classes had low firing rates (FR), late choice-selectivity, and broad laminar distributions concentrated in middle layers--hallmarks of excitatory pyramidal cells. Second, two sub-classes of NS neurons had high FR, early choice-selectivity, and strong decision-related responses. The laminar distribution of these neurons was consistent with our layer-specific histological counts of calbindin-/calretinin- and parvalbumin-positive inhibitory interneuron densities respectively. Third, an NS sub-class had identical FR and functional properties as candidate excitatory neurons--consistent with findings that PMd excitatory neurons possess biophysical machinery capable of producing narrow spikes. Fourth, another NS sub-class had FR, functional properties, and triphasic waveforms consistent with excitatory axons. Fifth, WaveMAP sub-classes explained heterogeneity in decision-related properties of PMd neurons over and above previously reported laminar differences. Notably, candidate cell types were unidentifiable with traditional feature-based methods--WaveMAP produced more candidate cellular sub-classes and these sub-classes were also better separable in terms of both waveform shape and properties. In summary, WaveMAP provides previously unavailable access to candidate cell types in vivo and enables investigation of microcircuit dynamics during decision-making and motor execution.

2-B-14 Proprioceptive intermuscular feedback: a comparison of femoral nerve stimulation and quadriceps muscle stimulation onto soleus motor output

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Proprioceptive feedback from muscle spindles and Golgi tendon organs (GTOs) have widespread intermuscular projections between muscles implying a role in motor coordination. Studying specific circuits between their input from select muscles of the lower extremity on motor output on other muscles could help to clarify their functional role and influence on motor impairments. Understanding these relationships is complex and continues to challenge researchers and clinicians wishing to improve limb control. Traditionally, nerve stimulation has been used to evaluate intermuscular neural effects, but this technique nonspecifically activates sensorimotor axons based on diameter, thus always biasing spindle feedback. Muscle contraction activates GTOs naturally and reduces spindle firing. This observation provides a unique opportunity to study activation of GTOs more selectively. Indeed, muscle stimulation-evoked twitch contractions were recently shown in the cat to bias intermuscular GTO feedback. Here, we extend this work to the human lower limb by comparing the influence of femoral nerve (FN) and quadriceps (Q) muscle stimulation onto ongoing soleus (SOL) EMG. First, we tested the hypothesis that FN but not Q stimulation will elicit excitatory feedback onto SOL. Second, we hypothesized that the magnitude and duration of inhibition will relate to the magnitude of twitch contractions elicited by FN and Q stimulation. Fourteen participants were tested in a dynamometer chair. They were instructed to maintain isometric contractions at 20% SOL MVIC during which time FN or Q stimulations were applied in separate trials. Two stimulation intensities for FN and Q were used and matched based on dynamometer torque. We found that FN stimulation produced a short latency excitation in SOL EMG for 10 participants, whereas Q stimulation elicited excitation in 4 with the magnitude less than ~40% of that observed for FN stimulation on average. Additionally, we observed that Q and FN stimulation similarly inhibition onto soleus EMG with their magnitude and duration scaled to twitch contraction magnitude. Our results suggest that muscle twitch contractions may be useful to bias intermuscular inhibitory pathways with reduced influence from muscle spindle feedback. In addition to force dependent GTOs, inhibitory feedback could additionally arise from recurrent inhibitory pathways.

2-B-15 Motor planning of sequences produced with different speeds: Evidence from EEG pattern decoding

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The accuracy of a movement sequence plan has been suggested to predict features of the following sequence production. Recent behavioural data demonstrate that a competitive pre-activation gradient of planned movements reflects the preparedness and accuracy of the sequence plan, rather than the timing of the prepared sequence. This study sets out to address whether the neural pre-planning of upcoming movements is modulated by accuracy or speed during a motor learning paradigm and Electroencephalography (EEG) recordings. Further, we aimed to directly compare the behavioural and electrophysiological markers of sequence planning. Eighteen healthy participants were trained for two days (Day 1 and 2) to retrieve and produce from memory a four-finger press sequence with two

different timings (slow vs fast) and a sequence-irrelevant control effector, as prompted by abstract visual cues. The behavioural data during the test phase (Day 3) replicated the previously reported competitive pre-activation gradient: Specifically, we confirmed a decrease in movement availability (RT and error rates) to probe cues 1.5 sec after sequence cue onset for movements associated with later relative to earlier sequence positions. No significant modulation of this pre-activation gradient during planning by sequence speed was found. Availability during sequence planning was more pronounced for sequential movements relative to an unprepared single press, suggesting a graded relative facilitation of all movements. However, the graded availability of movements showed a sequence cost manifested by elevated RTs and errors relative to a prepared single press of a control effector which was not part of any sequence plan. In contrast to the behavioural findings and previous MEG data, multivariate pattern decoding of whole-head EEG patterns obtained on Day 4 suggests a pre-rehearsal of patterns during sequence planning, which was scaled by speed. This pattern could not be observed at the muscular level (Electromyography), indicating a purely centrally driven rehearsal. Finally, using EEG source reconstruction we intend to probe differential contributions of premotor, primary motor and parahippocampal areas to competitive queuing and rehearsal during sequence planning. These findings shed light on the role of control parameters employed in motor sequence planning and their relevance to subsequent sequence performance.

2-B-16 Developing a novel, cost-effective and location-independent approach to investigate upper limb kinematics: remote monitoring of an unrestricted reaching task via smartphone application

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Though ideally motor behavior experiments should be conducted in a controlled environment, such as that found in the laboratory, there is a strong need to develop remote monitoring methods for populations with reduced mobility, allowing for examination of subjects in natural environments and conditions. Furthermore, due to the current pandemic, this necessity appears to be even more compelling. As a proof of concept, we present a novel approach to investigate reaching kinematics remotely. We took advantage of the fact that almost 72% of the smartphone-owners use an Android operative system and of the availability of a free data-logging app (i.e., Androsensor), which allows gathering data from the smartphones' sensors, including triaxial accelerometers, to reconstruct the devices' movement kinematics. We then combined this technological opportunity with the design of a simple and unrestricted reaching task, in which subjects were asked to perform upper-limb movements either in the ipsilateral or in the contralateral individual visual field. We tested this approach on healthy male and female volunteers (n=25, age=27.25 ± 5.4 yrs; 17 males, 8 females), monitoring the upper limbs movements during our reaching task while on one-to-one videoconferences. Following installation of the app on their smartphone, participants were instructed to execute the reaching movements for 20 consecutive times while holding the smartphone in their hand. The experiment included 8 conditions performed in randomized order, in particular ipsilateral and contralateral reaching movements were executed separately by both dominant and non-dominant hand, as well as with eyes open and closed. In order to obtain an acceleration signal baseline for each individual device, the dataset from every subject included an additional recording in which the smartphone was placed on the desk for about 5 seconds.

Pre-processing techniques were employed to transform the raw yxz accelerations to earth-centered inertial accelerations and to attenuate signal noise. From the processed linear acceleration signals we computed other kinematics parameters including the movement distance, the maximal speed achieved, and movement smoothness. Currently, we are performing statistical analysis of the obtained movement kinematics across conditions. Preliminary results seem to be encouraging in terms of discriminating between experimental conditions. The present approach for remote monitoring of reaching movements could provide the great advantage of being cost-effective, time-efficient and scalable which is a step toward a location-independent investigation of motor control.

2-B-17 New tools and refinements to interpret the role of spinal interneurons in motor modularity

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Novel motor plans are translated through the spinal cord, which must quickly and efficiently control the (possibly redundant) joints and musculature. One model explaining motor pattern diversity despite network convergence is motor modularity. Here, dynamic 'building blocks' are combined in sequence or parallel to compactly construct most motor commands. We define a motor 'module' as a neural element evoking stereotyped muscle groups during motor activity, extracted from kinetic or biological features. In the spinal frog, the intrinsic properties of these modules can be studied without influence of higher centers. To study motor modularity within this model, we use the hindlimb-to-hindlimb wiping reflex as an inducible behavior composed of three motor modules. During wiping, the spinal cord must control 1) when modules are recruited and 2) how modules activate groups of motoneurons to produce spatial muscle synergies. Previously we have used spike-triggered averaging of aggregate electromyography (EMG) to discover populations of interneurons whose activity coincided with motor synergies. How these interneurons precisely contribute to motor pool recruitment is unclear. Our new braided intramuscular EMG electrodes can record the activity of single motor units within a muscle, and thus the spiking of single motoneurons. How motoneurons within a motor pool are recruited in the context of modularity is fundamental to understanding spinal control of motor patterning. Spatial synergies could emerge from common interneurons projecting to subpopulations of motoneurons across synergist motor pools. Here, the spiking of two motoneurons in differing muscles would be causally linked. By concurrently recording single motor units within a muscle, or from multiple muscles within a module, we will test if spatial synergies are mediated through discrete subpopulations of the motor pool, and if there are state-dependent variations in this recruitment (e.g. resembling zebra fish swimming recruitment modules). Towards this end, we concurrently make extracellular recordings from populations of spinal interneurons, single motor units, and bulk EMG activity across all major muscles in the leg during reflexive wiping. Because the role of single neurons in the ongoing motor pattern may be relatively minor and spinal-state dependent, we utilize the stochastic dynamic operator (SDO) framework to evaluate relationships between point-processes and continuous state (e.g. neural spikes to EMG) and point-processes to point-processes (e.g. neural spikes to motor units). We have now recorded stable units over several days in spinal frogs. Currently we are evaluating best practices for maximizing the predictive utility of the SDO framework to map the activity of neurons and recruited single motor units to ongoing motor state. This advancement will generate large datasets to elucidate the mechanisms by which motor modules recruit from the motor pools in much greater detail.

2-B-18 Voluntary control of pelvic frontal rotations in belly dance experts

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The present study investigated how belly dance experts perform the "hip shimmy", a complex rhythmic dance movement consisting in a voluntary oscillation of the pelvis exclusively in the frontal plane with maximised amplitude, with no movement of the upper trunk. The aims of this study were to 1) assess whether the amplitude and stability of the pelvic movement can be maximised in certain postural and frequency conditions; and 2) investigate in a 1 to 3 Hz range whether it is indeed possible to oscillate the pelvis only in the frontal plane and to dissociate this one-axis pelvic rotation from potential spontaneous upper-trunk oscillations. Nineteen belly dance experts performed this task in three frequencies and three knee bending postures. Eight joints angles were calculated using the kinematic data of 20 markers over the entire body collected with a motion capture system. Mean amplitude, frequency, and spatial and temporal variability of frontal pelvic oscillations were analysed to characterise motor performance and movement stability. Five Continuous Relative Phases (CRP) were computed to identify the modes and stability of coordination patterns. The results showed that low posture enhances amplitude performance and that the pelvic oscillation amplitude tended to decrease at 3 Hz, although between-condition differences remained small. Temporal stability was highest at 2 Hz and significant inter-individual differences emerged at 3 Hz. CRP analysis revealed an unpreventable coupling between pelvis and upper-trunk oscillations in the frontal and transversal planes. A consistent antiphase coordination between transversal pelvis and upper-trunk may have been caused by anatomical and counter-balancing constraints. In the frontal plane, multiple stable pelvis-upper trunk patterns including inphase, out-of-phase, antiphase evolved to antiphase predominance and inphase disappearance upon reaching 3 Hz. In sum, increasing frequency highlighted the concomitance of two control phenomena: the inter-individual differentiation in performance and standardisation of the possible pelvis-upper-trunk patterns.

2-B-19 Humans do not directly control force during motion

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Despite long feedback delays and extremely low bandwidth actuators (i.e. muscles), humans excel at physical interaction. An understanding of how they do so is critical for designing robots that can safely and effectively interact with humans (e.g. prostheses, exoskeletons, physical human-robot collaboration, and rehabilitation robots). Practically speaking, this understanding should be in the form of a mathematical model that competently describes human interaction control with minimal complexity. A majority of the robotics and human motor control literature has successfully focused on regulating motion during free-reaching tasks. However, to understand physical interaction, information about force must be incorporated as well. If humans regulate motion during free reaching, a simple extension of this idea to contact tasks may be to regulate force during contact. In robotics, this is the basis of hybrid position/force control (Raibert and Craig 1981); in motor neuroscience, this idea is often implicitly assumed, e.g. in the description of internal models (Chib et al. 2009). In this work, we tested the hypothesis that humans can directly regulate force independent of motion during physical interaction. To do so, an experiment was conducted where subjects were instructed to apply a constant 5N tangential force on a robot manipulandum while it moved on an elliptical path. Subjects were occasionally given visual feedback of their force in relation to the target force. After initial learning (~10% of trials), the force error quickly reached steady state. Further practice, with or without feedback, did not further improve performance. Autocorrelation analysis revealed that the force errors observed throughout were position-dependent. Counter to our hypothesis, these results indicate that humans cannot directly control force independent of motion. Moreover, the level of force error was significantly higher than previous experiments where subjects performed the same task but were instructed to apply 0N force (Maurice et al. 2018). In that experiment, force error was also position-dependent. While fundamental aspects of human motor control during physical interaction will continue to be debated, this work demonstrates that during physical interaction motion and force are coupled. A mathematical model that competently describes the control of human interaction must entail both force and motion and the relation between them. Furthermore, to design devices that collaborate with humans, the effects of motion and force cannot be considered independently.

C – Posture and Gait

2-C-20 Neuromuscular coactivity, efficiency and complexity are differently affected by cognitive and mechanical constraints during beam walking

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Beam walking can detect subclinical impairments in dynamic balance. Restricting the use of arms may further increase the specificity and sensitivity, as arm movements counterbalance leg movements, contributing to stability. Adding a cognitive task can also affect dynamic balance by increasing attentional demand. However, it is still unclear how and if at all arm posture and cognitive task during beam walking would affect neuromuscular control of legs and trunk. Thus, our aim was to determine if and how cognitive and mechanical constraints could alter neuromuscular control and task performance during beam walking. Younger (18 - 30 y) and older (65 - 76 y) adults (44.2±23.1 y, n=31) walked on a 6-cm wide, 2-cm high, 4-m long aluminum beam with arms free and folded at the chest, with and without a cognitive task (serial subtraction by 3). Two video cameras positioned perpendicular to the beam on each side were used to determine the instant of balance loss (i.e., unfolding the arms or stepping off the beam). Beam walking performance was quantified as the normalized distance walked (i.e., total distance walked / max possible distance across all trials). We used non-negative matrix factorization to extract muscle synergies from surface EMG recordings of 13 right leg and trunk muscles. Differences in modular control complexity were assessed by comparing the number of muscle synergies (nsyn) and the variability accounted for by a single muscle synergy (VAF-1). The number of significantly active muscles per synergy (Wmus) and the sum of significantly active muscles per synergy (Wsum) were compared to assess muscle coactivity and modular control efficiency, respectively. Addition of the cognitive task decreased normalized distance walked (without: 0.79±0.15, with: 0.74±0.19, $p=0.033$; $d=0.3$), indicating the task was made more difficult, and also increased Wmus (without: 4.3±1.5, with: 4.9±1.6, $p=0.011$; $d=0.39$) and Wsum (without: 2.2±0.6, with: 2.4±0.6, $p=0.038$; $d=0.34$), implying increased muscle coactivity and less neuromuscular efficiency in the presence of distraction. On the other hand, restricting arm motion decreased the normalized distance traveled (folded: 0.73±0.18, free: 0.79±0.17, $p<0.001$; $d=0.35$), which was accompanied by increased VAF-1 (folded: 71.8±5.7%, free: 70.9±5.4%, $p=0.016$; $d=0.16$), suggesting less complexity of modular control with arms folded and also higher difficulty in beam walking performance. In conclusion, both cognitive and arm constraints made beam walking more challenging, which was met by greater neuromuscular coactivity and less efficiency, besides the reduced neuromuscular complexity, respectively. FUNDING: FAPESP/Brazil (Grants 2018/18081-0 and 2019/00387-9).

2-C-21 Impact of general anesthesia on gait and posture control

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The risks of General Anesthesia (GA) have decreased over the past 30 years thanks to improvement of the drugs and better monitoring of the patients. But in the meantime, the population is ageing and the proportion of outsurgery has dramatically increased to reach up to 70% of the cases performed. In that context a better understanding of the impact of GA on postural and gait control is critical, especially when considering that every "fit-enough" 75 or 85 year old patient will be asked to go back home immediately after surgery. What are the prerequisites to include a patient in an outsurgery protocol? A good understanding of the patient, the absence of predictable surgical complications, the possibility to reach the hospital in case of need and a next of kin available. Before allowing the patient to leave the hospital, a standard questionnaire is administered, most often by a nurse. This evaluation includes vital parameters, ability to walk, presence of nausea or bleeding, and pain. The gait and posture, and the neurological statut are rarely assessed and when they are it is by a clinical exam. In order to better assess the postoperative state of the patients, thanks to a recently developed platform, we have monitored 40 patients during the surgery, recorded their EEG throughout the procedure and we have quantified their postural control and their gait before and 3 hours after GA. Our first result was a significant impact of GA on gait and postural control in all the patients, including severe alterations of the gait parameters in 3 patients. One patient was a young and healthy man without any past medical history, the other two were older but without previous history of gait impairment. Our second result was that one third of the patients presented a persistent frontal increase in the alpha wave on the EEG (increase of the alpha wave in this territory being considered the signature of anesthetics). However, we did not find any correlation with their motor control. None of the patients that we identified as having an impaired gait control or a persistent alpha wave in the frontal area had any failed item on the usual test performed before hospital discharge. Further work is needed to better characterize the signification of the abnormalities that we have identified. But our results shed a new light on the outsurgery process and may help to identify patients that should be monitored more carefully. In the actual context of hospital bed constraints and the incentive to increase the outsurgery above 70% of the cases, an objective tool able to discriminate which patients may benefit from an hospitalization may be very useful for doctors.

2-C-22 Association of brain functional connectivity and regional gray matter volumes with mobility measurements in young and older adults

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Advancing age leads to peripheral and central nervous system (CNS) changes and, consequently, mobility declines. These CNS changes can be functional and/or structural. Here we test whether brain functional connectivity and regional gray matter volumes differ between young adults (YA), high-functioning older adults (h-OA), and low-functioning older adults (l-OA), and whether these metrics are associated with mobility performance. The mobility measures currently include the 400m walk test h-OA and l-OA subgroups are differentiated based on their performance on the short physical performance battery (l-OA<8/12). Results to date include 11 YA (24±4.4), 19 h-OA (76±3.8yrs), and 4 l-OA (80±3.7yrs). For brain functional connectivity, we first quantified ten different networks through a seed-to-voxel analysis on 110 subjects' (24±2.4yrs) resting state functional magnetic resonance imaging (fMRI) data from the Washington University 120 database. Three of these networks were generated from brain regions of interest (ROI) that we hypothesize are critical for mobility performance with advancing age, including left and right dorsolateral prefrontal cortices (l/r DLPFC), and the anterior cingulate cortex (ACC). We quantified within and between network connectivity for our participants, to generate network segregation scores ((within-between)/within) for l/r DLPFC and ACC networks. We quantified gray matter volume using CAT12 for the l/r DLPFC and ACC, assessed age group differences, and determined whether the measures correlate with mobility 400m walk time). The functional network segregation scores differed between YA, h-OA, and l-OA, where YA have greater segregation scores for each ROI (>0.8 Cohen's d). Regional gray matter volumes exhibited a similar pattern to the segregation results (~0.6 Cohen's d). Network segregation scores were positively associated with 400m walk speed for both OA groups (more segregation was associated with faster walk time). On average, across the networks of interest, the effect sizes (r) were 0.21, 0.33, 0.78 for YA, h-OA, and l-OA, respectively. Similarly, r/l DLPFC and ACC gray matter volumes were positively associated with 400m walk speed; across all three groups (YA: 0.67, h-OA: 0.33, l-OA: 0.74). Our preliminary results indicate that age-related differences in the function and structure of frontal and cingulate cortices are associated with mobility decline with age. Supported by National Institutes of Health (U01AG061389).

2-C-23 Vestibular contributions to walking vary with the stabilization demands of the gait pattern

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Stable walking relies critically on motor responses to head motion sensed by the vestibular system, which are phase-dependent and modulated differently within each muscle. Vestibular contributions to mediolateral stability, for example, may be related to foot placement produced by muscles around the hip and to ankle torque at push-off driven by muscles of the ankle. These vestibular-driven responses, however, are almost entirely absent throughout the gait cycle when the vestibular disturbance is directed in the sagittal plane. Because stability in the sagittal plane is maintained largely passively - due to passive dynamics of the legs - it may be possible that the control of whole-body stability during locomotion requires less feedback-driven control as compared to the frontal plane. Therefore, it remains unclear whether these phase- and muscle-dependent responses in the mediolateral plane also vary based on the stabilization demands of the locomotor tasks. To test this possibility, we investigated changes in vestibular control of stability while humans (N = 11) walked normally, with mediolateral stabilization, and when walking with a wide and narrow base. We estimated the coherence of an electrical vestibular stimulation (EVS) with muscle activity and mediolateral ground reaction forces and calculated the local dynamic stability of trunk kinematics as an estimate of the stabilization demands of walking. When subjects walked with external stabilization, local dynamic stability increased and coherence between EVS and all muscles/forces decreased compared to normal walking. Similarly, wide-base walking decreased vestibulomotor coherence (muscle activity and forces), though gait stability did not differ relative to normal walking. By making the body inherently stable in the mediolateral direction, the reduction in vestibular-evoked responses was similar to the near absence of vestibular contributions when a vestibular disturbance is directed in the anterior-posterior direction. On the other hand, narrow-base walking also increased local dynamic stability, but produced complex muscle-specific increases and decreases in coherence that led to a net increase in vestibulomotor output reflected in the ground reaction forces. This suggests that the highly regulated conditions of narrow-base walking, which is likely required to constrain body motion within restricted margins of error, are driven in part by a net increase in the use of vestibular input. Overall, these results show that while vestibular contributions may vary with gait stability, they depend critically on the stabilization demands (i.e. control effort) needed to maintain a stable walking pattern.

2-C-24 Characterizing the nervous systems control of human leg external forces

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Our legs act as our primary contact with the surrounding environment, generating external forces that enable agile motion. The control of the magnitude of this force, and of the position where the force is applied by the foot onto the ground are key determinants of translational and rotational acceleration. Effective control of these force properties may help explain differences between humans, between humans and other animals, and between humans and engineered systems. The objective of our work was to characterize the performance of the human leg in controlling the force-magnitude and position of an externally applied force. To accomplish this, we built an apparatus that constrained healthy young participants (f=4,m=10) standing above a ground embedded force platform. The constraints immobilized the body but allowed participants to exert variable but controlled forces onto the ground. This involved selectively pushing either more or less with their leg (force-magnitude) or shifting the position of the force beneath their foot (force-position). We provided real-time visual feedback of either the leg force-magnitude or position that participants were exerting against the force platform and instructed participants to best match their real-time signal to prescribed target step functions. We tested target step functions of a range of sizes and characterized the control of external forces in terms of speed (rise time,bandwidth), overshooting the target, steady-state error, and steady-state variability. We found that when controlling leg force-magnitude for step targets of size x0.45 bodyweight, participants required 205±64ms(mean±std) to approach a new steady-state value (rise time), achieving a bandwidth of 1.8±0.5Hz. Participants overshot the step target by 19±11%, had a steady-state error of 2.9±1.0% bodyweight, and had a steady-state variability of 3.1±1.0% bodyweight. We found similar control performance for a range of target step sizes and the control of force-position. In addition to this control characterization, we modelled the measured control of external forces as a 2nd order control system and used system identification methods to estimate the unknown model parameters. We found that our controller well-described the observed force control characteristics with best-fitted R^2 values for both force-magnitude and position control above 0.85 for the range of tested target step sizes. This controller, and by extension the human leg, rises to step changes in 165 ms but overshoots targets by

15%. It settles on targets in 170 ms and then exhibits no steady-state error or variability. It can accurately track changes to force-magnitude or position that oscillate twice per second (bandwidth of 2Hz). Benchmarking force control performance in young healthy humans will be useful for understanding the effect of age, disease, and injury on human agility. It will also be useful for understanding the limits to agility in legged robots, and wearable devices.

2-C-25 Removing artificial jumps from kinematic recordings with multiple cameras

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Summary In standard marker-based motion capture systems, the 3D position of each marker is reconstructed from the 2D views of a set of cameras. When the subset of cameras viewing a given marker changes, the reconstructed marker position jumps suddenly from one frame to the next. Alt-hough these jumps are small (0.1 - 1 mm), since frame rates are high (120 - 500 Hz), they cause drastic errors in speed estimates (up to 0.5 m/s). Typically, the problem is countered by low pass filtering which distorts the kine-matic data during abrupt changes in the marker move-ments, such as occurs at heel strike during running. We propose and compare 2 methods for identifying and re-moving these jump artifacts. We validate both methods on kinematic data of static balance, walking and running, recorded at 2 different frequencies using 2 different mo-tion capture brands. Both methods reliably remove jump artifacts while keeping the original signal intact, and largely improve estimates of marker speed.
Introduction The recording of kinematic data using modern high-speed cameras combines high spatial accuracy with very high recording speeds. However, the reconstruction of 3D marker positions from the 2D views introduces artifical jumps in marker positions, which effectively limit the accuracy of kinematic recordings. Methods For detecting jumps, we compare 2 methods: 1. the signal is high-pass filtered then differentiated, and a cutoff on the speed amplitude is used; 2. reversals in acceleration are detected. Once the jumps are identified, the speed dur-ing the jump is interpolated from the signal before and after the jump. The speed is then integrated to obtain posi-tion, and slow drift between the reconstructed and meas-ured positions is removed. We validated both methods on 3 datasets: 1. treadmill running recorded at 500 Hz, 2. overground walking and static balance recorded at 200 Hz; 3. artifical signals with large speed, abrupt changes in speed, and added noise and jumps. Results Both methods robustly identify and remove marker jumps, independent of the capture frequency and the movement velocity. They provide a drastic reduction in the noise of the marker velocities, without introducing signal distortions during abrupt changes in marker speed, such as at heel strike during running. The reconstructed marker position remains within 2 mm of the recorded marker position. Conclusions The proposed novel method for removing kinematic jumps is highly selective and reliable in all tested condi-tions. It is the first one available and is advised for kine-matic recordings with multiple cameras.

2-C-26 Changes in gait kinematics induced by applied stiffness using a hip exoskeleton

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Neurological disorders and aging induce impaired gait kinematics. Despite recent advances, effective methods using lower-limb exoskeleton robots for retraining individuals with abnormal kinematics are as yet limited. Robotic gait rehabilitation technologies have not outperformed current standards of physical care, possibly because they discourage active engagement of patients in making movements and may suppress the natural oscillatory dynamics of walking. In this study, applying virtual stiffness using a hip exoskeleton robot was investigated as a possible method to guide users to change their gait kinematics without discouraging their active engagement and without suppressing the natural dynamics of walking. With a view to applications in locomotor rehabilitation, either to provide assistance or promote recovery, this study aimed to assess whether imposed hip stiffness induced changes in the gait pattern; and whether any changes persisted upon removal of the intervention, which would indicate changes in neuro-motor control. Both positive and negative stiffness between the thighs induced immediate and persistent change of gait kinematics. However, the results showed little evidence of changes in neuro-motor control, not even short-lived aftereffects. In addition, stride duration was not affected by the applied stiffness during walking, suggesting that at least two dissociable layers exist in the neuro-motor control of human walking. The significant and reproducible changes in kinematics, without neuro-motor adaptation, suggest that applying hip stiffness with an exoskeleton may be more suitable as an assistive technology for compensation than as a therapeutic technology to promote recovery. The lack of neuro-motor adaptation also suggests that, within broad limits, the central nervous system is surprisingly indifferent to the details of lower limb kinematics.

2-C-27 Modulation of corticospinal drive during locomotor adaptation is task-specific

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Introduction: Corticospinal drive to the tibialis anterior (TA) quantified by intramuscular coherence is modulated in healthy young adults during split-belt treadmill adaptation and correlated with temporal asymmetry. Corticospinal drive to TA is also increased during visually-guided walking, but the changes during visuomotor locomotor adaptation are unknown. The objective of this study was to examine the differences in corticospinal drive to the TA and plantarflexors (PF) during split-belt adaptation (SB) and visuomotor locomotor adaptation (VM). We hypothesized that with VM, modulation in intramuscular coherence would be observed in the PF during stance phase as opposed to the TA during swing phase, as previous studies have shown that planning limb trajectory during stance is important for visually-guided gait. Methods: 16 young healthy adults participated in this study (Age: 23.4 ± 7.1 years; 9 Females). Participants were grouped into the SB group (n = 7) and the VM group (VM; n = 9). SB walked with the split-belt treadmill set at 0.6 m/s for the slow leg, and 1.2 m/s for the fast leg. VM walked with real-time visual feedback on the toe position and stepping targets. During adaptation, VM walked with altered relationship between treadmill and screen space on one side, where the targets on one side moved slower than the other. Kinematics were measured with reflective markers on the lower extremity, and electromyography (EMG) was collected using two pairs of surface electrodes placed at the proximal and distal ends of TA, on the medial gastrocnemius, and on the soleus. EMG-EMG coherence was calculated between the two pairs of EMG on the TA during the swing phase, and between the PF during the stance phase of gait for the beta (15-30 Hz) and gamma-bands (31-45 Hz). Results: In the SB group, TA and PF coherence was modulated in the slow leg only (TA β: $p = 0.006$; TA γ: $p = 0.005$; PF β: $p = 0.040$). Beta- and gamma-band TA coherence and beta-band PF coherence in the slow leg was higher during early adaptation compared to baseline and late adaptation. In the VM group, there was no evidence of modulation in both TA and PF coherence in the slow leg, and in TA coherence in the fast leg, but PF coherence in the fast leg was modulated in both the beta- and gamma-bands (β: $p = 0.002$; γ: $p = 0.008$). Both the beta- and gamma-band fast leg PF coherence was lower during early adaptation compared to baseline. Discussion: With the split-belt locomotor paradigm, corticospinal drive was increased to the TA in swing phase during early adaptation, while visuomotor locomotor adaptation decreased corticospinal drive to the PF in stance phase. The decrease in corticospinal drive during early visuomotor locomotor adaptation may be indicative of an inhibitory cortical mechanism that occur during stance phase. Together, our results suggest the modulation observed in corticospinal drive during locomotor adaptation is specific to the type of adaptation task.

2-C-28 Frequency-dependent force direction elucidates neural control of balance

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Balance is a challenging task that requires control of translational and rotational motions. Humans use foot-ground interaction force, characterized by direction, point of application, and magnitude, to manage body accelerations. Previous work identified that the vertical height of the point where foot-ground interaction forces intersect exhibited a consistent, frequency-dependence across multiple subjects. To test whether this frequency-dependent behavior provided a distinctive signature of neural control or was a necessary consequence of biomechanics, i.e., maintaining upright balance, this study simulated quiet standing and compared the results with human subject data. When a standing human was modeled as a single inverted pendulum, no controller could reproduce the experimentally observed frequency-dependence of the intersection point. The simplest competent model that approximated a standing human was a double inverted pendulum with torque-actuated ankle and hip joints. It was stabilized by a linear feedback controller based on position and velocity errors of each joint. Three key parameters were explored. First, the simulation was set to ensure minimal control of ankle and hip torques. Then, the noise ratio between the ankle and hip torques was adjusted to match the high-frequency asymptotic behavior of the frequency-dependent intersection point. Finally, the relative penalty on the ankle and hip joint torques was varied to fine-tune the intersection point curve in simulation. Numerous controller parameter sets could stabilize this model and produce the change in the vertical position of the intersection point with increasing frequency observed in human individuals. Such decrease in height appears to reflect a biomechanical constraint. However, the controller that best reproduced the results observed in human standing used minimal control effort and penalized the use of the hip torque more than the use of the ankle torque. These observations imply that human subjects employed a neural strategy that minimizes overall control effort to balance and prioritizes the use of the ankle torque. This work introduces a systematic method by which human data can be reproduced by selecting specific, quantitative control and noise parameters. The present innovative approach may serve as a powerful tool to match simulation data with human subject data, thereby quantifying subtle differences in neural strategy for a variety of human balance conditions.

2-C-29 Navigation of unexpected obstacles while fatigued: Considerations for workers in physically--demanding professions.

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In various occupational settings, workers are in an unpredictable environment that disposes them to trips and falls that can lead to injury and lost work time. Under conditions where one is in a physically fatigued state, this risk of injury may be compounded due to a decreased ability to perceive tripping hazards and/or safely negotiate them. However, there is a lack of work detailing the impact of physical fatigue on obstacle negotiation ability. Therefore, the purpose of this study is to better understand how highly fit individuals, who represent those in physically demanding occupations, navigate a suddenly appearing obstacle. Twenty-one young, healthy participants were tasked with walking across a dark room. When they came within 50 cm of an obstacle placed in a random location it would become illuminated--requiring participants to quickly perceive and step over the obstacle. Participants did this task five times in a rested state first and again after completing an exercise protocol that mimicked the movement patterns of firefighters and a validated inclined walking fatigue protocol. To quantify spatiotemporal obstacle negotiation mechanics, three-dimensional motion capture was used to track coordinate data of anatomical markers placed on the pelvis and legs. Results indicated that a significant main effect of fatigue. Specifically, follow-up comparisons indicate that participants had a significantly decreased leading and tailing toe clearance as well as significantly higher leading heel clearance. Secondly, there was also a significant increase in gait velocity post-exercise, which is perhaps indicative of a need for greater gait stability while approaching the obstacle. Finally, regression analysis found that height and participant's estimated VO2max significantly predicted their leading foot placement during the obstacle approach, while only VO2max significantly predicted trailing foot placement. In total, results suggest that physical fatigue leads to riskier obstacle negotiation behaviors for highly fit individuals. In addition, higher cardiovascular fitness levels correlate with safer crossing strategies when in a physically fatigued state. This relationship may be due to higher fitness mitigating the physiological effects of fatigue on visual perception and control of the legs during obstacle negotiation. These findings emphasize how occupational health and safety guidelines should consider introducing exercise programs to increase cardiovascular fitness, and thereby reducing the risk of trips and falls in the workplace.

2-C-30 Binocular rivalry dynamics during locomotion

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Perception is affected by internal states, such as arousal and attention. Recent animal models have noted that during locomotion these states are altered. These alterations may influence visual function, such as binocular rivalry. Therefore, we investigated the effect of locomotion on perceptual alternation dynamics in binocular rivalry. The rivalry stimuli were orthogonal gratings, one contrast-modulating at 0.8Hz (matching average gait frequency) and the other at 3.2Hz. Stimuli were presented in a virtual reality headset and two conditions were compared: stationary and walking. Foot position was monitored continuously using tracking devices so that gait cycle could be measured. During the walking condition, participants viewed the rivaling gratings for 60s trials while following a circular path (20m circumference) that was rendered in a minimal virtual reality environment. During the stationary condition, observers viewed the same stimuli and environment while standing still. The task was to continuously track the dominant precept with handheld controllers. Overall predominance (proportion of viewing time) indicated that the 0.8 Hz modulation dominated the 3.2Hz modulation (0.52vs0.48, stationary; 0.53vs0.47, walking). Average duration of dominance periods increased during walking, but more for 0.8Hz (by 3.5%) than for 3.2Hz (2.1%). Distributions of dominance times also showed the 0.8Hz modulation dominated longer than 3.2 Hz during walking, with the distribution peak shifting to a shorter duration. To assess the effect of locomotion on rivalry dynamics, the rivalry switches were binned as a function of stride cycle timing. For the majority of participants, there was an increased frequency of switches between 40-50% and 90-100% of the stride cycle. Overall, the results indicate that the act of walking causes a slowing of rivalry and may constrain alternations in rivalry to occur at key phase points in the gait cycle.

D – Integrative Control of Movement

2-D-31 Effect of gait variability on prefrontal cortical activation during normal walking among community dwelling older women

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Background: Impairments in mobility and cognition are common in older adults and, are expected to worsen with age. Among these mobility impairments, gait abnormalities related with cognitive decline includes increased gait variability and are associated with increased aging. However, their relationship to brain activation while walking is still unknown. The objective of this study was to examine the effect of gait variability on prefrontal cortical (PFC) activation during normal walking among community dwelling older women. We evaluated PFC activation through mean oxygenated hemoglobin (HbO2) levels and deoxygenated hemoglobin (Hb) levels. We hypothesized that there will be higher PFC activation, i.e., higher HbO2 levels and lower Hb levels, with increases in gait variability. Further, we expected this change to higher in high gait variability (HV) group compared to low gait variability (LV) group. Methods: We recruited twenty older women which were divided into HV (n=9, 64.78±4.7 years, 1.42±0.28m/s) and LV (n=11, 68.18±5.2 years, 1.32±0.29m/s) group based on stride width standard deviation as gait variability metric (SD= 0.022). We collected their normal walking (NW) data on instrumented treadmill through Cuefors 2 software while wearing Functional Near-Infrared Spectroscopy (fNIRS) headband. FNIRS was used to quantify PFC HbO2 and Hb levels. A linear mixed effect model (LMM) was conducted to investigate the effects of cohort (HV vs LV), task (NW1 vs NW2), and interaction between cohort and task on HbO2 and Hb levels. To control for multiple comparisons, post-hoc Least-Squares Means tests were carried out. Results: Before conducting the LMM analysis, we carried out group comparisons for gait speed (GS), Womac pain score (WS), and BMI. We found significant differences among the two groups (HV vs LV) for GS ($t=4.39$, $p<0.001$) and WS ($t=-10.07$, $p<0.001$), which were included as covariates for LMM analysis. The LMM showed that HbO2 levels increased in HV group compared to LV ($p<0.001$). We also found significant differences among the tasks (NW1 vs NW2) ($p<0.001$). Also, there was a significant 2-way interaction in Hb level between cohort and task ($p<0.001$). Post-hoc t-tests showed that: 1) HbO2 levels increased significantly in HV group compared to LV during NW1 ($p<0.001$) and NW2 ($p=0.01$); 2) HbO2 levels decreased between NW1 and NW2 among LV group; 3) Hb levels decreased in HV compared to LV during NW2 ($p<0.001$); and 4) lastly, there was significant Hb level differences between NW1 and NW2 among LV group ($p<0.001$). No other significant differences were found. Conclusion: We found that as the gait variability increases during a normal walking task, there was increase in PFC activation seen among older women. This suggests that as the gait abnormalities increases among older adults, there could be an issue of executive dysfunction, as suggested by the decreased efficiency in PFC activation using fNIRS, which may lead to cognitive decline.

2-D-32 Persisting impact of multitasking on the reaction time in simulated car driving: Beyond the PRP effect

Presenting Author: Otmar Bock

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In simulated car driving, participants' braking responses are delayed when an additional task is administered shortly before the braking task. This delay is limited to stimulus onset asynchronies (SOA) of up to 400 ms, and was attributed to a psychological refractory period (PRP) necessitated by a central processing bottleneck (e.g. Levy et al., 2006). Here we investigate whether some delay persists even when SOA is substantially longer than 400 ms. Data from 120 older persons were analyzed (69.56 ± 3.62 years of age; 53 females). They were instructed to follow a lead car in a driving simulator, and to brake whenever the lead car brakes. In the multitasking condition, additional tasks (typing, reasoning or memorizing, presented visually or auditorily) preceded the braking tasks with an SOA of 11.34 ± 2.36 s. In the control condition, additional tasks were absent. Linear mixed models were used for data analysis. Dependent variables were reaction time (RT, brake light onset to gas pedal release) or movement time (MovT, gas pedal release to brake pedal engagement). The random effect was "participant ID". Depending on the model, fixed effects were "SOA", "condition", or "SOA" and "RT". Responses in the multitasking and in the control condition were categorized as anticipatory ($RT < 0.2$ s, 20.3%), regular ($0.2 \text{ s} \leq RT \leq 2.5$ s, 59.3 %) and delayed ($RT > 2.5$ s, 20.4%). Analyses of regular responses yielded that (1) in the multitasking condition, RT didn't depend on SOA ($p = 0.397$), (2) RT was significantly longer in the multitasking condition than in the control condition ($p < 0.001$; mean difference 0.1589 s) (3) in the multitasking condition, MovT tended to increase slightly with SOA ($p = 0.055$) and increased significantly with RT ($p < 0.001$), and (4) MovT was not significantly longer in the multitasking condition than in the control condition ($p = 0.755$; mean difference 0.031 s). Our findings document that multitasking can have a persisting effect on the reaction time of braking responses, that last for at least 11 s. This effect is partly compensated by speeding up the movement time of braking responses. We attribute the observed persisting effects to the formation of a task expectancy for braking ("task set") in the control condition, but not in the multitasking condition. Supported by Priority Program, SPP 1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), grants BO 649/22-1, VO 1432/19-1, VO 1432/22-1, and by European Social Fund and the Free State of Saxony grant 100342331

2-D-33 Expected intensity of action outcome is embedded in action kinematics

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At the base of any goal-directed action lies the expectation of its sensory consequences. Previous studies showed that when sensory stimuli are the consequence of self-generated, voluntary actions, neural evoked responses and perceptual reports of those stimuli are modulated relative to those evoked by physically identical stimuli triggered by an external source. It is suggested that such modulations are driven by prediction signals originating from the motor system, with respect to the sensory outcome. However, while most studies focus on how motor output modulates responses to sensory outcomes, there is little evidence demonstrating how such expectations affect motor output. In the current study, we examined participants' motor output (button press force trajectories), which were explicitly coupled with sensory outcomes of two intensities: faint and salient. Participants' force trajectories were measured during generation of either auditory, tactile, or visual stimuli. We found that across all modalities, participants (n=72) applied greater force when they pressed buttons to generate faint compared with salient stimuli. Importantly, this effect was absent when participants pressed the buttons in response to (rather than to generate) the same faint or salient stimuli. In addition to our behavioral findings, preliminary EEG results show a reduction in N100 amplitude for auditory stimuli triggered by stronger button presses, suggesting a possible link between press force and sensory evoked response. Such a link supports a mechanism in which the degree of motor inhibition on sensory regions is proportional to the degree of motor output. Taken together, our results provide a potential explanation for the commonly reported sensory modulations of self-triggered stimuli.

2-D-34 Does time matter? Quick performance changes during a short series of trials in a cognitive-motor integration task

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Spatial locations of guiding sensory information and the required motor action are often in alignment, representing a coupled visuomotor task. Eye and hand movement directions can also be decoupled, which can require rule-based visuomotor transformations, or cognitive-motor integration (CMI). CMI performance across a short series of trials has been well characterized in healthy and neurologically impaired populations. However, little is known about CMI performance changes along these trials. Thus, we investigated time-related performance changes during a short series of coupled and decoupled visuomotor tasks. We re-analyzed data from 20 healthy young adults (m=21 yrs., 10 females) who performed two visuomotor tasks. In a coupled "Direct" task, participants slid their finger along a vertical touch screen to move a cursor from a central target to one of four peripheral targets, with eye- and hand movements aligned. In a decoupled "CMI" task, targets were in a different plane from the hand movement, and cursor feedback was 180° reversed, i.e., decoupled eye- and hand movement direction. Twenty trials were performed in each task condition and included five movements to four peripheral target directions (up, down, left, right). For analyzing, trials were split into five blocks of four trials (trial 1-4, 5-8, 9-12, 13-16, 17-20). Each block included one movement to each target direction. Temporal and spatial movement preparation and execution variables were analyzed across Block (1-5) and Condition (Direct, CMI). ANOVA revealed significant effects of Block for reaction time ($p<0.01$) and movement time ($p<0.05$), significant effects of Condition suggesting superior performance in condition Direct (all $p<0.001$) except for initial direction error and path length ($p>0.05$), and a significant Block x Condition interaction for movement time ($p<0.05$). Post-hoc analysis revealed a decrease in movement time in the CMI task until the third block, but no changes along the Direct task (all $p>0.05$). Similar patterns were found for reaction time, however, the interaction showed only a strong trend ($p=0.055$). No significant Block or Block x Condition effects were found for initial direction error, path length, peak velocity, and endpoint error (all $p>0.05$). Our results quantify performance changes during a short series of trials during a CMI task when the eyes and hand moved to distinct spatial locations, but no changes when eye- and hand movements were made to similar directions. Quick CMI performance improvements were present only for temporal aspects of movement execution and indicated a similar trend for temporal characteristics of movement preparation. The present findings reveal quick CMI changes in young healthy individuals and provide further insights into basic mechanisms of CMI performance during decoupled eye-hand movement control. Future studies could investigate whether the same patterns of findings occur in elderly or neurologically impaired individuals.

2-D-35 The timing of catching: Visual and kinesthetic information in experts and novices

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Catching a ball is a complex, 3D movement, which is difficult to study given the many degrees of freedom, the spatial nature of the movement and the variable endpoint. The movement is planned on the basis of kinaesthetic (in case the ball is self-thrown) and visual information which enrolls gradually. We have recently developed a method for analysing the control of such free, unperturbed movements on the basis of the empirical knowledge that planned movements are smooth. Jugglers and novices caught balls that were either self-thrown or thrown by the experimenter, and either entirely visible or invisible until reaching the highest point in the trajectory. We analysed the time from which the hand's trajectory could be fitted by a minimum jerk trajectory. Experts, but not novices, showed an advantage of 60 ms for self-thrown balls. For externally thrown balls, both groups were alike. In the externally thrown-occluded condition, all catchers' smooth-phase were considerably delayed, by about 60 ms for jugglers and 100 ms for novices. Our results thus show, that the timing of the available information is reflected in complex and rapid catching movements in 3D. Kinaesthetic information from the throwing hand was only advantageous for jugglers. Moreover, the results confirm that visual information is most helpful in the second half of the flight, and that jugglers can use this information earlier than novices. We conclude that the smoothness of free movements is indeed an important diagnostic property for studying the process of motor control.

2-D-37 Reduced descending modulation of spinal reflexes in neurotypical older adults

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Aging-related declines in information transmission and processing of synaptic inputs along the neural axis can impair sensorimotor function, resulting in poor balance, reduced walking ability, and increase fall risk (Li et al., 2018; Horak 2006). There are significant knowledge gaps in our understanding and ability to quantify aging-related effects on sensorimotor neural circuit function. Here, we utilized paired cortical and peripheral nerve stimulation (PNS) to evaluate aging effects on descending modulation of spinal segmental reflexes. When a subthreshold transcranial magnetic stimulation (TMS) conditioning pulse is delivered before or after PNS, the resulting early and late-interval facilitation of Hoffman's (H-) reflexes probes the influence of direct, fastest descending and indirect, slower conducting descending volleys on the spinal motoneuron pool, respectively (Lopez et al., 2020; Gray et al., 2017; Nielsen and Petersen, 1995). We hypothesized that descending cortical modulation of spinal reflexes would be reduced in older versus young adults. We predicted that older adults would have less facilitation of H-reflex responses when spinal circuits were conditioned with subthreshold TMS. To date, 8 older adults (6 females; 50-79 years) and 10 young healthy adults (8 females; 22-28 years) have been evaluated. PNS was delivered to the posterior tibial nerve to elicit a soleus H-reflex recruitment curve. Subthreshold TMS to the soleus M1 hotspot was paired with PNS (intensity 50% Hmax) using inter-stimulus intervals (ISIs) ranging from -6ms to 10ms. TMS-conditioned H-reflex amplitudes were used to calculate %modulation (conditioned/unconditioned*100%). Preliminary results revealed that young adults showed an earlier onset of %modulation (-4 ± 1ms ISI) compared to older adults (-1 ± 5ms ISI) ($p=0.015$), which suggests that aging-related declines in transmission may contribute to delays in descending modulation of spinal reflexes. Moreover, the magnitude of %modulation at the -1.5ms ISI was larger for young adults (172% ± 68%) compared to older adults (118% ± 32%) ($p=0.09$), demonstrating potentially reduced modulation from direct, faster descending pathways. At +10ms ISI, consistent with indirect, slower descending pathways, %modulation for young adults (263% ± 118%) was significantly larger compared to older adults (152% ± 41%) ($p<0.05$). Our results suggest that modulation of spinal reflexes mediated by direct, faster conducting pathways is delayed in older adults, which could be due to reduced structural integrity of descending tracts. However, modulation of spinal reflexes via indirect, slower conducting pathways, possibly involving brainstem circuits, may be more impaired by aging. These results may have implications for aging-related changes in the neural control of balance and movement from subcortical to cortical mechanisms.

2-D-38 Action costs rapidly and automatically interfere with reward-based decision-making in a reaching task

Presenting Author: Emeline Pierrieau

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It is widely assumed that we make decisions in order to choose actions we value the most. Although costs associated with a movement can affect action values similarly to rewards, their influence on decision-making is less understood. The relevance of investigating motor costs has been highlighted by recent evidence demonstrating that motor costs can affect not only decisions based on motor information but also those based on abstract rules. Still, whether these costs are automatically integrated to decisions and how long it takes to integrate them are still open to question. The goal of the present study was to determine if motor costs can influence simple reward-based decisions and if so, at what latency. Twenty-two right-handed participants had to perform a reward-based target selection task by reaching with their right arm from a fixed starting position toward one of two visual targets. The two targets differed in their relative position in the workspace, thus influencing their motor cost. One target was positioned in a low biomechanical cost location, the other in a high-cost location. Targets were also rewarded or not depending on a simple binary color code. A timed-response paradigm was used to control the elapsed time between target appearance and movement onset (i.e., reaction time, RT). Results revealed that not only target choices but also reach kinematics differed at short RTs depending on the motor cost necessary to reach the rewarded target. Movement trajectories were deviated toward the non-rewarded target when it was associated with the lowest cost. Crucially, in this context participants needed an additional 140ms delay to reach the same percentage of trials oriented toward the rewarded target compared to when the low-cost target was rewarded. Consequently, motor costs affected the amount of rewards participants ultimately earned. In summary, this study demonstrates a robust and automatic interference of motor costs on a simple and well-studied context of reward-based choices, thus highlighting the need to consider motor costs when using dynamic motor tasks for studying decision-making, especially under temporal pressure. Furthermore, these results argue for a rapid specification of motor representations of actions as previously proposed by parallel models of action selection. The bias induced by motor costs may manifest within the competition between neuronal ensembles that represent reach plans along the parieto-frontal pathways.

2-D-39 Dissociating the impact of movement time and energy costs on decision-making and action planning in humans

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A large amount of empirical evidence indicates that in choice-tasks, humans and non-human primates not only prefer the most-rewarded option but also move faster and with shorter reaction time toward items that they value more. Likewise, in effortful conditions, subjects save on the costs required to make movements even if this delays gratification. This pattern of observations is consistent with the "implicit motivation" hypothesis, according to which the vigor of behavior reflects a compromise between the costs of an action and the reward associated with it. Crucially though, action costs are themselves intertwined in a trade-off: to reduce the time delaying the reward, the energy required to shorten behavior duration must be increased. Yet, whether and how movement duration and/or energy influence action selection and initiation is poorly understood. Thirty-one subjects (24 y.o. ± 4; 20 females) performed a visually-based decision-making task in which they had to make an arm movement to report their choices. Reaching requirements were varied between 3 blocks of trials and decision difficulty was controlled to be similar across blocks. In the Reference condition, reaching movements were self-paced, usually short and inexpensive energetically. In the Effort condition, movement duration was the same as in the Reference block, but the required amplitude was doubled, leading to more effortful movements. In the Time condition, both the required amplitude and duration of the movement were doubled compared to the Reference block. To evaluate their reaction times (RTs) in each motor condition, subjects also performed a delayed-reaching (DR) task in which no volitional decision is required. Results in this DR task show that the increase of movement time cost extended RTs for the vast majority (24/31) of subjects compared to the Reference condition. By contrast, energy-consuming movements usually led to similar (23/31) RTs compared to the Reference block, although some participants (7/31) reacted faster. In the choice task, half of the subjects decreased their deliberation durations (DDs) in the Time condition compared to the Reference block, while the impact of energy cost on DDs was less pronounced and more variable across the population. Despite DDs were often modulated by motor costs, decision accuracy was overall similar across blocks. These results first indicate that motor temporal and energy costs strongly affect perceptual decision-making and movement planning. In agreement with the implicit motivation hypothesis, time cost appears to be uniformly viewed as penalizing in a simple motor task, possibly explaining why many subjects aimed at limiting a drop of reward rate by shortening their decisions in the choice task. Results also confirm that motor cost sensitivity is idiosyncratic, especially with regard to energy expenditure, which does not systematically impact action selection and initiation according to the implicit motivation hypothesis

2-D-40 tDCS facilitates the retention of typing skill in healthy young adults

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INTRODUCTION: Numerous studies suggest that the non-invasive brain stimulation techniques, such as transcranial direct current stimulation (tDCS), can facilitate the acquisition of new motor skills in humans. However, they use short periods of practice of 5 days or less and that makes it difficult to extrapolate the results to the reality of complex motor skills. Therefore, the aim of the present study

was to explore the long-term effect of tDCS on the primary motor area in learning to typing. We hypothesized that the application of tDCS online during motor practice would facilitate the retention of typing skill. METHODOLOGY: 60 healthy young adults (age 21±2 years) participated in this double-blind, randomized experiment. Participants completed 20 typewriting sessions over a period of 2.5 months ("Tipp10" typing software). The 15-minute-long sessions were separated by a minimum of 48 hours. Typing performance was tested three times: (1) at baseline (T1) (2) after Session 10 (T2), and (3) after session 20 (T3). During these Tests, participants were instructed to type as fast and accurately as possible the same text, which included all the letters of the Spanish alphabet. In addition, participants performed an incremental typing during the Test at 20, 30, 40, 50, 60 and 70% of their maximal typing speed. The software recorded the speed (number of characters [letters and punctuation marks] per minute) and accuracy (percentage of correct keys). After T1, participants were ranked based on typing performance and trios of participants were randomized assigned to 1) tDCS, 2) sham, or 3) control (CON) group. Anodal tDCS was delivered to the left M1 while participants were typing during 20 sessions. Stimulation intensity was set to 1.5 mA. RESULTS: In the training lessons, participants maintained typing accuracy and speed, while the difficulty of the text increased from session to session (accuracy: 96±2%; speed: 130±26 characters/minute). However, these changes did not differ between the three groups ($p= .68$; $\eta p^2= .31$). Maximal typing speed increased across T1, T2, and T3 ($p= .001$; $\eta p^2= .71$). Typing accuracy did not change ($p= .37$; $\eta p^2= .04$). Thus, all three groups improved typing performance. However, tDCS had no effect on typing performance compared with sham and CON ($p= .84$; $\eta p^2= .01$). In the number of errors in the incremental typing test, there were significant Time ($df= 1$, $F= 31.14$, $p< .001$) and Group ($df= 2$, $F= 4.98$, $p= .01$) main effects but no Time*Group interaction. Only during the first 10 sessions, there were reductions in error only in the tDCS group but not SHAM or CON. CONCLUSIONS: 20 sessions of typewriting practice over a period of 2.5 months significantly improved healthy young adults' typing performance. tDCS only facilitated the retention of typing skill in the fast phase of motor learning. It is possible that tDCS could further facilitate retention especially in individuals with motor impairments or in other complex skills.

2-D-41 An investigation of distributed bimanual coordination

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Bimanual control of the upper limbs typically involves an unequal distribution of control between the limbs (e.g., hammering a nail). Although there is a growing literature on the processes involved when humans learn new motor patterns using one limb, there is a substantial gap in the understanding of how the two hands coordinate control in accomplishing a single task when faced with external perturbations. Using a novel bimanual paradigm, this preliminary study addresses adaptation of interlimb control during manipulations of a jointly controlled object perturbed using altered visual feedback. More specifically, the two limbs controlled different aspects of the object: the right hand controlled the Cartesian coordinates of the trajectory while the left hand controlled the orientation. Subjects utilized a two-arm robotic manipulandum with the goal of placing a rectangular cursor in an oriented rectangular target. The experimental design contained 3 blocks: baseline, adaptation, and decay. For the baseline, the cursor had two possible start orientations (horizontal and vertical) and six possible target orientations (0, 90, 30, 60, 120, and 150 degrees). The distance between the start and end target positions was 12 cm and the gain was 1.0 (the cursor directly represented the hand position). The adaptation block utilized the same target location and orientations with an applied gain decrease of 25%. In the decay block, the gain returned to 1.0 and the decay of the adaptation was examined. Four subjects completed the experiment with each of the 12 orientation combinations presented 8 times in a randomized order for a total of 96 trials in each block. The combined adaptation across the two limbs was observed by manipulating the movement gain for the right hand (cursor movement) and assessing the compensation in the left hand (cursor orientation). Our preliminary results suggest that the angular difference between the start orientation and the target orientation influenced the ability to learn the movement coordination pattern. That is, a start orientation of 0 degrees and a target orientation of 30 degrees showed a faster learning curve for the required coordination than a start orientation of 0 degrees and a target orientation of 60 degrees. Additionally, when the gain decrease was applied, subjects increased the duration of the object rotation to match the longer movement duration of the right limb. Upon returning to the baseline gain in the decay block, subjects demonstrated the ability to revert to original movement patterns in fewer trials than the initial learning observed in the baseline block. Our preliminary study lays the groundwork to systematically examine the influences of handedness on the joint control of object manipulation. In addition, in our future work we plan to couple these behavior observations with noninvasive neural recordings to determine the role of the primary motor cortex in this interlimb distribution of control.

E – Disorders of Motor Control

2-E-42 Electrode placements and deep brain connectivity on a single image for children with motor disorders

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Deep brain stimulation (DBS) has been an important treatment for movement disorders such as dystonia or Parkinson's disease. 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 true 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 deviations from the norm results in the standard neuroimaging tools being insufficient for use in these patients. Here, we present a new approach to fusion the magnetic resonance (MR) structural, computerized tomography (CT) and diffusion tensor imaging (DTI) images into a single image, in children with movement disorders, also accounting for smaller head sizes and brain deformations compared to a healthy adult head, whose neuroimaging tools can be used as a standard procedure. A post-surgery CT is acquired after the implantation of the DBS electrodes, and is then warped and co-registered onto a high-resolution MR anatomical (T1*-weighted) image. This procedure allows us to visualize the final electrode positions in high-resolution brain images. Moreover, DTI images acquired during the pre-surgery MRI are warped and fixed onto the T1*-weighted image, providing an evaluation of the surgical effect. Volume tissue activated (VTA) are also reconstructed using the spatial electrode positions provided by the CT, and a MR structural imaging, which has not yet been used in children. The reliability and reproducibility of the method is proven through optimal parameters chosen during the MRI acquisition, as well as post-acquisition analysis, based on normalization tools. All of these procedures are essential to elucidate the clinical outcomes in DBS and its mechanism of action - which is still unclear. In addition, this approach allows us to study connectivity in deep brain. In conclusion, our method provides relevant information for evaluating the specific treatment effect of DBS surgeries in each child.

2-E-43 3D kinematic measures of motor impairment and activity in sub-acute stroke participants

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The ability to perform isolated joint movements in stroke patients is compromised at the expense of increased stereotypic movement patterns. For example, post-stroke participants execute reaching movements while flexing their shoulder, elbow and wrist instead of extending the elbow and wrist joints. These abnormal stereotypical movements are also known as a flexor and extensor synergies. Post-stroke movements during functional tasks also include spasticity and suffer from reduced strength. These impairments have a profound effect on the functioning of post-stroke participants and on their ability to resume their daily lives. It is therefore imperative that motor impairments will be assessed throughout the rehabilitation process. Here, we aim to examine the contribution of joint coordination, strength, sensory impairment and spasticity to deficits in functional movements, utilizing a novel approach for analyzing 3D kinematics (DeepBehavior) with a convolutional neural network algorithm (OpenPose) that was trained to detect the joint poses in humans. 20 stroke patients in the sub-acute stage, and 15 healthy controls were recorded while performing two tasks: a drinking task that required shoulder and elbow flexion, and a reaching task that required shoulder flexion and elbow extension. Additional impairment measures of spasticity (Modified Ashworth Scale), strength (grip dynamometer), and sensory impairment (Fugl-Meyer sensory functioning score) were collected. Joint coordination was calculated using Pearson's correlation of the shoulder flexion and elbow extension, and shoulder abduction and elbow extension angles of each movement segment. Consistent with previous findings, in the drinking task, that requires movement within the flexor synergy, the performance of stroke participants (movement duration, peak velocity and smoothness) was closer to the performance of the controls, compared to the reaching task that required a movement outside the synergy. Furthermore, when examining the correlation between performance outcome measures, such as movement extent, and impairment measures, movement extent in both tasks was significantly correlated with the coordination measures in the reaching task, but not with sensory and strength impairments. In conclusion, joint coordination in sub-acute patients greatly affect performance, especially in tasks requiring joint movements outside flexor and extensor synergies. Quantification of performance in functional tasks suggests that abnormal synergies plays a central role in motor impairments after stroke.

2-E-44 Activity of motor cortex during locomotion after inactivation or lesion in the ventrolateral thalamus

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Thalamic stroke is a common disease that leads to ataxia if the cerebellum-receiving ventrolateral thalamus (VL) is affected. The compensation mechanism for this deficit and the contribution of different brain regions to the compensation are unclear. This slows development of rehabilitation approaches. The goal of this study was to clarify neuronal mechanisms of motor cortex that are involved in

compensation for ataxia during locomotion when a part of the VL is inactivated or lesioned. In freely ambulating cats we recorded the activity of neurons in layer V of motor cortex as cats walked on the flat surface and horizontal ladder. Walking on the ladder is an accuracy demanding task that suffers if the VL is damaged. We first reversibly inactivated approximately 10% of the VL unilaterally using an AMPA/kaniate glutamatergic transmission antagonist CNQX and analyzed how this 2-4 hour long small inactivation affected the activity of motor cortex during locomotion. We focused on pyramidal tract projecting neurons (PTNs) and on subpopulations of neurons with somatosensory receptive fields on different segments of the forelimb. We next lesioned 50-75% of the VL bilaterally with kainic acid and recorded the activity of motor cortex neurons for a month after. We found that when a small portion of the VL was inactivated unilaterally for few hours, cats were still able to walk on the flat surface and ladder with no apparent abnormalities. The average discharge rates of layer V motor cortex neurons was lower than normal, particularly during the swing phase of the stride on the ladder, but otherwise the activity was unchanged. Individual neurons retained their ability to respond to the accuracy demand of the ladder, however, the great majority changed the manner of their response. In many neurons, preferred phases of the activity were now slightly different between flat surface and ladder locomotion, which was not seen in the control condition. When 50-75% of the VL was lesioned bilaterally, cats were still able to normally walk on the flat surface, but during first 4 post-lesion days showed ataxia on the ladder by often missing the crosspieces. When ladder locomotion normalized, the population activity of motor cortex remained lower than normal. Its activity pattern on the ladder was different from that before the lesion. Rather than to peak in the end of the stance phase it now peaked in the end of the swing phase of the stride. Subpopulations of neurons with somatosensory receptive filed on different segments of the forelimb and PTNs with axons conducting with different velocities responded differently to VL inactivation or lesion. We concluded that in locomoting subjects motor cortex compensates for a reduced signal from the VL when VL is locally inactivated or lesion by reorganizing responses of individual neurons and neuronal subpopulations to the accuracy demand during locomotion, and by shifting population activity to the swing phase of the stride.

2-E-45 Quantifying the impact of lacunar stroke in proprioception: A novel active proprioceptive task

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Internal capsule (IC) stroke leads to a motor impairment syndrome known as pure motor hemiparesis that affects voluntary movement control while preserving sensory information. One important sensory component for voluntary movement regulation is proprioception, which relies on muscle stretch to sense our position and motion in space. Along with efferent motor fibers, studies have found sensory proprioceptive efferent fibers projecting into the spinal cord through the IC. These efferent pathways might actively regulate the excitability of motor neurons and peripheral spindle afferents during voluntary movements by pre-synaptic inhibition and gamma-drive. Consequently, its disruption at the level of the IC should also have an impact in proprioception during the regulation of active voluntary movement. To evaluate this premise, we developed novel active proprioceptive tasks using the KINARM robot to assess two components of proprioception: position sense and kinesthesia. To isolate motor from proprioceptive impairments, we first evaluate the participant's residual range of motion of the affected limb. For this, participants are asked to perform a visual guided reaching task in which they have to reach one of eight targets quickly and accurately starting from a central position. Three target locations with the straightest and smoothest trajectories are then selected for the proprioceptive tasks. During the active position matching (APM) task, the participant is asked to actively reach one of the selected targets using the affected limb (dominant limb for healthy controls) and report when they perceive the target is reached. Loads against the movement are applied, adding complexity to the task. The shift between the end-point position of the active limb and the target location is then calculated to assess active sense of position. Similarly, for the active kinesthetic matching task (AKM), the subject is asked to actively move the limb following a dynamic target. The latter moves in a straight-line from the central target to one of the target locations following a bell-shape velocity profile with peak speeds proportional to the average peak velocity obtained from the visually guided task. The subject's ability to match the speed, direction, and length of the dynamic target is then measured for each trial. We tested these tasks in able-bodied subjects and found that for the APM task, the addition of the loads generates a disturbance in the location of the target, however, the variability to reach each target remains consistent across trials. In the AKM task, reduction of the velocity profile increases the accuracy during movement. Our tasks will help to understand the importance of active proprioception after stroke and support the development of novel rehabilitation techniques. Specifically, in participants with lacunar stroke we expect to find discrepancies from healthy control's performances proportional to amount of destroyed efferent fibers.

2-E-46 Internal globus pallidus oscillations at low frequency in children with secondary dystonia

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Dystonia is defined as a movement disorder in which involuntary sustained or intermittent muscle contractions cause twisting and repetitive movements, abnormal postures, or both. It has been hypothesized that the mechanism underlying childhood dystonia is related to an imbalance between midbrain dopaminergic and striatal cholinergic signaling, or excessive or abnormal patterns of subcortical activity, but the correct explanation is still unknown. An approach to elucidate how the basal ganglia are involved is through deep brain stimulation (DBS), which allow us to measure brain oscillations in deep brain structures. DBS studies in Parkinson's disease (PD) have discovered the presence of high-amplitude beta oscillations (13-35 Hz) in the subthalamic nucleus (STN), and other studies have recorded oscillatory alpha activity (8-12 Hz) in the internal globus pallidus (GPi) in patients with general dystonia. To build upon this, we study the oscillatory power in GPi in children with secondary dystonia, which has not yet been characterized. Here we present a preliminary study based on two patients with secondary dystonia showing oscillatory power in theta and delta frequency (1-6 Hz) bands in GPi during reaching movements. The reaching movements were repeated six times, with 30 s of rest between movements. DBS surgery with externalized test leads were used to record the oscillation in GPi, and electromyography (EMG) was implemented to record contralateral upper and lower muscle activity while the patients executed the task. GPi oscillations in the beta frequency band has been related to the cortex and the cortico-pallidal circuit in patients with primary dystonia. Our results show that GPi oscillation in the 1-6-Hz frequency band clearly correlates with muscle activity during the voluntary movements. Similar results have been shown in patients with primary dystonia. These preliminary results lead us to think that this frequency band in GPi can be both used as a

physiomarker for DBS in secondary dystonia and employed as feedback for adaptative DBS or brain-computer interfaces (BCI).

2-E-47 Activity-dependent modulation of interhemispheric inhibition reveals individual differences in upper limb motor behavior in chronic stroke survivors

Presenting Author: Jasmine Mirdamadi

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Cortical-cortical interactions in motor cortex (M1) (e.g., interhemispheric inhibition (IHI)) are essential for normal motor control. However, the role of IHI in paretic arm motor recovery post-stroke remains controversial. The classical IHI imbalance model posits that reduced inhibition from the ipsilesional (ipsi-M1) to the contralesional hemisphere (contra-M1), resulting in hypoexcitability in ipsi-M1 and hyperexcitability in contra-M1, impairs recovery. However, recent evidence challenges this view, reflecting the heterogeneity of stroke neurophysiology and its relation to behavior. Our understanding of IHI is incomplete due, in part, to limited consideration of state-dependent effects on interhemispheric circuits. Specifically, IHI is often measured with the paretic arm at rest, which may not represent the role of IHI during movement. Here, we investigated state-dependent modulation of IHI in chronic stroke survivors (N=12) and neurotypical older adults (NOA) (N=10), and characterized relationships to motor behavior. We used dual-coil transcranial magnetic stimulation (TMS) to measure IHI targeting the first dorsal interosseous (FDI) M1 representation in two states: 1) rest and 2) during contralateral FDI isometric contraction. IHI was measured by delivering a suprathreshold conditioning stimulus 8-msec (short IHI (SIHI)) or 50-msec (long IHI (LIHI)) prior to a suprathreshold test stimulus over contralateral M1. IHI was quantified as the ratio of the conditioned motor evoked potential (MEP) amplitude relative to the unconditioned MEP. We assessed paretic arm impairment with upper extremity Fugl-Meyer Assessment (UEFMA) and strength with Shoulder Abduction/Finger Extension (SAFE) score. In both groups, we assessed manual dexterity with the Nine-Hole Peg Test. Stroke survivors demonstrated less IHI compared to NOA, with similar IHI between ipsi- and contra-M1. Stroke survivors showed less IHI modulation (IHI active - IHI rest) compared to NOA. Individual differences in IHI modulation were related to paretic motor behavior. Greater SIHI disinhibition in ipsi-M1 was related to lower UEFMA scores (i.e., more impairment) ($R= -0.728$, $p= 0.032$). Similar associations were observed for LIHI modulation in ipsi-M1, though did not reach statistical significance. Greater LIHI disinhibition in contra-M1 was related to lower UEFMA and SAFE scores ($R= -0.681$, $p= 0.030$; $R= -0.656$, $p= 0.028$). In contrast, there were no relationships between IHI at rest and behavior. In NOA, there were no associations between IHI and NHPT. Contrary to previous work, more typical state-dependent IHI modulation was associated with reduced motor behavior. Therefore, state-dependent compensatory cortical reorganization may support paretic arm motor behavior. Since these relationships were absent at rest, state-dependent interhemispheric interactions could offer biomarkers of functional cortical reorganization that may predict recovery and inform future models of stroke recovery.

2-E-48 Sex-related differences in rule-based visuomotor performance during concussion recovery.

Presenting Author: Nicole Smeha

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Simple, direct interactions with the environment are contingent on our brain's ability to integrate sensory and motor system information in order to execute an efficient motor plan. This process requires intact connections between frontal, parietal, and subcortical brain regions. The integrity of these connections becomes all the more crucial during the execution of more complex, rule-based movements that require cognitive-motor integration (CMI), in which the guiding visual information and motor action are dissociated. Previous research has shown that following concussion, the integrity of these networks may be compromised[1], resulting in an impaired ability to integrate rules into coordinated motor tasks. We have also previously observed sex-related differences in the brain networks which control CMI[2]. Here, we investigate the relationship between visuomotor skill performance, symptom resolution, and sex during the course of a post-concussion management program involving osteopathic manual treatment (OMT). Symptomatic concussed individuals (n=15), 10-90 days post-injury, and healthy controls (n=17) completed a 4-week program involving OMT. Prior to and after the program, CMI performance and symptom number were assessed. Two visuomotor tasks were used to assess CMI performance: 1) a standard condition requiring direct interaction with visual targets on a touchscreen, and 2) a non-standard condition requiring CMI (movements on a horizontal touchscreen while viewing targets on a vertical monitor, with visual feedback reversed). We observed a significant reduction in number of false initial movement directions ("direction reversals"), movement accuracy, and movement time in the concussed group over time on the CMI task ($p<0.05$, all 3 variables), such that there were no differences at the end of the treatment period between healthy and control groups ($p>0.05$), but significant differences pre-treatment (as expected, $p<0.05$). Interestingly, we found significantly slower movement times for the CMI task in concussed males compared to concussed females at the post-treatment time point ($p<0.05$). Further, concussed females were no different than non-concussed females at post-treatment($p>0.05$), while males were significantly slower($p<0.05$). Lastly, we observed a significant correlation between CMI performance (direction reversals) and number of concussion symptoms ($p<0.05$) at pre-treatment, and no difference between healthy and concussed groups on symptom number post-treatment ($p>0.05$). These data show that in general, rule-based visuomotor skill recovers in concussed adults at the same rate as symptom recovery over a program of active OMT intervention. However, our observed slower recovery in males suggests a potential sex-related difference in the recovery of brain networks for skilled performance in this group. 1.Cook MJ et al. Neuroimage clinical. 2020 Jan 1;25:10212. 2.Gorbet D & Sergio (2007). EJN 25(4), 1228-1239.

2-E-81 Dopamine genetic risk score predicts impulse control behaviours in Parkinson's disease

Presenting Author: Alison Hall

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Background: Up to 40% of Parkinson's disease patients taking dopamine agonist medication develop impulse control behaviours which can have negative consequences for the patients and their families. Objective: The current study aimed to utilise dopamine genetics to identify patients most at risk of developing these behaviours. Methods: Demographic, clinical, and genetic data were obtained from the Parkinson's Progression Markers Initiative for de novo patients, patients taking dopamine agonists, and healthy controls. Impulsive behaviours were identified using the Questionnaire for Impulsive-Compulsive Disorders in Parkinson's Disease. A dopamine genetic risk score was calculated for each patient according to polymorphisms in genes coding for dopamine D1, D2 and D3 receptors, and catechol-O-methyltransferase. A higher score reflected higher central dopamine neurotransmission. Results: Patients on agonists with a low dopamine genetic risk score were over 18 times more likely to have an impulsive behaviour compared to higher scores ($p = 0.04$). The 38% of patients taking agonists who had at least one impulsive behaviour were more likely to be male and report a higher Unified Parkinson's Disease Rating Scale I&II score. With increasing time on dopamine agonists, only patients with a high dopamine genetic risk score showed an increase in number of impulsive behaviours ($p = 0.033$). The predictive effects of the gene score were not present in de novo or healthy control data. Conclusions: A dopamine genetic risk score can identify which patients are most at risk of developing impulsive behaviours on dopamine agonist medication and predict how these behaviours may worsen over time.

F – Adaptation & Plasticity in Motor Control

2-F-49 Task complexity and variability in grasp strategy influence reach peak velocity and sensorimotor neural activation during prosthesis use

Presenting Author: Bennett Alterman

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Examining differences in neurobehavioral and functional performance provides vital information about sensorimotor reorganization at amputations of different levels. However, kinematic performance may depend on several factors including task complexity and grasp strategy variability by the prosthesis user. This study examines differences in neurobehavioral and functional outcome measures in participants completing goal-directed reach and grasp motor actions, and provides a preliminary basis for evaluating grasp strategy variability as a mechanism of differentiation in motor learning. Here, sound-limb participants completed a kinematically simple and a kinematically complex reach and grasp task using either a transradial ($n=17$) or partial-hand ($n=16$) prosthesis simulator. The simple task involved the lateral translation of a metal disk between two points. The complex task involved the rotation and translation of a marker from a horizontal position to a vertical position. We hypothesized that the complex task would lead to greater grasp strategy variability, and that partial-hand prosthesis users would exhibit higher reach peak velocities than transradial prosthesis users. Furthermore, we anticipated that partial-hand users would exhibit more lateralized brain activation patterns during action execution compared to transradial users. We find that in the complex task, partial-hand users stratify into uniform graspers and variable graspers (used the same grasp strategy for <85% of grasps). Kinematic results show a main effect of both group and trial bin, where there were significant differences between the transradial and partial-hand groups in later trial bins. Furthermore, partial-hand users show increases in reach peak velocity over time, while transradial users do not. In the simple task, there is no stratification in grasp strategy. Kinematically, there is a main effect of trial bin driven by partial-hand users. Neural results show that in the beta band, there is a bilateral increase in neural activity of the sensorimotor cortex at both levels of simulation after movement onset. Counter to our hypothesis, this effect is more strongly lateralized in the transradial users. This work forms the foundation for examination of how level of amputation may affect grasp strategy and kinematic outcomes during rehabilitation, as well as providing initial evidence for a mechanism of differential control at different levels of prosthesis use.

2-F-50 Neural excursions from low-dimensional manifold structure in cognitive and sensorimotor brain networks explains intersubject variation in human motor learning
Presenting Author: Corson Areshenkoff
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Sensorimotor learning requires that the brain generate new patterns of activity. Conventionally, neurophysiological studies of learning have focused on changes in the activity of single neurons or single brain areas in isolation. However, recent studies have shown that large-scale neural population activity primarily occupies a low-dimensional subspace or manifold, reflecting covariance patterns across the entire population. This indicates that the neural principles that govern learning can be difficult to resolve at the level of single neurons or perhaps even single brain areas. This intrinsic manifold structure has been shown to limit the capacity for learning (Sadtler et al., 2014), indicating that learning involves a reconfiguration of this manifold structure. The macroscale activity of cortex is also thought to be coordinated along a manifold architecture. For instance, covariance patterns in fMRI activity between brain regions have been widely studied, with whole-brain functional networks known to exhibit low-dimensional structure at both rest and during task. Here we wondered whether human sensorimotor learning results from an excursion from this manifold structure, and if so, whether the extent of this excursion predicts fast versus slow learning across subjects. To test this, subjects (N=32) performed a classic visuomotor rotation (VMR) task in the MRI scanner on two consecutive days, allowing us to assess subject-level differences in both initial learning and relearning of the rotation. For each subject, we estimated their intrinsic manifold structure prior to learning (during rest) and examined neural excursions from this low-dimensional structure across both days in separate cognitive- and motor-related brain networks. We show that fast and slow learners exhibit differences in excursion from intrinsic manifold activity during learning, with fast learners showing greater excursion in cognitive brain networks. Further, we identify a subset of slow learners who achieve comparable performance to fast learners by the end of the first day, and relearn the rotation rapidly on the second day. We find that these subjects, on the first day, exhibit patterns of excursion remarkably similar to fast learners, suggesting that they may have developed an explicit cognitive strategy later in the task. Together, these findings suggest that excursion from intrinsic manifold structure provides an index of the relative engagement of distributed brain networks in learning, and that fast versus slow learning is the result of different reconfiguration processes of cognitive and motor systems during learning. These findings provide neural support for data suggesting that sensorimotor learning involves distinct implicit and explicit systems operating in parallel, and provide novel evidence that explicit processes, which lead to faster learning, involve changes in the activity of higher-order brain networks.

2-F-51 Revisiting sensitivity of implicit visuomotor adaptation to errors of varying magnitude
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The motor system has a remarkable ability to improve motor performance by learning from errors. The sensitivity of the system to variations in error size has been a subject of considerable debate. While much of the size-dependent change in performance comes from explicit strategic processes (Bond and Taylor 2015), the role of implicit processes has been more controversial. We set out to re-examine this question using a visuomotor learning task that isolates implicit adaptation. While moving the hand to a visual target, the cursor follows an invariant (clamped) path that is deviated from the direction of the target, and thus independent of the hand path. Despite instructions to ignore the irrelevant cursor, participants show implicit adaptation, with the hand path shifting in a direction away from the target (and cursor) (Morehead et al. 2017). For large errors (>~5°), the adaptation function does not vary with error size (Morehead et al. 2017; Kim et al. 2018). Kim et al. also showed that for smaller errors, the adaptation function scaled with error size only in the early phase of learning; at asymptote, the functions converged with that elicited by larger errors. However, Morehead et al. (personal communication) failed to observe convergence. Importantly, there were two main differences in the Kim and Morehead studies. First, Kim used a between-participant design where the error size varied between participants, but each participant was exposed to a single error; this may lead to a standardization process in which there is a uniform updating of the sensorimotor map. In contrast, Morehead used a within-participant design where each participant experienced multiple error sizes, each associated with a different target; with exposure to different errors, the updating process remains size-dependent. Second, while both studies presented targets around a 360° workspace, Kim used 8 target locations while Morehead used 4. With more targets, the time interval between successive reaches to a given target is longer, resulting in adaptation decay (Zhou et al. 2017) that may vary across errors. We examined the influence of these two factors, Design (Between vs Within) and Targets (4 vs 8), on the size-dependent effect of implicit adaptation in a 2 x 2 experimental design. We compared the learning functions in response to clamped feedback of 4° or 15°. The results showed a marked effect of Design, with no effect of Targets. For both 4 and 8 targets, the overall adaptation to 4° and 15° clamps was comparable in the Between condition. However, the learning functions scaled with clamp size in the Within condition, with the asymptotic value in response to the 4° clamp ~50% less than that observed in response to the 15° clamp. These results suggest that the lack of scaling of adaptation for small errors may be due to the standardization of the behavioral response to an invariant error, a process that does not happen when a range of errors is experienced.

2-F-52 Overcoming a virtual surgery by learning new muscle synergies: Effect of multiple practice sessions and inter-individual differences

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Remapping of pulling directions of arm muscles simulated in a virtual environment using myoelectric control (virtual surgeries) is a novel experimental approach that allows to investigate motor adaptation and motor skill learning in a simple task. If control relies on the synergistic recruitment of groups of muscles, motor adaptation can be achieved by recombining existing muscle synergies while learning a new motor skill may require the organization of new muscle synergies. Compatible virtual surgeries, i.e., a remapping of muscle pulling directions that allows to generate forces at the hand in all directions by recombining existing synergies, can be used to investigate the changes in muscle coordination underlying motor adaptation. In the same experimental setup, incompatible virtual surgeries, i.e., a remapping that makes the existing synergies unable to span the force space, can be used to investigate motor skill learning. In a previous study (Berger et al., 2013) we demonstrated that participants, practicing a task in which they used myoelectric control in a virtual environment to reach targets in multiple directions, in a single session were able to adapt to compatible surgeries but not to incompatible ones. However, it was not clear whether it is possible to overcome incompatible surgeries with more practice, thus learning new muscle synergies through a slower motor skill learning processes. In this study, nine participants practiced the same reaching task after an incompatible virtual surgery in three daily sessions. An EMG-to-force mapping was estimated by linear regression of the tri-dimensional isometric force exerted in a handle on the EMG signal of 15 shoulder and elbow muscles. The incompatible surgery was constructed by real-time simulation of a rotation of recorded muscle pattern vectors such that force generated through the EMG-to-force mapping was always aligned along a single direction. Feedback of the remapped force was provided as the displacement of a stereoscopic image of a spherical cursor in a virtual three-dimensional desktop. Participants were instructed to reach one of eight spherical targets uniformly distributed on a circle in the horizontal plane. Remarkably, we found a significant increase in the success rate at the end of session 3 with respect to the success rate at the beginning of session 1, suggesting that participants could overcome the incompatible surgery when practicing for multiple sessions. Moreover, retention of the success rate across sessions and re-learning speed at the beginning of a new session (savings) increased during the experiment. However, participants differed strikingly in their ability to overcome the perturbations, suggesting that the capability of learning new muscle synergies varies significantly across subjects. Future work will investigate neuroplasticity associated to extended practice with virtual surgeries.

2-F-53 Investigating de novo learning online: Learning of a mirror reversal task is fast and generalizes across the workspace and hands

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As people move within an environment, changing circumstances may lead them to commit movement errors. During de novo learning, or motor skill acquisition, we process these errors and learn to produce the correct movement. De novo learning has been shown to be distinct from motor adaptation, as acquiring a new skill should require more time to learn and does not lead to reach aftereffects or the persistent deviation in reaches after perturbation removal. These behavioral results have been observed as people learn a mirror reversal task, where participants are trained to reach to targets while visual feedback of their hand position is reversed in the opposite direction of a mirror axis. However, there is still much to investigate regarding the behavioral mechanisms underlying de novo learning. Here, we developed an online version of the mirror reversal task and conducted two experiments to explore these mechanisms further. In experiment 1, we compared how learning progressed when either providing participants with explicit instructions about the nature of the mirror reversal (N = 105) or not providing such instructions (N = 519). Two targets were located in the upper-right quadrant of the workspace (30 and 60 degrees in polar coordinates), and the mirror was located along the vertical midline axis. Surprisingly, we found that learning occurred quickly, even for the non-instructed participants. Moreover, asymptotic learning of participants in both groups differed depending on target location, and reach aftereffects were not observed. In experiment 2, we investigated how learning in the mirror reversal task generalizes to different target locations across the workspace, as well as to the opposite and untrained hand. Non-instructed participants from experiment 1 returned to complete experiment 2 (N = 361; days apart: M = 16.88, SD = 13.97). In the first block, participants reached in the same

condition as in experiment 1, to assess retention of learning. For the following blocks, we switched the target locations to either the lower-right quadrant (300 and 330 degrees) or the upper-left quadrant (120 and 150 degrees) of the workspace, while the mirror was kept along the vertical axis. Finally, we had participants switch to their opposite hand to reach to targets in the upper-right quadrant. We found that participants retained learning from experiment 1, as they were immediately reaching towards the correct direction relative to the mirror. We also observed that learning generalized to the different target locations and to the opposite hand. In short, we show that the development of de novo learning can occur quickly, and that learning generalizes across the workspace and to the untrained hand.

2-F-54 Manipulating the behavioral state of the grasping network during parietal rTMS increases motor excitability and skilled grasp control

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Repetitive transcranial magnetic stimulation (rTMS) can induce changes on brain and behavior that outlast the stimulation period. While rTMS provides relatively focal stimulation, the effects of stimulation propagate to interconnected brain regions in ways that are poorly understood. Furthermore, the effects of stimulation appear to be highly state-dependent, in which the rTMS-induced response depends on excitability levels in specific neuronal populations. Here, we focused on interactions between posterior parietal cortex (PPC), a higher-order area significantly involved in skilled grasp control, and primary motor cortex (M1). Using intermittent theta burst stimulation (iTBS) to PPC, we examined whether constraining the behavioral state during stimulation enhanced the specificity of iTBS aftereffects between PPC (target site) and functionally connected M1 and concomitantly improved motor function. Twenty-four subjects were randomly assigned to one of three rTMS intervention groups. One rTMS intervention applied iTBS to the PPC, while subjects concurrently performed a grasp task (iTBSPPC + Grasp). Another rTMS intervention applied iTBS to the PPC, while subjects were in an unconstrained, resting state (iTBSPPC alone). This allowed us to elucidate the effects of targeted rTMS enhancement of the parieto-motor grasping network and motor function, and the interaction between parietal iTBS and behavioral state. To test the functional specificity of stimulation to the PPC, a third rTMS intervention applied iTBS to a parietal region outside of the cortical grasping network while subjects concurrently performed the grasp task (iTBSCTRL + Grasp). Electrophysiological measures with TMS (e.g., motor evoked potential, MEP, as an indicator of excitability in M1) and behavioral measures (e.g., 9-hole pegboard manual dexterity test, 9HPT) were taken before (baseline) and 30 and 60 min after each rTMS intervention. Results showed that manual dexterity improved exclusively in the iTBSPPC + Grasp group when underlying brain activity was manipulated by the behavior. Specifically, the mean time to complete a manual dexterity task decreased by ~1.5s after 30min and ~2.5s after 60min for the iTBSPPC + Grasp group relative to baseline. The action performance improvements were highly consistent across the eight subjects due to iTBSPPC + Grasp but were at chance due to iTBSPPC alone and iTBSCTRL + Grasp. Parietal stimulation increased MEP amplitudes when paired with the grasp task (iTBSPPC + Grasp) for 60 min but not when delivered during rest (iTBSPPC alone) or over the control site (iTBSCTRL + Grasp). These results suggest that manipulating behavioral state with a motor task during rTMS enhances the specificity of induced plasticity within a well-characterized parieto-motor grasping circuit to optimize motor function. This approach can be translated into clinical settings to optimize future neuromodulatory therapies for individuals with neuromotor impairments.

2-F-55 Anterograde interference emerges along a gradient as a function of task similarity

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Anterograde interference emerges when two differing (A vs B; Lerner et al., 2020 Cereb Cortex) or identical tasks (A vs A; Hamel et al., 2021 Proc Roy Soc B: Biol Sci) are learned in close temporal succession, indicating that interference emerges even if memories do not compete. Recent neurobiological development indicates that initial learning perturbs neural homeostasis and results in the emergence of homeostatic constraints that restrain subsequent synaptic plasticity in a neural network-specific manner. Whether such a metaplasticity mechanism could account for anterograde interference remains unknown. Here, this work tested the hypothesis that anterograde interference is graded as a function of the overlap between the neural networks involved in two learning sessions. In a fully within-subject and counter-balanced design, participants (n = 24) took part in a total of 4 experimental conditions where they adapted to a gradual visuomotor adaptation paradigm twice over two distinct learning sessions separated by a 2-min interval. Namely, the putative overlap between the neural networks involved in the two learning sessions was behaviorally manipulated by having participant adapt to opposite visual deviations (+21° vs -21°; right hand; upper quadrant), to the same imposed visual deviation twice (-21° vs -21°; right hand; upper quadrant), to the same imposed visual deviation in the lower then in the upper workspace quadrant (-21° vs -21°; right hand), and to the same imposed visual deviation with the left and then right hand (-21° vs -21°; upper quadrant). The results showed that anterograde interference emerges along a gradient as a function of the learning sessions' similarity; similar learning sessions generated more anterograde interference than dissimilar ones, suggesting that anterograde interference depends upon the degree of putative overlap between the neural networks of the two learning sessions. One ramification is that anterograde interference may be driven not by competing memories but by the emergence of homeostatic plasticity constraints in learning-specific neural networks.

2-F-56 Freely chosen cadence is dependent on pedalling history

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History dependence can refer to the fact that parts of the human (e.g. one or a group of muscles [1]), the nervous system [2, 3], or functional aspects of the human (e.g. stereotyped rhythmic motor behaviour [4], or performance [5]) depend on prior muscle activation. In the present study, it was investigated whether initial cycling at relatively low and high preset target cadences affected the subsequent freely chosen cadence at the end of the same bout of submaximal ergometer cycling. The cadence that occurs during cycling has a practical significance. As an example, the cadence can affect the result of a submaximal ergometer cycling test performed to evaluate training status. Twenty-two participants (18 males and 4 females, healthy and recreationally active, 185.0±9.8 cm, 79.9±10.0 kg, 23±2 years) performed a single test session, which consisted of three separate bouts of submaximal ergometer cycling. In one bout, cycling at 50 rpm was followed by cycling at freely chosen cadence. In another bout, cycling at 90 rpm was followed by cycling at freely chosen cadence. In yet another bout (considered a reference), the cadence was freely chosen throughout. Behavioural (cadence), biomechanical (internal power and tangential pedal force), and physiological (heart rate) responses were measured. Increased cadence resulted in increased internal power and decreased maximal tangential pedal force, and vice versa, in accordance with existing knowledge [6]. Initial cycling at 50 rpm and 90 rpm caused freely chosen cadence to be - on average - around 5% lower and higher ($p<0.05$), respectively, than the reference freely chosen cadence (72.4±11.3 rpm) at the end of the submaximal bout where the cadence was freely chosen. These differences in cadence were not accompanied by statistically significant differences in heart rate. In conclusion, the freely chosen cadence at the end of an ergometer cycling bout depended on the preset target cadence applied at the beginning of the bout. This finding may be denoted a phenomenon of motor behavioural history dependence. References: [1] Abbott BC, Aubert XM (1952) The force exerted by active striated muscle during and after change of length. J Physiol 117(1):77-86. [2] Majczynski H, Cabaj AM, Jordan LM, Slawinska U (2020) Contribution of 5-HT2 receptors to the control of the spinal locomotor system in intact rats. Front Neural Circuits 14:14. [3] Miller MW (2019) GABA as a neurotransmitter in gastropod molluscs. Biol Bull 236(2):144-156. [4] Hansen EA, Ebbesen BD, Dalsgaard A, Mora-Jensen MH, Rasmussen J (2015) Freely chosen index finger tapping frequency is increased in repeated bouts of tapping. J Mot Behav 47(6):490-496. [5] Young WB, Jenner A, Griffiths K (1998) Acute enhancement of power performance from heavy load squats. J Strength Cond Res 12(2):82-84. [6] Hansen EA (2015) On voluntary rhythmic leg movement behaviour and control during pedalling. Acta Physiol 214(Suppl 702):1-18.

2-F-57 Neural and behavioral dissociation in development of coordination and control using a prosthesis simulator with vibrotactile feedback

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Rejection rates of upper-extremity prostheses remain high and clinical measures of their efficacy remain unchanged despite recent engineering advances in their construction. One technology purported to improve outcomes is augmented somatosensory feedback from the prosthesis. The question of whether augmented feedback from the prosthesis improves motor learning and control and the neural effects of this feedback remain open. We recruited healthy intact participants (n = 10) to use a prosthesis simulator to perform a reach-and-grasp task using three differently-sized discs. Vibrotactile feedback indicative of successfully grasping was supplied during the transport phase of the task during half of their trials. A second group of participants (n = 10) performed the same task using a pair of tongs without augmented feedback. Task phases of interest were reach-to-grasp and transport, using grasp aperture and velocity as measures of interest. Kinematic results during reach-to-grasp show a greater overshoot of grasp peak aperture for all disc sizes for prosthesis users compared to tongs users, with no effect of vibrotactile feedback. Participants using the prosthesis without feedback compared to with feedback demonstrated higher velocity during the initial 5%-15% of the reach-to-grasp phase, as well as during 10%-50% of the transport phase. The participants using the prosthesis in either condition (with or without feedback) demonstrated atypical velocity profiles during the reach-to-grasp phase, while their velocity profile during the transport phase was more stereotypical. Participants using the tongs showed a more efficient grasp peak aperture (less overshoot) than either prosthesis condition, as well, their velocity profiles for both reach-to-grasp and transport phases followed the bell-shaped velocity profile typical of human upper-extremity movements. Electroencephalographic data were analyzed on a trial-by-trial basis for three cortical regions of interest (frontal, left motor, left parietal) and two times of

interest (grasp peak aperture and transport peak velocity) for alpha-band (10--14 Hz) power. At grasp peak aperture, results show that frontal midline and left motor activity were modulated by end-effector (prosthesis or tongs), as well as vibrotactile feedback, while left parietal activity was modulated solely by end-effector. At transport peak velocity, frontal and left parietal activity were modulated by end-effector. Left parietal activity was modulated by the presence or absence of feedback in the prosthesis group, while left motor only demonstrated a difference between tongs and prosthesis with feedback. Together, these differences in neural and behavioral results may suggest that participants establish coordination of muscle synergies during the time frame of the study, demonstrating an ability to develop synergies across the movement construction hierarchy, while control or scaling of movements remains under developed.

2-F-58 Finger somatotopy is preserved after tetraplegia but deteriorates over time

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Following spinal cord injury (SCI), the brain is deprived of sensory input from and motor output to the limb(s). While attempted movements with the paralysed and sensory deprived body part can still evoke signals in the sensorimotor system, this task-related 'net' brain activity in SCI patients differs substantially from healthy controls. Such reorganised and/or altered activity is thought to reflect abnormal processing. It is however possible that this altered net sensorimotor activity in SCI patients conceals preserved somatotopically-specific representations of the paralysed and sensory deprived body parts that could be exploited in a functionally meaningful manner (e.g. via neuroprosthetics). Here we investigated whether a functional connection between the periphery and the brain is necessary to maintain somatosensory representations. We used fMRI and an (attempted) finger movement task to characterise the somatotopic S1 hand layout in 14 tetraplegic SCI patients who differed in terms of lesion completeness, retained sensorimotor functioning, and time since injury. By measuring a group of tetraplegic SCI patients with varying amounts of spared tissue at the lesion level (quantified as midsagittal tissue bridges based on sagittal T2-weighted spinal scans) we uniquely assessed whether preserved connections between the brain and periphery are necessary to preserve fine somatotopic mapping in S1. We also investigated what clinical and behavioural determinants may contribute to preserving S1 somatotopy after chronic SCI. Our results revealed somatotopic representations of patients' hands in which neighbouring clusters showed selectivity for neighbouring fingers in contralateral S1, qualitatively similar to those observed in healthy controls. To quantify whether patients' hand representations were normal we correlated each participant's intricate representational distance pattern across all fingers (revealed using representational similarity analysis) with a canonical inter-finger distance pattern obtained from an independent control sample. The resulting hand representation typicality scores were not different between patients and controls. This was even true when considering two patients with no sensory hand functioning, no hand motor functioning, and no spared spinal tissue bridges. However, a correlational analysis revealed that over years since SCI S1 hand representation typicality deteriorates. Together, our results show that somatosensory representations can be maintained for several years following SCI, even in the absence of peripheral inputs. Such preserved S1 hand representations could be exploited in a functionally meaningful way by rehabilitation approaches that attempt to establish new functional connections between the hand and the brain after an SCI (e.g. via neuroprosthetics). However, time since SCI may critically influence the somatotopic representations and might thereby impact the success of such rehabilitation approaches.

2-F-59 Perceptual target shifts do not account for the limited extent of auditory-motor adaptation in speech production
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It is well known that typical speakers monitor their acoustic speech output and gradually adapt over several trials to compensate for altered auditory feedback. However, it is still unclear why speakers only show limited adaptation (~1/3 of the perturbation) for an applied auditory perturbation such as a shift of the formant frequencies of the feedback signal. One hypothesis is that exposure to altered feedback changes speakers' intended perceptual targets. Indeed, perceptual adaptation has been reported to occur in parallel with motor adaptation such that the perceptual boundaries between speech sounds shift over the course of sensorimotor adaptation (e.g., Shiller et al., 2009; Lametti et al., 2014). Here, we studied (a) whether the speaker's perceptual target--rather than merely the boundary between targets--shifts during adaptation, (b) whether playback of a speaker's most typical production before each trial could prevent such target shifts, and (c) whether the extent of auditory-motor adaptation is more complete with such repeated presentations of the self-generated baseline production. The experiment consisted of three main tasks: a pre-test, a sensorimotor adaptation task, and a post-test. The goal of the pre-test was to select representative baseline productions for the participant as they repeatedly read three test words (tech, tuck, talk) under unaltered auditory feedback. The subsequent adaptation task involved reading the same words out loud, but this time an initial baseline phase with unaltered feedback was followed by a ramp phase during which the formant frequencies of the speaker's auditory feedback were gradually increased up to a maximum of 2.5 semitones. In this task, one group of participants heard their own, most typical pre-test production on each trial immediately before producing the word. This played-back stimulus served as a perceptual reminder, or anchor, of the speaker's typical production and, thus, the perceptual target for the test word. Participants in another group did not receive this repeated anchor presentation. Finally, each participant also completed a post-adaptation perceptual test. They manually selected what they believed to be their "best" utterance out of various formant-shifted versions of their most typical productions from the pre-test. The post-test was conducted immediately after the adaptation task, without interruption, to minimize the decay of any potential target shift that may have occurred. Our findings indicate that participants who heard their typical production played back before each trial and control participants without played-back stimuli showed a similar extent of adaptation and also performed similarly on the perceptual post-test. On average, participants in both groups tended to select versions of their own productions that had slightly upshifted formant frequencies. Overall, results do not support target shifts as a limiting factor in speech auditory-motor adaptation.

2-F-60 Forcefield adaptation by observing: how long do the effects of observation last?
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Motor learning is based on the brain learning new representations of the forces required for movement. While this process typically involves extensive physical practice, recent evidence suggests that motor learning can also occur by observing the movements of others--an influential idea that could have implications for stroke neurorehabilitation. 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 durable, learned changes in the motor system. Using a forcefield learning paradigm, we measured human subjects' force generation patterns before and at various time points (one, 10, 30, or 60 minutes) after they had either performed or observed movements that were perturbed by novel, robot-generated forces (i.e., a velocity-dependent forcefield). Our preliminary findings show that 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. Adaptive changes in force control remained present after a 60-minute delay period, demonstrating that observation-related effects can persist for at least an hour after observation. These results are consistent with the idea that neural representations of the forces required for movement can be learned by observing.

2-F-61 Generalization of fast and slow processes of motor adaptation in reaching

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In motor adaptation, generalization refers to the transfer of a learned compensation to other relevant contexts. For example, if participants have adapted their reaching movements in one movement direction, compensation is also seen in neighboring movement directions. This generalization is typically thought to be of Gaussian shape, centered on the planned motion states, although recent studies associate generalization with the actual motion states (e.g. Gonzalez-Castro et al. 2011). Because motor adaptation involves multiple interactive processes with different time constants (e.g. Smith et al., 2006; Forano and Franklin, 2020), it can be hypothesized that these processes have different, time-dependent, contributions to the generalization. Guided by a model-based approach, the objective of the present study was to experimentally examine these contributions. We first reformulated the two-state adaptation model of Smith et al., (2006) as a combination of weighted motor primitives (Thoroughman & Shadmehr, 2000), each specified as a Gaussian-like tuning function. Adaptation in this model is achieved by updating individual weights of the fast and slow adaptive process separately. Depending on whether updating occurred based on errors relative to the planned motion states or the actual motion states, the model predicted distinct contributions of the slow and fast adaptation process to the overall generalization in a spontaneous recovery paradigm. Next, we performed a behavioral experiment to test these predictions. We tested adaptation to a curl force field in 24 participants. Participants performed 5 successive blocks of a spontaneous recovery paradigm, each containing 250 trials (of which 44 error clamp) of exposure to perturbation A, followed by 15-50 trials exposure to perturbation B, and 44 error clamps to probe spontaneous recovery. Participants were exposed to a CW or CCW force only when reaching in the forward direction, but were tested in error clamps for generalization in eleven movement directions relative to this direction (0°, ±5°, ±10°, ±15°, ±35°, ±60°). Our behavioral results show clear, single peaked, generalization profiles in the error clamps in the extended exposure blocks (A). More importantly, in the spontaneous recovery phase, the force measured switches from compensation for the recently experienced forces to compensation for the earlier experienced forces, for trained and untrained movement directions. In multiple participants, the generalization pattern shows time-dependent asymmetries indicative of updating of the primitive weights based on motion referenced errors by both the fast and slow process. Currently, we examine our data to chart out the two components of generalization curve at every trial during the learning. Our results suggest that fast and slow adaptive processes individually contribute to generalization, with updating presumably based on errors relative to experienced motion states.

2-F-62 Separation of multiple motor memories through implicit and explicit processes
Presenting Author: Yuval Shaine

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Acquisition of multiple motor skills without interference is remarkable in sport and daily life. A common paradigm to study the ability to simultaneously learn multiple tasks is sensorimotor adaptation to opposing perturbations. In this challenging environment, each perturbation can be successfully learned when a dynamical contextual cue, such as a follow-through movement, is associated with the direction of the perturbation. Whether these explicit contextual cues allow learning via cognitive strategy-based explicit process and/or implicit process that occurs without conscious awareness, remains unclear. Here, we designed three reaching experiments to separately untangle the effect of the explicit and implicit components while participants learned opposing visuomotor perturbations that were randomly selected for each trial, with a second unperturbed follow-through movement. In Experiment 1 we replicated previous force-field results and showed that follow-through movements also allow learning for opposing visuomotor rotations that otherwise interfere. In Experiment 2 we isolated strategic explicit learning in one group of participants by inducing a 2-second time delay between movement and end-point feedback. In a second group, we isolated the implicit component by using task-irrelevant error-clamp visual feedback. Data showed that opposing perturbations can be fully learned by explicit strategies; but when strategy is restricted, distinct implicit processes contributed to learning. In Experiment 3, we further investigated the effect of follow-through location and the generalization to untrained targets of the implicit processes. We found that implicit processes existed even when the plan-based contextual cues partially overlapped, and that participants showed global generalization of the implicit separation to adjacent targets. The results demonstrate that both explicit and implicit processes are sensitive to follow-through contextual cues and contribute to separation of multiple motor memories. While the explicit process is dominant over the implicit component, distinct implicit processes show robust learning and global generalization.

2-F-63 Unexpectedness enhances anterior cingulate responses to seated locomotor perturbations
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Locomotor perturbations create significant cortical activity in the brain's mid-prefrontal region (i.e., the anterior cingulate cortex), which increases with greater fall risk. This suggests that locomotor perturbations during seated movements with little fall risk would not elicit significant anterior cingulate activity. The purpose of this study was to determine whether perturbations applied during a seated locomotor task, recumbent stepping, elicits anterior cingulate activity. We hypothesized that mechanically perturbing the stepping motion would elicit anterior cingulate activity that could be detected using high-density electroencephalography (EEG), independent component analysis, and source estimation. Young adults (n=17) completed four 10-minute arms and legs stepping tasks where in each task, a single perturbation type was applied in every stride during the middle 6 minutes of perturbed stepping while the first and last 2 minutes were unperturbed. The 4 perturbation types were left mid-extension, right mid-extension, left extension-onset, and right extension-onset. A random no-perturbation "catch" stride occurred once in every five perturbed strides. We instructed subjects to follow a pacing cue set to 60 steps per minute and to step smoothly. We quantified temporal errors as the difference between each stride's duration and the pacing cue. We defined the spatial error as the maximum difference between time-normalized stepping profiles and the average pre-perturbation profile. We recorded high-density (n=128) EEG as subjects stepped on a robotic recumbent stepper. We used independent component analysis (ICA) and current dipole source estimation to identify the electrocortical brain sources. Using optimal k-means clusters, we identified cortical clusters that included sources from >70% of the subjects. After the initial perturbed strides, temporal errors were ~50 ms but increase to >150 ms during catch strides. Spatial errors did not decrease from early to late for perturbed or catch strides. The anterior cingulate cortex was one of the 5 clusters identified, supporting our hypothesis. The anterior cingulate cluster showed significant theta-band (3-8 Hz) synchronization (increased spectral power) following a perturbation. Despite significant motor errors during catch strides, anterior cingulate activity was minimal, suggesting that the presence of the perturbation is necessary to activate the anterior cingulate cortex. Random catch strides also created unexpectedness during perturbed stepping. For the perturbed stride immediately following a catch stride, anterior cingulate synchronization was significantly enhanced compared to the synchronization of perturbed strides that followed other perturbed strides. These results suggest that anterior cingulate elicitation in this locomotor task was related to the presence of the mechanical perturbations and unexpectedness of a perturbation, rather correlated with the motor errors.

2-F-64 Strategy learning and implicit motor adaptation converge on cortical beta power

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Motor learning results from interacting learning mechanisms. The physiology underlying these interactions is largely unknown. We show that two major learning mechanisms, learning a movement strategy and implicit motor adaptation, share as a common neural pathway a modulation of cortical beta power. We recorded human electroencephalography when a visuomotor rotation induced implicit adaptation of reaching in the presence, or absence, of learning a re-aiming strategy. In young, healthy individuals (n=34), post-movement beta power decreased only when subjects had to learn to re-aim, but not when the latter was obviated through instruction, regardless of ongoing implicit adaptation. Cerebellar pathology (n=15 patients), however, revealed that implicit adaptation does decrease post-movement beta power, a decrease masked by strategy use in controls. Implicit motor adaptation, strategy learning, and strategy use converge on the dynamics of cortical beta power. This convergence could explain how a network disturbance following cerebellar pathology impairs both learning mechanisms.

2-F-65 Improvements in hip extensor rate of torque development influence hip and knee extensor feed-forward control: A neuromuscular training study

Presenting Author: Rachel Straub
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Background: Deficits in hip strength have been proposed to contribute to the higher incidence of ACL injury observed in females. Similar to what has been reported for hip strength, females exhibit decreased rate of torque development (RTD) of the hip extensors compared to males. Females have been reported to utilize a feedforward control strategy in which they compensate for decreased RTD of the hip extensors through earlier pre-activation of the knee extensors.[1] Purpose: The current study represents an extension of our previous work, by evaluating whether hip-focused training, previously found to improve maximum isometric hip extensor strength and biomechanical changes consistent with reduced ACL injury risk,[2] also alters feedforward control of the hip and knee extensors. We hypothesized that hip-focused training would increase hip extensor RTD and result in a decrease in hip and knee extensor electromyographic (EMG) onset times. In addition, we hypothesized that the increase in hip extensor RTD would be associated with a decrease in EMG onset of the hip and knee extensors. Methods: Twenty-one recreationally active females (18 to 25 years) participated in a 4-week hip-focused training program consisting of plyometric and balance perturbation exercises (3 times/week, 30 minutes/session). Pre- and post-training, hip extensor RTD was assessed during a rapid isometric contraction, followed by EMG analysis of the gluteus maximus (GMAX) and vastus medialis (VM) during a drop-jump task. All RTD and EMG assessments were conducted within 5 days of the initiation and completion of the training program. Hip extensor RTD and EMG onset times were compared pre- and post-training. In addition, the association between changes in hip extensor RTD and the change in EMG onset timing of GMAX and VM were assessed. Results: Post-training, there was a significant improvement in hip extensor RTD (21.68 ± 5.44 Nm/kg-s to 23.33 ± 5.45 Nm/kg-s, $p = 0.009$), and pre-activation of the GMAX (87.1 ± 63.6 ms to 56.2 ± 60.9 ms, $p < 0.001$) and VM (272.3 ± 113.8 ms to 124.0 ± 67.7 ms, $p < 0.001$) occurred closer to ground contact. A significant negative association was found between the change in hip extensor RTD and change in VM onset ($r = -0.48$, $p = 0.03$). There was no significant association between the change in peak hip extensor RTD and change in GMAX onset ($r = 0.38$, $p = 0.07$). Conclusion: We propose that the observed change in feedforward control is reflective of decreased need for preparatory muscle activity owing to improved capacity of the hip extensors to rapidly generate force. ACL injury prevention programs targeting hip extensor RTD may be important in altering neuromuscular activation patterns thought to be associated with increased risk for ACL injury in females. [1] Stearns-Reider et al., J Mot Behav 2018;50(3):321-9. [2] Stearns et al., Am J Sports Med 2014;42(3):602-9.

2-F-66 Aiming evokes explicit motor adaptation

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In recent years it has become exceedingly clear that explicit learning plays an important role in motor adaptation. The most used method to measure explicit adaptation is aiming: participants are asked to indicate what angle, relative to the target, they will aim at for their next reach. While useful and straightforward, this method may also reveal the nature of the manipulation to participants, by forcing them to consider reach direction on every trial. This may evoke explicit adaptation where normally there wouldn't be any. To test this we had three groups of participants adapt to a 30° rotation. These were an instructed group (N=24) who were explained the manipulation and given a strategy to counter it, an aiming group (N=24) who pointed an arrow at where they said they would aim their reach on the next trial (without landmarks or reminder instructions) and a control group (N=24) who neither received instructions nor did aiming. Except for an initial benefit of instructions, each group adapted similarly. In all three groups we measured explicit and implicit contributions at the end of adaptation by asking people to either include (explicit+implicit) or exclude (implicit only) whatever strategy they thought they had. As expected, there was no difference between these two measures in the control group indicating fully implicit adaptation. The two measures differed in the instructed group, indicating partially explicit adaptation. The distribution of differences was uni-modal in these two groups, but in the aiming group, the distribution was bi-modal, with one peak around zero, akin to the control group, and one peak lined up with the peak of the instructed group. This shows that in about one third of participants aiming has the same effect as an instruction, so that aiming not only measures, but also causes explicit adaptation.

2-F-67 A unified model of the sensory constraints on implicit adaptation

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Multiple learning processes contribute to successful goal-directed actions in the face of changing physiological states, body structures, and environments. Among these processes, implicit sensorimotor adaptation is of primary importance for maintaining appropriate calibration of sensorimotor maps over both short and long timescales. A large body of work has focused on how sensory prediction error (SPE), the difference between predicted and actual feedback, drives implicit adaptation. Recent visuomotor rotation studies have assumed that SPE is computed only taking visual feedback as input (SPE = visual cursor feedback - aim location), neglecting the role of proprioceptive feedback. Here, we offer a new perspective on implicit adaptation, presenting a computational model that brings proprioception to the forefront. The proprioceptive re-alignment model focuses on how an integrated SPE arises from the cross-modal interaction of visual and proprioceptive feedback. Specifically, this error signal is based on the difference between sensed hand position and desired hand position (target location), and that sensed hand position is a weighted signal composed of the predicted hand position, actual hand position, and a proprioceptive bias induced by a visual-proprioceptive discrepancy (i.e., proprioceptive shift). In a classic visuomotor learning paradigm the visuo-proprioceptive discrepancy (e.g., 30 clockwise) biases the sensed hand position towards the visual cursor (typically between 5° - 10° in the direction of the rotated cursor). The sensed hand position, now misaligned with the target, triggers the motor system to nullify this SPE by driving the hand in the direction away from the cursor. Implicit adaptation would cease to increase when the sensed hand position is re-aligned with the target (assumed to be the aiming location). In contrast to standard visuo-centric models, the proprioceptive re-alignment model uniquely predicts that: 1) The sensed hand position will initially be biased (shifted) towards the visual feedback during early learning, but eventually re-align with the target position during late learning (Tsay et al, 2020a); 2) Individuals who exhibit a large proprioceptive shift towards the visual cursor will exhibit a larger adaptive response (Tsay et al, 2020b); 3) Given that the proprioceptive shift saturates for large visuo-proprioceptive discrepancies, the adaptive response will saturate for large rotation sizes (Kim et al, 2018). In addition to providing a qualitative account for these effects, we also fit the proprioceptive re-alignment model to the data from three published studies, which used a variety of tasks to study sensorimotor adaptation. In each case, the proprioceptive re-alignment model provided a better fit compared to standard models of adaptation that take visual feedback as the sole input for computing a SPE. Together, these findings highlight the role of proprioception as a key constraint on implicit adaptation.

2-F-68 Residual errors in visuomotor adaptation persist despite extended motor planning periods

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During visuomotor adaptation, individuals gradually learn to counter a rotational offset between movement direction and an on-screen cursor, reducing their movement errors until an asymptote is reached. However, this learning asymptote rarely reflects full compensation of the rotation and persistent residual errors remain. Although this behaviour has previously been described as an in-built, unavoidable feature of adaptation, recent research has highlighted that when an obligatory elongated waiting period is introduced between target presentation and movement initiation, individuals have the ability to fully counter the imposed rotation. It is suggested that without this extended wait period, individuals fall foul of an intrinsic speed-accuracy tradeoff, whereby they interrupt cognitive planning processes, such as mental rotation, in order to make fast responses - resulting in more timely but less accurate movements. In this study, we sought to extend these findings in order to further understand the potential role of extended planning periods and mental rotation in the extent asymptotic levels of adaptation. We designed an online visuomotor adaptation task, where participants were required to use a mouse or trackpad to direct an on-screen cursor towards targets that appeared on their screen. Participants were first pseudorandomised into one of three groups which differed in the amount of motor planning time provided (long = 2.5 seconds, medium = 1 second, or short = 0.35 seconds) and then again into either a small (30°), moderate (45°) or large (60°) rotation group (n = 20 per group, 180 participants total). We hypothesised that shorter planning periods would be sufficient to eliminate residual errors for smaller rotations, as less cognitive processing is required, which would then scale accordingly for larger rotations. In opposition to this hypothesis we found very little evidence to suggest forced extended motor planning periods allow for the elimination of residual errors during visuomotor adaptation. In the 30° group, we found the extent of planning time provided had no effect on the final adapted level, with no differences between groups ($F(2,57) = 0.37$, $p = 0.69$, $\eta p^2 = 0.013$) and all groups displaying a learning asymptote significantly different from 30° (all $p < 0.001$). In both the 45° and 60° groups, unsurprisingly we found a restricted planning period of 0.35 seconds impaired the asymptotic level of learning compared to when longer preparation times were given. However, we found that an obligatory wait time of either 1 or 2.5 seconds was not sufficient for participants to fully counter the imposed rotation, with learning asymptotes significantly different from 45° and 60° respectively (all $p < 0.001$). These results suggest that prolonging motor planning periods alone, is insufficient to eliminate persistent errors during visuomotor adaptation in a number of different rotation magnitudes.

2-F-69 Human reaching movement adapts to environmental noise

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The environment in which motor tasks are performed is often noisy. Previous studies have shown that people tend to choose specific movements that minimize motor noise. However, how people adapt their movements to minimize the effects of environmental noise is not clear. To examine this question, we designed a paradigm where participants performed center-out reaching movements with a computer mouse. Environmental noise was simulated by adding an angular offset to visual feedback of the cursor, sampled from a uniform distribution. For each participant, we randomly selected a 'least noisy' direction (no noise), with the width of the uniform distribution increasing linearly as a function of angular deviation from this direction. In each 'choice' trial, 3 targets (separated by at least 90°) were presented in randomly selected directions and participants could choose which target to reach towards. To ensure that participants experienced the full environment, we inserted 'forced' trials (1 after 3 choice trials) in which a single target was presented in a random direction. Most participants adapted over the course of 400 trials, eventually clustering their target selection around the least noisy direction. We compared two models of learning. Model 1 assumes that participants maintain a simple global measure of their expected error (uniform in all directions), which they use in combination with the error experienced on the last reach to make their target choice. Specifically, on each trial the model uses a softmax on a von Mises function (centered on the last target direction and scaled by the last and expected errors) to determine probabilities of selecting targets with different angular deviations from the last target. The expected error is then updated by the difference between actual and expected error (sensory prediction error) with a learning rate. In contrast, Model 2 establishes and maintains a map of expected error as a function of target direction. The model assumes that participants start with a prior belief of the expected error as a scaled von Mises function of target direction. After each reach, the expected error function is updated by the sensory prediction error using a learning rate and a von Mises generalization function centered on the chosen target direction. For target choice, a softmax on the expected errors is used to calculate the probabilities of selecting each target. For each participant we fit both models to their data by maximizing the likelihood of their choices. We compared the two models using the Bayesian information criterion: For 54 out of 57 participants, Model 2 was preferred to Model 1. Moreover, Model 2 was able to account well for participants' initial biases and change in performance over the experiment. This suggests that participants represent the environmental noise by forming a map between direction and expected error.

G – Theoretical & Computational Motor Control

2-G-70 Humans control complex objects by composing dynamic primitives

Presenting Author: Salah Bazzi

Authors: Salah Bazzi[1], Stephan Stansfield[2], Dagmar Sternad[1], Neville Hogan[2]

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Studies on manipulation in humans have primarily focused on rigid objects, examining grasp or transport. However, humans are also skilled at manipulating non-rigid objects possessing internal degrees of freedom, like a cup of sloshing coffee, that create complex interaction forces. Manipulation of such complex objects is considerably more challenging and is likely to require different control models. The few existing studies on non-rigid objects only considered linear mass-spring systems which do not have the significantly more complex nonlinear dynamics of the broad range of objects that humans interact with. Moreover, those models were descriptive and aimed to identify the objective functions that humans optimize in such tasks, namely smoothness. Online solutions of such optimization problems combined with the inverse dynamics computations to generate the desired trajectories is daunting, not only for the human brain, but also for artificial controllers. A model that specifies how the control input may be generated in such complex tasks is yet to be found. We hypothesized that humans simplify control demands for physical interactions with complex objects by using dynamic primitives: submovements for discrete actions and oscillations for rhythmic actions coupled with mechanical impedance. To test this hypothesis, we designed an experiment in which participants transported a simplified, yet nonlinear and underactuated model of a cup of coffee in a virtual environment with a haptic robotic interface. Participants were instructed to move the cup from a start to a target position such that the ball comes to a full rest. 'Zeroing out' terminal oscillations of the ball presented a major challenge. To avoid trivial solutions where the subjects would move the system very slowly, a metronome specified a relatively short movement duration. Experimental data was compared to three different control models. The first two models were optimization-based, postulating that humans seek to optimize smoothness of the object or the hand kinematics. The third model was comprised of dynamic primitives, specifically submovements for the point-to-point movement and impedance. Human data exhibited two features that opposed the predictions of the optimization-based models: 1) human cup velocities exhibited two peaks with consistently different peak velocities; 2) the minimum velocity between the two peaks did not decrease for faster movements. In contrast, the primitives-based controller generated asymmetric peaks in the cup velocity, consistent with the data. When submovement parameters were selected based on a simplified internal model of the object and hand impedance, results better matched experimental observations than those generated from the fully-fledged model. These results provide evidence that humans may simplify the control of complex objects by using pre-structured elements for control that are adapted with a mechanical impedance, i.e., dynamic primitives.

2-G-71 Conservation of direction-dependent neural trajectories in primate motor cortex regardless of movement features

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Motor cortex has been proposed to control both static (direction, target position, distance) and dynamic (speed, acceleration) features of movement. Here we study if and how static and dynamic features of movement during a sequential arm movement task are encoded in the low-dimensional subspaces of population activity in primate dorsal premotor cortex (PMd) and motor cortex (M1) (data from Perich et al, 2018). We found that during each arm movement the population's joint activity forms a rotational trajectory starting during preparatory movement activity and finishing shortly after the arm movement ends. These trajectories were strongly stereotyped: the rotational trajectories started and ended in the same region of the subspace during each arm movement, regardless of that movement's direction, duration, distance or speed; moreover, the different durations, speeds, and distances of movement minimally varied the trajectories for a given direction. Yet trajectories corresponding to different directions of movement each occupied a different region of the subspace. Thus, while direction was encoded in the geometry of joint neural activity throughout the preparatory and movement periods, other static and dynamic features of arm movement were not. Our results suggest that neural coding of

these features of arm movement is superimposed on stereotyped trajectories of joint activity in motor cortex. 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

2-G-72 The relationship between local field potentials and neural population activity is region-specific and frequency-dependent

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The activity of neural populations is well described by a subset of population-wide activity patterns. This "latent activity" is shaped by constraints imposed by the synaptic connections. These same synaptic connections play a key role in the biophysical generation of the local field potentials (LFPs). LFPs are intriguing signals: changes in LFP power in specific frequency bands correlate well with processes such as movement initiation or selection among different actions, yet their relationship with the activity of the neurons that drive these processes remains elusive. Since both the latent activity and the LFPs reflect aspects of network connectivity, we hypothesised that there should be a clear association between the two. We recorded LFPs and single neuron population activity as monkeys performed an instructed delay reaching task. We studied three cortical regions, dorsal premotor (PMd), primary motor (M1) and area 2 of somatosensory cortex, to assess the potential influence of region-specific cytoarchitecture on the relationship between LFPs and latent activity. We calculated the latent activity from the single neurons using Principal Component Analysis, and computed the LFP power in eight standard frequency bands, together with the moving average of the broadband LFP. We first studied the similarity between M1 latent activity and each LFP frequency band during movement execution using Canonical Correlation Analysis. The relationship between LFPs and latent activity was consistent across subjects, but frequency dependent: the low and high frequency bands were most strongly correlated with the latent activity. This association was virtually identical during movement preparation, as expected given that synaptic connections are unchanged between the two. After finding this robust association between LFPs and latent activity in M1, we asked whether the same would be true of other cortical regions. For PMd and area 2, the LFP-latent activity correlations were again frequency dependent, yet consistent across monkeys for a given cortical area. Intriguingly, the LFP-latent activity correlation profiles in the mid-range frequencies differed dramatically among brain regions. We finally asked whether the robust LFP-latent activity correlation profiles could result from features of single neuron firing. We compared the correlations between LFPs and the firing rate of neurons recorded from the same electrode to that of signals recorded on different electrodes. Both distributions of correlations were remarkably similar, ruling out that our results capture a straightforward relationship between single neuron firing and LFPs. In summary, there is a robust frequency-dependent association between LFPs and latent activity, which varies across sensorimotor cortical areas and remains stable between movement planning and execution, Thus, specific LFP bands capture the shared activity of local neural populations in an area-specific, stable manner.

2-G-73 State-space model reflects contextual interference effect in force field adaptation

Presenting Author: Michael Herzog

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The contextual interference effect (CIE) in motor skill learning states that interleaved (high contextual interference) in contrast to repetitive (low contextual interference) practice protocols lead to lower performance gains during practice but superior retention and transfer [1]. The aim of this study was to investigate the CIE with respect to retention and spatial transfer in force field adaptation [2]. First, we experimentally tested whether the CIE is detectable in force field adaptation. Then, we fitted an extended state-space model (SSM) [3] to the data to test if it can account for the CIE. Subjects adapted to a viscous, counter-clockwise force field (F=[0,20;-20,0]*v) during 800 trials. Four practice targets with 10cm distance (1.30, 12, 9, 7.30h) were used. The blocked group (N=16) practiced 200 times the same target before the next. The random group (N=16) practiced all targets in random order. After ten minutes and 24h, subjects were tested for retention and transfer (target interpolation (10.30h), target extrapolation (4.30h) and four targets with the same directions as the practice targets but shifted 10cm into direction of 1.30h). Adaptation was quantified by maximum perpendicular distance and force field compensation factor. The progress was then subject-specifically modelled with a n-slow-n-fast SSM accounting for generalization and set breaks [4,5]. The blocked group adapted faster, yet with no statistically significant better adaptation at practice end (p=.85). We found statistically significant better retention (10min), interpolation (10min), and transfer to shifted targets (10min & 24h) for the random group (each p<.05). No statistical differences were found for retention and the interpolation target after 24h (p=.06, p=0.07). No group showed transfer to the extrapolation target. Our SSM accounted for most results. Its fast process was more engaged during the blocked practice, resulting in faster adaptation. The slow process reached a higher value at practice end in the random group. The experimental findings conform to CIE findings in the skill learning [1], motor adaptation retention and generalization literature [6,7]. Our SSM findings add to the prevailing notion that SSMs reflect multiple phenomena in force field adaptation. The higher end level of the slow process seems to account for the better retention and transfer of the random group. SSMs are descriptive and can thus not infer the result's causes. Still, the present findings help enhance our understanding of the CIE. [1]Shea and Morgan. (1979). J Exp Psychol Hum Learn Mem, 5: 179-187. [2]Shadmehr and Mussa-Ivaldi. (1994). J Neurosci, 14: 3208-3224. [3]Smith et al. (2006). PLoS Biol, 4: e179. [4]Lee and Schweighofer. (2009). J Neurosci, 29: 10396-10404. [5]Albert and Shadmehr. (2018). J Neurophysiol, 119: 1367-1393. [6]Gandolfo et al. (1996). Proc Natl Acad Sci USA, 93: 3843-3846. [7]Criscimagna-Hemminger and Shadmehr. (2008). J Neurosci, 28: 9610-9618.

2-G-74 Stabilizing brain-computer interfaces with nonlinear manifold alignment
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Intracortical brain-computer interfaces (iBCIs) can restore voluntary movement control to people with paralysis by translating brain activity into a control signal for an external device. Currently, iBCI performance declines over time due to instabilities at the neural interface, such as shifts in electrode position or changes in electrode properties. Such instabilities result in a degradation of decoding performance that can only be recovered by retraining iBCI decoders with additional movement data. To solve this problem, an emerging class of methods seeks to find population-level latent manifold structure that exhibits a stable mapping between brain activity and behavior, allowing recalibration using only neural data. In a recent proof of concept, Degenhart et al (2020) performed linear manifold discovery using factor analysis (FA) to achieve stable closed-loop iBCI control over five days without decoder recalibration. However, nonlinear manifold discovery has outperformed linear methods in retaining the behavioral information necessary for high-performance iBCI decoding (Pandarinath et al., 2018). Thus, we developed a platform for nonlinear manifold alignment decoding (NoMAD) that seeks to stabilize iBCI decoding using nonlinear manifold discovery. In NoMAD, manifold discovery is performed by Latent Factor Analysis via Dynamical Systems (LFADS), a deep learning approach that uncovers manifold structure by modeling the shared dynamics underlying population activity. NoMAD combines LFADS with unsupervised distribution alignment (Dyer et al., 2017; Farshchian et al., 2019) to produce consistent manifold estimates that are robust to changes in the recorded neurons. We tested whether NoMAD could improve the stabilization of decoding performance in an offline analysis of motor cortical activity from a monkey performing an isometric wrist force task throughout 12 sessions spanning over three months. NoMAD achieved stable, high-performance decoding of the monkey's exerted force over all sessions without requiring supervised recalibration. NoMAD's force-decoding performance ranged from 0.73-0.89 R2, with a median performance of 0.85 R2. By contrast, a preliminary investigation of FA-based stabilization (Degenhart et al., 2020) achieved a median performance of 0.46 R2, with significant variation ranging from -0.48 R2 to 0.58 R2 in performance across sessions. By combining accurate, nonlinear manifold discovery with unsupervised manifold alignment, NoMAD improves upon current methods, potentially enabling higher-performing and stable iBCIs that are better suited for real-world application.

2-G-75 Manipulating a bullwhip: Exploiting wave physics facilitates motor control

Presenting Author: Aleksei Krotov

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Daily life is full of interactions with objects with underlying complex dynamics; examples include spreading a tablecloth or tying shoelaces. To date, motor control studies have examined simple movements to facilitate scientific rigor. However, existing insights into motor control may not extrapolate to understand human dexterity in daily interactions. To confront the full complexity of human-object interactions, we examined the task of manipulating a bullwhip, an object with nonlinear dynamics and infinitely many degrees of freedom. The typical assumption that movement control is based on an internal model is challenged with this infinitely-dimensional object. We, therefore, hypothesize that humans simplify their dynamic interaction with complex objects and exploit the passive dynamics of the whip. Specifically, we tested whether the whip displays smooth unfolding and whether humans benefit from it. In the experiment, 16 participants used a 1.60m-long whip to hit a target 300 times in a single session, in discrete style with pauses between successive trials, and in rhythmic style, connecting successive trials without rest. 3D motion capture obtained continuous kinematic data from the subject (18 markers) and the whip (12 customized high-endurance markers). The task was achieved by all subjects with varying accuracy; the overall error was smaller in the discrete than the rhythmic style; however, both error and variability decreased only in the rhythmic style.

Analysis of the 12 markers on the whip showed a smooth unfolding, resembling a wave. The speed profiles of the markers featured peaks; these progressed smoothly from the handle to the tip in the rhythmic style and showed an irregular pattern in the rhythmic style. The smooth pattern was simulated with an analytical 1D model of an unfolding thread, with momentum conserved and no explicit stiffness or internal friction specified. Not only did this model reproduce the observed propagation of a 'loop' along the whip during a throw, but also agreed with the aggregated speed profiles, with a better agreement in the rhythmic than in the discrete style. The smooth unfolding, captured with a relatively simple model, suggests dimensionality reduction while manipulating the whip, that might simplify control. This reduction might result from a possible control strategy that exploits the passive oscillatory dynamics of the whip, especially during rhythmic manipulation. It remains unclear why the discrete performance was superior to rhythmic performance, but we speculate this strategy afforded the improvement of accuracy during rhythmic interaction. Although the details of such a strategy remain to be revealed, this study takes a step towards understanding human motor control. It demonstrated the simplified behaviour of a prodigiously complex object during a rhythmic manipulation, possibly resulting from humans exploiting its passive dynamics.

2-G-76 Effect of resistance on endpoint jerk decomposition in a constrained arm movement task.

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The endpoint jerk in multi-joint arm movements can be decomposed into terms related to joint angular velocities, accelerations and jerks and to arm pose and its rate of change. The contribution of these terms to total endpoint jerk may depend on the motor task and on external constraints. Jerk decomposition has been earlier analyzed for reaching and cranking arm movements. The integral of the squared total endpoint jerk was decomposed into 4 components. For reaching, 1 component dominated the total jerk (>90%). This component directly correlated to angular jerk. For arm cranking with practically no crank resistance, 2 components dominated the total endpoint jerk, one was related to angular jerks and one to the arm configuration and its time derivatives (ca. 40%-40%). Thus, the jerk decomposition depends on the motor task. Here we investigate whether external load (crank resistance) effects the jerk components. Twenty-two able bodied persons performed arm cranking on an arm cycle ergometer (MEYRA, Kalletal, Germany), with a cadence of 60 revolutions per minute against 3 crank resistances: low, moderate and high; single-manually with the right and left arm and bi-manually. Ultrasound emitting markers of a movement analyzer system (ZEBRIS CMS HS, Germany) were placed on the participant's arm. Marker positions were recorded with 100 Hz sampling frequency. Inter-segmental angles in the shoulder, elbow and wrist were computed from marker positions and angular velocities, accelerations and jerks were derived from joint angles. The relation between endpoint (hand) velocity and joint angular velocities, was given by the Jacobian. Successive derivatives of this relation gave 4 components of the jerk cost function. We calculated a multiple ways mixed factor analysis of variance (ANOVA) for each component. We considered factors such as hand ={'left', 'right'}, mode ={'Double', 'Single'}, crank resistance= {'low, 'moderate, 'high}, and the subject as a random factor and thus made this a mixed model with interactions up to the 3rd order. The jerk component that is directly related to angular jerk, is influenced by crank resistance (p=0.0004). No interaction between two factors is significant. The jerk component that is related to the arm configuration and its time derivatives, is also influenced by the crank resistance ($p<0.0001$). No interaction between two factors is significant. Thus, the external load influences the major jerk components. In particular we have observed that the increase in load increases one dominant component (that relates to angular jerk) and simultaneously degreases the other dominant component (that relates to the change of arm configuration). This suggests that, when normalizing all the components to the total jerk, for higher load the jerk at the angle increases while the change in the arm pose becomes more consistent. We assume that this depends on how well the subjects are able to separately control kinematics and force.

2-G-77 Force variability is not motor noise

Presenting Author: Akira Nagamori
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Many computational theories of human sensorimotor control of movement have tried to account for noise and variability in the motor system. In particular, the experimentally observed `signal-dependent motor noise', a linear increase in standard deviation (SD) of muscle force with its mean level, is assumed to arise from noise intrinsic to muscle force generation. The physiological origin of such noise has been attributed to the discharge variability of motoneurons due to synaptic noise and unfused twitches of motor units during muscle contraction. Here, we systematically investigated the physiological validity of such assumptions and their impact on force variability. This required developing a novel computational model of a motor unit population that addresses several previously unmodeled principles/features of motor unit physiology: 1) neuromechanical matching between electrical properties of motoneurons and mechanical properties of muscle fibers they innervate, 2) a scheme of recruitment and rate coding that can account for both the onion-skin and reverse onion-skin phenomena, 3) fusion of motor unit twitches, and 4) a series-elastic element to account for the aponeurosis and tendon. Our results demonstrate the insufficiency of the current simplistic assumption that force variability arises predominantly from `noise' in our motor systems. We find that the degree of stochasticity of motoneurons decreases with increasing levels of synaptic input. So does the SD of the output force of individual motor units due to progressive fusion of motor unit twitches. Moreover, neuromechanical matching between motoneuron and muscle fiber properties further ensures twitch fusion occurs in the normal range of motor unit discharge rates, reducing the contribution of unfused motor unit twitches. Finally, the in-series elasticity allows contraction dynamics even during an externally isometric contraction of a viscoelastic musculotendon unit. This low-pass filters high-frequency force fluctuations due to unfused twitches and further attenuates the amplitude of motor noise at all force levels. As a result, motor noise arising from the population of motor units does not account for the reported amplitude of force variability or the proportional increase in its amplitude with mean force levels that has been observed experimentally. The patterns of motor noise that emerged from our model do not justify the implementations of linear additive signal dependent noise that have been popular in theoretical models of optimal control to cope with force variability. Instead, our results suggest that the majority of force variability is a consequence of sensorimotor control rather than a fixed input to its control strategies. Force variability is thus a rich source of information about how the overall nervous system executes voluntary action. Changes in force variability may therefore be informative biomarkers for healthy aging and various neuropathologies.

2-G-78 Transition of control objectives in the manipulation of complex objects

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Skilful object manipulation often involves switching between different control objectives. When swirling a glass of cognac, the primary goal of control is to bring the cognac (internal degree of freedom) into a rhythmic circular motion; when subsequently bringing the glass to the mouth, the goal is to translate the glass itself. Examining the transition of control objectives, from rhythmic to discrete, and from internal to external degrees of freedom, can provide insights into dexterous object manipulation. This study designed a novel experimental paradigm where subjects manipulated a cup with a ball rolling inside (akin to a glass of cognac) on a horizontal plane. The task was implemented in both virtual and real settings. In the virtual task, the cup-and-ball movements were displayed on a screen in top-down view and subjects controlled the cup via a robotic manipulandum, which provided haptic feedback. In the real setup, subjects grasped the handle of a custom-made cup with a ball rolling inside and slid the cup on a smooth table. The task parameters of the real and virtual set-ups were matched to afford analogous analysis. The task was to rhythmically "swirl" the ball close to the rim while keeping the cup within a "home position". An auditory cue signalled subjects to translate the cup in a reach-like manner towards a target position, while maintaining the ball swirling. The aim of the study was twofold: 1) We examined how humans transitioned their control objective between rhythmic (ball) rotations and discrete (cup) translations in the context of complex object manipulation. 2) We asked how such transition policies contrasted between virtual and real implementations of the task. The primary results on both settings were that subjects initiated the transition from rhythmic ball rotation to discrete cup reaching by converging to a specific ball rotation phase prior to and after the reach. This indicated that the cup discrete movement was integrated into the ball rhythmic cycle. More interestingly, the reach duration showed a multimodal distribution whose peaks were separated by approx. one ball rotation period. This suggested that the planning of the reach was also influenced by the preceding rhythmic ball rotations. By simulating the task dynamics, we found that for both real and virtual settings the observed modulation of the ball's rhythmic phase and the reach duration lay on a solution manifold that maximized smooth transitions and stable ball rotations. However, the real and virtual settings showed notable differences: the real setting revealed exploratory features of control by spreading the data along the solution manifold, while the virtual setting exhibited exploitation of a subspace of the manifold. Our findings suggest that the motor system merges the discrete and rhythmic movements to facilitate transitions, but depending on the context (real versus virtual), it might take an exploration- or exploitation-based approach.

2-G-79 A unified mathematical model for locomotor adaptation capturing both fast and slow time-scales

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Humans adapt their locomotion patterns to different circumstances, sometimes quickly, sometimes more slowly, and sometimes across time-scales, usually in a manner that improves their locomotion along some dimensions. We do not yet have a unified model that predicts the changes that accompany such locomotor adaptation and subsequent de-adaptation. Here, we show that a normative model, prioritizing stability in the short time-scale and prioritizing energy in the long time-scale, explains locomotor adaptation phenomena across time-scales. Walking on a split-belt has become a standard paradigm for studying locomotor adaptation and deadaptation. When a person walks on a split-belt treadmill, with the two belts going at different speeds, their gait undergoes various stereotypical changes in gait symmetry. These symmetry changes happen both during adaptation (when the person is walking on split-belts after having just walked on regular equal-speed belts) and de-adaptation (when the person is walking on regular equal-speed belts, after having walked on split belts). Researchers have focused in particular on step length asymmetry and step time asymmetry as high-level descriptors of the symmetry changes. The symmetry changes observed in experiment have multiple timescale, fast changes during 'early adaptation or de-adaptation' over a few steps and slower changes over tens of minutes during 'late adaptation or de-adaptation'. We present a unified model that qualitatively captures all the symmetry changes, both fast and slow and both during adaptation and de-adaptation. The model simply enshrines the principle that at short time-scales (e.g., when the belt speeds have just changed), stability or not falling down is important and on slower time-scales, other objectives, specifically energy, is important. This principle is realized in a minimal biped model with a controller with an inner and an outer loop: the inner loop is a stabilizing feedback controller that keeps the biped from falling and the outer loop gradually tunes the parameters of the control policy via local reinforcement learning to improve the steady state energy cost of walking. This model qualitatively captures the sudden jumps in symmetry (early adaptation and de-adaptation), the slow transients, and the steady state in both step length and step time symmetry. To the extent we know, this is the first unified model that predicts both the transients as well as the steady state in locomotor adaptation. The model also predicts some phenomena in other locomotor adaptation scenarios, for instance, walking on a novel exoskeleton and changing distal masses. We outline how this model can be used to create protocols that accelerate learning a new task.

2-G-80 Musculoskeletal anatomy of the forearm and hand is imbedded in the spatial organization of the motoneuron pools

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The neural motor system incorporates the complex mechanics of the body and its external environment to provide adequate motor control, a concept termed neuromechanical tuning (Enoka, 2015; Mizrahi, 2015; Nishikawa et al., 2007; Prochazka and Yakovenko, 2007). At the spinal level, this tuning is expressed through modular control units often referred to as synergies or primitives (d'Avella and Lacquaniti, 2013; Berniker et al., 2009; Cheung 2005; Thoroughman and Shadmehr, 2000). The musculoskeletal anatomy and the neural control units are closely linked, i.e., muscles that perform one particular action are mechanically coupled (Gritsenko et al., 2016). However, it remains unknown if the anatomical organization of spinal motoneuron pools is related to the mechanical motor primitives. The objective of our study was to quantify the extent to which the anatomical locations of motoneuron pools reflect the motor primitives derived from the musculoskeletal anatomy of the forearm and hand muscles that they innervate. We hypothesized that the motoneuron pools with similar agonistic mechanical actions will be located closer together than the motoneuron pools without functional overlap. To achieve our objective, we have constructed a 3D model of the spatial locations of upper extremity motoneuron pools, similar to our previous work (Yakovenko et al., 2002). Anatomical data for 16 forelimb muscles was derived through retrograde labeling with horseradish peroxidase in macaque monkeys (Jenny and Inukai, 1983). The images of grey matter outlines and the labeled motoneuronal cell bodies were scanned and digitized using Adobe Illustrator. The metadata was then imported into Matlab to create a 3D model of motoneuron locations in spinal cord segments C5 to T1. To account for differences in animal size, motoneuron locations were normalized to one set of grey matter outlines. The relative distances between motoneuron pools were then analyzed using a hierarchical clustering method. In a separate analysis, the same hierarchical clustering method was applied to quantify the relationship between muscle lengths across the whole repertoire of hand postures in two OpenSim models of human and monkey arms (Chowdhury et al., 2020; Gritsenko et al., 2016). The clustering analysis revealed that spinal cord motoneuron pools are spatially separated into two groups, characterized by flexor versus extensor actions around the elbow, wrist and finger joints. This broadly mimics the anatomical groupings based on muscle lengths. This suggests that the functional organization of the musculoskeletal system is embedded in the spinal cord anatomy and underlies motor primitives.

Poster Session 3

A – Control of Eye and Head Movement

3-A-1 Signals from parietal area 5 to superior colliculus for coordination of gaze with strides

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The parietal cortex receives both visual and movement-related information, and is involved in the control of limb movements, including accurate steps during locomotion. The activity of parietal area 5 neurons projecting to the pyramidal tract changes when the animal steps over an obstacle (Andujar et al. 2010), and lesions in the area compromise step accuracy (Lajoie & Drew 2007). Accurate steps on a complex terrain relay on visual information about it, and gaze behavior is coordinated with strides (Matthis et al. 2018; Zubair et al. 2019). The spinal locomotor CPG plays a significant role in the coordination (Combes et al. 2008), and vestibular signals resulting from head movement during locomotion also contribute. The contribution of the brain visual and motor centers to the coordination of the gaze with strides remains poorly understood. In this study, we investigated the activity of parietal area 5 neurons projecting to the superior colliculus, the midbrain center for control of gaze, as the cat walked on the flat surface and horizontal ladder. Walking on the flat surface does not require vision, while accurate stepping on the ladder does. Comparing neuronal activity between these two tasks allows identification of components of the activity that are related to gaze control and visual processing vs. limb movement. We investigated the activity of 30 neurons projecting to the superior colliculus (a5-SCs) and thus presumably participating in the control of gaze, the activity of 33 pyramidal tract projecting neurons (a5-PTNs), which presumably participate in the control of limbs, and the activity of 130 unidentified neurons (noIDs), all recorded in cortical layer V of the same or neighboring microelectrode tracks through the most rostral part of the suprasylvian gyrus. We found that, as reported earlier for area 5 noIDs (Beloozerova & Sirota 2003;Lajoie et al., 2010), the activity of the majority of a5-SCs and a5-PTNs was step-related. On the flat surface, the depth of the activity modulation was higher in a5-PTNs. Upon transition to the ladder, most neurons in all groups changed the discharge rate, and/or depth of its modulation, and/or stride phase distribution. The a5-SCs, however, changed the distribution of the activity much more often than the a5-PTNs, and as a group increased the depth of the activity modulation. This indicated that the activity of a5-SCs on the ladder was significantly influenced by visual information. We concluded that a5-SC neurons may contribute to the coordination of the gaze with limb locomotor movements by conveying to the superior colliculus visual information from the cortex that is superimposed on the locomotion rhythm-related discharge.

3-A-2 The effect of vergence eye movements and target deceleration on speed perception

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It is important to acquire accurate visual information in a three-dimensional (3-D) visual environment in daily life or sports situations. Speed perception is one of the factors to accurately observe the target motion. It is known that a moving target with acceleration is perceived differently from a moving target having constant velocity, even though the average velocity is kept the same. Previous studies have investigated the relationship between eye movements or target acceleration and speed perception in fronto-parallel plane. However, these relationships have never been determined in a 3-D visual environment. Therefore, the purpose of this study was to explore the effect of vergence eye movements and target deceleration on speed perception using a visual target that moves from far to near. Participants in this study were 11 college students with normal vision. We used a two alternative forced choice paradigm with the method of constant stimuli in order to measure psychometric functions for duration discrimination. Participants are presented with a constant standard and a variable comparison stimulus and their task is to judge which of these two stimuli is the shorter duration. The visual target, which was a green laser with a diameter of 2 mm, moved from a vergence angle of 3 to 20 degrees. The standard stimulus always moved at a speed of 48 cm/s for 2000 ms and participants were asked to fixate on the stationary target. On the other hand, the comparison stimulus was used five different durations (1800, 1900, 2000, 2100, 2200 ms) with or without deceleration (deceleration stimulus or constant stimulus). Participants were also asked to pursue the moving target or fixate on the stationary target (pursuit and fixation tasks). During the discrimination task, we measured eye movements by corneal reflex used infrared camera and detected eye position by a video-based eye tracking system. We evaluated a possible perceptual bias as the point of subjective quality (PSE) and detected gain of vergence eye movements. PSE represented the target's duration at the point of 50 % on the fitted psychometric function. The vergence gain was defined as the ratio of the eye velocity to the target velocity. We compared four conditions to determine the PSE: deceleration stimulus and pursuit task (DP), deceleration stimulus and fixation task (DF), constant stimulus and pursuit task (CP), constant stimulus and fixation task (CF). As a result of the PSE, participants jugged that the deceleration stimulus was shorter than the constant stimulus, and pursuit task was shorter than fixation task in the deceleration stimulus. The vergence gain was lower for the deceleration stimulus than constant stimulus during an initial phase of the target motion. Therefore, these results suggest that the retinal signal in the initial phase of target motion influences the speed perception in a 3-D visual environment.

3-A-3 Importance of location information in remembering the weight of multiple objects

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Many real-world tasks involve interacting with objects, and dexterous performance requires quickly and accurately anticipating their physical properties, such as weight. Previous studies have shown that people can use visual information about object size, material and identity to anticipate the weights of specific objects. However, when interacting with multiple objects, a potentially important source of information that could be used to predict weight, but that has never been investigated, is object location. Here we investigated the contribution of spatial associative memory to the encoding and recall of object weights in the context of action. We examined the efficacy of location and size information, both in isolation and when combined. We developed a novel task in which a subject grasped the handle of a 3D robotic interface and viewed a virtual scene of 3 objects resting on a surface. When ready, they pressed a button, causing a randomly selected object to slide--over a 600 or 800ms time window--to a platform, which was coupled to the robot handle. The platform was clamped in place until the object reached the platform, and the subject's task was to increase the vertical force they apply to the platform from ~0N to the weight of the object, so that the platform (and object) did not move at the time of release. The weights of the 3 objects (0.4, 0.7, and 1Kg) were the same for all groups. For the size group, object size varied linearly with weight and the locations of the objects were randomized at the start of each trial. For the location group, the objects were all the same size but their locations were fixed (such that object weight could only be predicted from location). Subjects in these two groups completed 300 lift trials. To test whether subjects use location information even when size information is available, we ran a third size+location group who received both size and location information; i.e., object size varied with weight and locations were fixed. For this group, after 300 trials we then removed location information for 20 additional 'transfer' trials by randomizing the object locations on each trial. In early trials, subjects could effectively use size information (size group) to predict weight whereas location information (location group) was far less effective. However, by the end of 300 trials, location and size information were equally effective. Moreover, once learned, this indicated that subjects could learn the mapping between weight and location and then exploit this information to predict weight. The group with both size and location cues (size+location group) learned quickly but critically on the transfer trials there was a significant decrement in performance showing that subjects were relying on location information when weight could be coded by either size or location. These results demonstrated that location can provide a powerful cue for weight prediction even in the presence of reliable size information.

B – Fundamentals of Motor Control

3-B-4 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.

3-B-5 A Hessian-based decomposition characterizes how performance in complex motor skills depends on individual strategy and variability

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In complex real-life motor skills such as unconstrained throwing, performance depends on how accurate is on average the outcome of noisy, high-dimensional, and redundant actions. What characteristics of the action distribution relate to performance and how different individuals select specific action distributions are key questions in motor control. Previous computational approaches have highlighted that variability along the directions of first order derivatives of the action-to-outcome mapping affects performance the most, that different mean actions may be associated to regions of the actions space with different sensitivity to noise, and that action covariation in addition to noise magnitude matters. However, a method to relate individual high-dimensional action distribution and performance is still missing. Here we introduce a decomposition of performance into a small set of indicators that compactly and directly characterize the key performance-related features of the distribution of high-dimensional redundant actions. Central to the method is the observation that, if performance is quantified as a mean score, the Hessian (second order derivatives) of the action-to-score function determines how the noise of the action distribution affects the average score. We can then approximate the mean score as the sum of the score of the mean action and a tolerance-variability index which depends on both Hessian and action covariance. Such index can be expressed as the product of three terms capturing noise magnitude, noise sensitivity, and alignment of the most variable and most noise sensitive directions. We apply this method to the analysis of unconstrained throwing actions by non-expert participants and show that, consistently across four different throwing targets, each participant shows a specific selection of mean action score and tolerance-variability index as well as specific selection of noise magnitude and alignment indicators. Thus, participants with different strategies may display the same performance because they can trade off suboptimal mean action for better tolerance-variability and higher action variability for better alignment with more tolerant directions in action space.

3-B-6 Online adjustments in control policy in human reaching movements reflect dynamical changes in target structure

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While performing reaching movements, humans integrate many task-related parameters to select the appropriate control policy. For example, the structure of the goal target is taken into account while performing movements: we will not reach to a wide target the same way as we reach to a narrow one. Recently, we showed that these goal-directed control policies can be adjusted online in response to an unexpected change in target structure or in the environment. It is still unknown whether these online adjustments could be tuned to dynamical changes in target structure, or whether they could result from switches among a limited set of pre-defined controllers. Here we investigate this question in an experiment where the width of the reaching target changed dynamically. More specifically, we varied the velocity of changes in target width to probe whether this parameter was take into account in the associated motor adjustments. Participants (N = 8) had to reach to a rectangular goal target (30 x 2.5 cm) whose structure could unexpectedly change during movement. Three types of changes in target structure were investigated: one condition was an abrupt change where the target instantaneously turned into a square (2.5x2.5 cm), and the two remaining conditions were gradual changes in which the target width decreased continuously following movement at slow or fast speed (respectively 45 and 33 cm/sec). In addition to these changes in target structure, we introduced unexpected mechanical perturbation loads to the hand, orthogonally to the main reaching direction, in order to assess change in control policy associated with the change in target structure. We analysed kinematics of the hand during trial to determine whether and how fast the feedback responses to mechanical perturbations reflected the dynamical changes in target width. We found that the final hand position was dependent on the target change condition: more eccentric positions were associated with slower decrease in target width. We also observed differences in lateral hand acceleration such that the responses to the perturbation loads scaled with the continuously changing target width. We revealed that these differences in lateral hand accelerations could occur in as little as 150 ms following the onset of the change in target structure. Altogether, our results suggest that the factors that contribute to updates in control consider time-varying changes, suggesting a continuous monitoring of task variables and corresponding changes in state-feedback control.

3-B-7 Mirror-system-like excitability to kinaesthetic stimuli in the human motor cortex

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The mirror neuron system integrates sensory stimuli into our own motor control. Mirror behavior is best known in human and monkey motor neurons being activated when seeing or hearing another individual's actions. An open question is how this mirror behavior relates to one's own kinaesthetic input. Here we present data showing that motor evoked potentials (MEP) by transcranial magnetic stimulation (TMS) are the same for passive viewing of other's wrist movement and passive movements of one's own wrist. The kinaesthetic influence on the motor threshold was even slightly stronger than the visual stimulation, whereas combined visual and kinaesthetic stimulation further increased the MEPs. We thus provide, for the first time, evidence for the integration of passive kinaesthetic- and visual-sensory stimuli.

3-B-8 Modulation of auditory cortical response to self-generated sound by walking during split-belt treadmill adaptation

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It has been demonstrated that the auditory cortical responses to self-generated sounds are generally attenuated compared to those with externally generated sounds. Previous studies suggested that the N1 attenuation in auditory evoked potential (AEP) could be caused by the intention and/or prediction signals from the cortical and cerebellar motor areas. This was because the movements used in the previous study were discrete and voluntary movements controlled in those areas (e.g., speech and button pressing). In addition, the N1 attenuation was reported to be less related to auditory-motor adaptation. However, it remains unclear whether the N1 attenuation is also observed for sounds generated by semi-automatic movements such as walking, which are controlled at the lower level of the central nervous system (CNS). It is also unclear whether the attenuation depends on the control at the higher level of CNS during adaptive walking than normal walking. In this study, we examined the AEPs to sounds generated by walking during the split-belt treadmill adaptation paradigm. Thirteen participants walked on the split-belt treadmill as they listened to the sounds synchronized with their heel contacts (walking condition). In the walking condition, we carried out an adaptation paradigm using the split-belt treadmill. This experimental paradigm consists of baseline, gait on two independently controlled belts driving at two different speeds (adaptation, consisted of the first half phase and the second half phase), and walking on the treadmill with a fixed belt speed (washout). Each phase took 6 minutes. In the resting condition, the participants listened to the sounds by an experimenter normal walking without observing the walking. Anterior ground reaction force (GRF) was measured using two force plates mounted underneath the treadmill belts. The anterior GRFs difference between two legs was calculated as the index of the degree of adaptation. EEG signals were recorded and obtained the first negative peak amplitude in AEP as N1 amplitude. The N1 amplitudes and anterior GRFs were compared between 5 phases: resting, baseline, the first half adaptation, the second half adaptation, and washout. The N1 amplitude was significantly attenuated during the washout phase compared with the second half phase of adaptation ($t(12) = 3.14$, $p < 0.05$, Bonferroni corrected). The anterior GRFs during washout was gradually changed compared with the baseline ($t(12) = 5.64$, $p < 0.05$) and the second phase of adaptation ($t (12) = 3.56$, $p < 0.05$). The N1 amplitude during walking was not attenuated compared with the resting condition. These results suggest that the auditory cortical response to self-generated sounds by walking are altered by the aftereffect in the adaptation paradigm. To conclude, the N1 modulations to self-generated sounds by semi-automatic movements may depend on the level of control at CNS.

3-B-9 Effects of environmental intervention on learning in a novel motor skill task

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Despite the abundance of research on motor learning, we still have a limited understanding of how novel real-world motor skills are learned and the best ways to teach these skills. Building upon the recent progress in the field of reinforcement learning, specifically in designing a curriculum for training artificial agents, we aim to develop methods for designing curricula for systematically teaching motor tasks to human participants. We introduce a novel, complex motor task that might serve as a test-bed for understanding motor learning and the role of curricula in teaching motor skills. In this preliminary work, we present an online version of the motor task that is challenging enough for the participants to learn and improve their performance with practice in a few sessions. In our 'Reach Ninja' task, loosely based on the popular touch-screen game 'Fruit Ninja', participants' hand movements are live-tracked using a camera and translated to the movement of a cursor on a computer screen. The participant is asked to interact with dynamically moving targets, of varying colors and sizes, by reaching towards them using the on-screen cursor, resulting in positive or negative score increments. The objective of the game is to maximize the score within a set timeframe. Preliminary results showed that participant performance improves significantly with practice over a few sessions. Motivated by these early results, we further modulated the difficulty of the task by introducing additional challenges in the environment, including (a) modifying the dynamics of the interaction between the participant's hand movements and targets, and (b) introducing intermittent observability of the participant's cursor. These challenges offer increased scope for performance improvement through curriculum-based practice. We present data comparing four versions of the Reach Ninja task and discuss the effects of the additional challenges. Our initial results validate the potential of the Reach Ninja task as a platform for studying the learning process of challenging motor skills and the role of a curriculum. In future work, we aim to selectively teach desirable motor behaviors through administering these and other interventions in a controlled order, in the form of source tasks in a curriculum. We anticipate that curriculum-based motor training might be beneficial not only to better understand and control learning of motor tasks in healthy participants, but also in designing rehabilitation protocol for participants surviving neurological impairments.

3-B-10 Age-related modifications of muscle synergies and their temporal activations during overground walking

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Healthy ageing modifies neuromuscular control of human overground walking. Previous studies found modifications of gait biomechanics as humans age, but whether there is concurrent ageing-related modulation of neuromuscular control is less clear. Given that the muscle synergies for walking change during child-to-adult development, we hypothesized that these synergies also change during ageing. We analyzed gait kinematics and EMGs (14 lower-limb and trunk muscles) collected at three gait speeds during overground walking in 11 young adults (7 females; age 23.4 ± 2.5 years) and 11 elderlies (7 females; age 67.2 ± 4.3 years) without history of neurological disorder. We quantified the inter-subject variability of k-means-clustered muscle synergies and of their temporal activations. At all speeds, the number of synergies of the older group was higher than that of the younger group. At the population level, a synergy involving the tensor fasciae latae was more frequently identified in the elderlies while another involving the gluteus maximus, less frequently identified in the elderlies, consistent with the finding that elderlies had a larger range of hip flexion ($p<0.05$). For these two synergy clusters, the synergies for the two groups also differed subtly but consistently and significantly. For the synergies shared between both groups, the elderlies had higher inter-subject variability of the synergies' temporal activations than young adults. Interestingly, across synergies in elderlies but not young adults, the inter-subject variance of the temporal activations correlated negatively with the sparseness of the synergy vectors. In conclusion, as humans age, not only are the muscle synergies for walking fine-tuned in structure, but the synergies' temporal activations are also more heterogeneous in pattern across individuals, presumably reflecting individual differences in prior sensorimotor experience or ageing-related changes in gait biomechanics.

3-B-11 Comparison of the responses induced by motor point and peripheral nerve stimulation

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Transcutaneous peripheral nerve stimulation (PNS) is often used to examine the spinal neural circuits, and its characteristics are well-understood. However, an alternative method to activate peripheral nerves, i.e., motor point stimulation (MPS), which delivers electrical stimulation over the muscle belly is not well-studied, even though MPS is often used in neurorehabilitation. Revealing its neural characteristics will help to improve neurorehabilitation. Here we investigated F-waves induced by MPS in comparison to PNS in the soleus muscle. The F-wave is a motor response induced by electrical stimulation of peripheral nerves via the antidromic firing of the motor nerves, which in general reflects the motor neuron excitability. F-waves have been reported using PNS but never reported using MPS. Thirteen able-bodied individuals participated in this study. We applied MPS and PNS on the participant's soleus muscle. In both MPS and PNS, participants were given a supramaximal monopolar single-pulse to elicit the maximum M-wave. To evaluate pain of MPS and PNS, they were asked to mark a 10cm-visual analog scale (VAS) line on paper after stimulation. Wilcoxon signed-rank tests were conducted to compare MPS with PNS. We found that MPS induced motor responses at the latency of F-waves. Compared to PNS induced F-waves, the MPS induced motor response at F-wave latencies had a greater amplitude (MPS 137.5±38.1 µV, PNS 75.8±31.9 µV, $p = 0.003$) and higher persistence (MPS 98.2±2.4 %, PNS 67.1±32.5 %, $p = 0.006$). MPS preferentially activates superficial motor units depending primarily on the distance between stimulation site and locations of motor nerve endings, whereas PNS recruits motor units with a wider spatial distribution throughout the muscle. Thus, differences in F-waves can be related to differences in the spatial distribution of activated motor nerves in MPS and PNS. Although the stimulation intensity for MPS at supramaximal stimulations was significantly higher than that for PNS ($p = 0.004$), the current density for MPS was lower than that for PNS ($p = 0.001$). This accounts for the results regarding pain where the VAS score for pain in MPS was significantly lower than that of PNS ($p = 0.002$). We also examined responses in a double-pulse stimulation with an interval of 100ms. In the double-pulse stimulation, the second H-reflex amplitude induced by PNS significantly decreased ($p = 0.001$), the second MPS induced motor response at F-wave latencies did not change (amplitudes: $p = 0.553$, persistence: $p = 0.593$). This indicates that the response induced by MPS was not a H-reflex, but a F-wave. We conclude that MPS induces F-waves that are more robust and less painful when compared to F-waves induced using PNS. The F-wave is often used to assess spinal motoneuron excitability. Therefore, MPS has the potential to be a notable and better tool to diagnose spinal neural circuits in patients with neurological disorders and to understand spinal motor control.

3-B-12 Association between cosine tuning and endpoint force in the lower limb

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Background and aim: An estimation of the muscle activity that contributes to the desired joint torque exertion can be approximated by cosine tuning from the maximum activation direction of the muscle. Moreover, the maximum activity direction of the muscle (preferred direction, PD) is associated with a high covariance of endpoint force (CEF). However, synergistic muscle activity is inevitable in movements that require hip and knee joint extension, such as gait, as there is no muscle that can simultaneously extend the knee and hip joints in the lower limb. Therefore, the CEF in a direction-dependent manner may be low, even in the presence of PD. This study aimed to clarify whether the CEF increases depending on the PD, even in the lower limb. Methods: Eleven male volunteers were placed in a left lateral position on a bed and asked to perform isometric force exertion in various directions (0-360°) using a 6 axis force sensor fixed to the right ankle. Surface electromyography (EMG) data from eight muscles (gluteus maximus (GM), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), semitendinosus (ST), and biceps femoris long head (BF)) in the right leg were collected at 1000 Hz using a wireless EMG system. The hip and knee joint torques were calculated using the endpoint force vector and lever arm of the thigh and shank segments. Multiple linear regression analysis was performed on a 3D plot constructed by the knee and hip torque and the activity level of each muscle to define a single plane. PD was calculated as the direction of the steepest increase in muscle activity. The CEF was evaluated for each direction. A low covariance indicates that the endpoint force is generated by the synergistic activity of multiple muscles. The difference in covariance in each direction was evaluated using the Kruskal-Wallis test (p=0.05). Additionally, the consistency between each PD and the CEF in each direction was visually assessed. Results: The areas of hip extension - knee flexion and hip flexion - knee extension with PDs of RF, ST, and BF in the torque plane showed significantly high CEF. Conversely, the range of hip-knee extension with PDs of GM, VM, and VL, and flexion of both joints without PD showed low CEF. Discussion: The direction of the high CEF is reportedly close to the direction of the muscle action. In our results, the PDs of the bi-articular muscles coincided with the direction of high CEF. However, despite the presence of PDs, the range of hip-knee extension showed a low CEF. In cosine tuning, the contribution of the muscle to the desired torque vector is proportional to the orthogonal projection from the PD, i.e., when muscle PDs are close to each other, both muscles are strongly affected. In the lower limb, the PD of monoarticular muscles shifts in the same range. Therefore, this would have required synergistic activity by each muscle, which would have reduced the CEF.

3-B-13 Modulation of somatosensory signal transmission in the primate cuneate nucleus during voluntary hand movement

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Descending motor drive may depress the self-generated peripheral sensory signals that are concomitant with voluntary actions. This modulation, known as the sensory gating or sensory gain modulation, should occur at several relays where sensory and motor commands converge (e.g., spinal cord, brain stem, and cerebral cortex). The cuneate nucleus in the medulla is the first relay in the ascending lemniscus pathway of the somatosensory system. The cuneate nucleus does not only receive ascending somatosensory information of the upper body, but also receive descending signals from cortical and/or subcortical motor areas. This convergent projection from both afferent and efferent pathways implies that the sensory gain modulation may take place at the first relay, whereby influencing the somatosensory processing at the all subsequent stages. Because a majority of knowledge about the cuneate nucleus comes from previous studies in the anesthetized animals, little is known about the processing of sensory information in the cuneate nucleus during voluntary movement. To address this issue, we assessed the neuronal responses of the cuneate nucleus to the electrical stimulation to peripheral nerves in alert monkeys performing a voluntary motor task. We trained monkeys to perform a wrist flexion-extension movement with the aid of visual feedback of wrist position (active movement) using spring-loaded manipulandum. In a separate session, we also trained monkeys not to resist while the manipulandum reproduces a comparable movement of active movement (passive movement). During both active and passive movement, we recorded neuronal responses such as local field potentials and multi-, and single neuron discharges of the cuneate nucleus that were evoked via repetitive electrical stimuli at a constant current to the forearm cutaneous afferent (superficial radial nerve; SR) or muscle afferent (deep radial nerve; DR). Preliminary results indicate the suppression of the evoked responses (both local field potential and single- and multi-unit activity) during both active and passive movements. These results suggest that, indeed, the sensory gating occurred in the cuneate nucleus. Moreover, the evoked responses in active movement session were more suppressed compared with that of passive movement, which probably points to top-down gating mechanisms occurring in the cuneate nucleus. We will introduce how these afferent inputs from the ascending pathway may be modulated during voluntary movement, by comparing neuronal activity between active and passive movement.

3-B-14 The property of the implicit visuomotor control to visual motion stimuli

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It has been well established that the arm trajectory during reaching movement is corrected by a visual target displacement. Since this corrective response occurs even without perception of target perturbation, it is regarded as an implicit response. One of the notable characteristics of the implicit response is the short latency response which is approximately 120-170 ms from the onset of the displacement. With the short latency, the implicit motor response allows for online control during the ballistic movements which is hardly corrected voluntarily. Previous studies have suggested that the mechanism of the implicit motor response is based on an error signal between the efference copy that predicts sensory information and the actual feedback information. Although this error signal plays an important role in the visuomotor response, most previous studies have used a target jump (displacement) paradigm. It is still uncertain whether the implicit motor response is affected by visual motion. Therefore, the purpose of this study was to investigate the implicit visuomotor response to target motion stimuli. We attempted to clarify the property of the response to different target motion velocities. The experimental apparatus consisted of a digitized tablet to capture the movement of a stylus, a monitor displayed a visual stimulus and a cursor which is controlled by the stylus. Participants sat facing the monitor with their heads positioned by a chin rest and were asked to move the cursor from a start circle to a target. The start circle and the target were located 25 cm in front of the subject's chest and 27 cm in front of the start circle, respectively. First, participants were required to place and stay the cursor over the start circle. After around 2 s, the target appeared on the monitor and participants started the reaching movement toward the target. The target moved to the leftward or rightward when the cursor passed 2 cm from the start circle. Target motion trials were given in two-third of the total trials, and the remaining trials had no target motion. Four different target velocities

(10, 20, 30 and 40 deg/s) were randomly presented. We detected the arm trajectory in each target velocity from position data captured by the digitized tablet. Our results showed that the amplitude of the implicit visuomotor response increased in accordance with the velocity of the target motion. These results indicate that the implicit visuomotor response is induced by not only the target jump paradigm but also the target motion. It is most likely that this response is automatically modified for the target velocity, considering the short latency response. Therefore, it is suggested that the implicit response is highly sensitive to the target motion, which could be associated with the dorsal visual pathway for motion processing.

3-B-15 High-density silicon probes reveal signatures of neural circuit organization in motor cortical dynamics

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Recent advances in silicon electrode technology enable dense, simultaneous sampling of many neurons. As significant computational and theoretical work has begun to understand the computations performed via neural population dynamics, these tools open experimental avenues to explore how these dynamics are organized within neural circuits. Using NeuroPixel probes, we collected a dataset comprising 6,990 neurons (36 sessions, 2 monkeys) from rhesus M1 and PMd. We analyzed neural responses during a reaching task to investigate the spatial, laminar, and synaptic organization of neural populations engaged in motor control. We first revisited a long-held view that the motor cortex exhibits columnar architecture organized along shared preferred movement directions (PDs; Georgopoulos et al. 1984). This columnar organization predicts that spatially proximal neuron pairs should share preferred directions; instead, we observed nearby neurons with differing preferred directions. To assess whether motor cortical organization is consistent with columnar organization, we simulated recording from a virtual columnar cortex, preserving the spatial organization of our recorded neurons but substituting synthetic PDs from the underlying columns plus estimation noise. We then compared the preferred direction of each neuron (θ) with its nearest neighbor in space (θnn). Across a range of column widths (20-100µm) and simulated penetration angles (up to 45°), the correlation between θ and θnn was significantly higher in the synthetic columnar organization than in the real dataset, where θ and θnn were nearly statistically independent. Spatial proximity was also not predictive of similarity in neural responses assessed via PSTH correlation nor angles between Gaussian process factor analysis loading vectors. A coarse laminar division of neurons into superficial and deep cells revealed increased similarity among superficial neurons, reflecting increased similarity in the condition-independent component of neurons' movement responses and shorter latency to respond to task cues. Cross-correlation analysis revealed 5,639 / 843,033 (0.67%) neuron pairs with sharp, low-latency peaks after jitter correction, suggestive of putative synaptic connectivity. These neuron pairs exhibited more aligned preferred directions and more correlated PSTHs, reflecting increased similarity in both condition-independent and dependent response components. Collectively, these analyses depict highly heterogeneous, finely intermingled neuronal responses throughout M1 and PMd. Laminar structure is detectable in the large, condition-independent response component, reflecting targeted innervation by corticocortical and thalamocortical afferents which initiate and guide movement dynamics. In contrast, condition-specific response dynamics are densely, spatially intermingled and organized along a network of spatially interwoven, putative synaptic connections.

3-B-16 Proactive inhibitory control alters the planned movement for interceptive reaches

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Successful behaviour often requires a combination of appropriately timed initiation and skilled execution. Poorly timed starts can render even expert movements ineffective. Indeed, in a study with 537 school children, adolescents, and adults (ages 5-42 years) manually intercepting moving targets of various speeds, we found performance depended not only on accurately integrating sensory estimates into the movement plan, but also on successfully inhibiting conditioned responses following inter-trial changes in timing demands. The tendency to move early (>200ms prior to the mean initiation time) varied with age, with younger children jumping the gun more frequently (5-10 years: 15%[± 2.9]; 11-15 years: 8.3%[± 2.5]; Adults: 5%[± 2.7]). Interestingly, both the ability to make accurate movements and to inhibit early starts independently explained academic attainment in Maths, suggesting this simple task captures fundamental processes that are broadly relevant to other domains of performance. While we observed false-starts in our initial task, they were not elicited experimentally and it was not designed to measure inhibitory control. To better understand inhibition in the context of interception, we developed a novel, web-based, interceptive stop-signal task, capable of estimating proactive and reactive measures of inhibition with short movements of a mouse or track pad. The design featured certain "go" trials, wherein participants always intercepted the target, and an uncertain condition wherein on 30% of trials, a stop signal appeared at a delay staircased relative to initiation. In our online study, participants (n=24, ages 22-69 [median = 38]) showed behaviour that was consistent with traditional stop-signal tasks (Verbruggen et al., 2019). Specifically, our sample demonstrated reactive inhibition by responding to stop cues 195(±23)ms prior to initiating movement, and proactive inhibition by delaying movement initiation by 141(±32)ms on uncertain relative to certain trials. Moreover, proactive inhibition was not limited to a delay in initiation. Participants exhibited an instant shift towards briefer movements, additionally developing a compensatory strategy over ~50 trials that changed its spatial goal on uncertain trials. These movements appeared to be aimed at the back half of the moving target, rather than the front. These data indicate that proactive control involves the development and selective use of a qualitatively different movement plan in response to the possibility that a movement may need to be inhibited at short notice. Similar compensatory shifts in spatial goals of movement plans have been observed in "go before you know" reaching tasks (Haith et al., 2015) and visuomotor adaptation (Taylor, Krakauer & Ivry, 2014). Our results suggest inhibitory control makes an important contribution to performance in interception tasks, and that under the uncertainty of whether to move there may be adjustments to movement planning.

3-B-17 Proprioceptive accuracy responses to trial-by-trial changes in speed, direction, and length of movement

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Proprioception is essential to the proper execution of movement. Neurologic disease or injury can significantly disrupt proprioception and recently we have shown that proprioceptive deficits occur in 50-60% of individuals after stroke. Beyond this fact, our understanding of how proprioception is impacted after stroke is limited. First, this is because clinical assessment tools can be subjective and unable to identify sensorimotor impairments. Second, newer, more objective, robotic tools have only recently been developed and thus have just begun to assess fundamental aspects of proprioception after stroke. Here, we aimed to build upon these previous tools to design a robotic task capable of assessing a broad range of proprioceptive function through examination of variety of movement speeds, lengths, and directions. The following work is a pilot study to determine broad characteristics of proprioception in neurologically intact controls to be implemented for comparative assessment in individuals with stroke. Ten control participants performed a bi-manual proprioceptive matching task where the robot passively moved one of the participants arms. Participants were instructed to mirror-match the speed, direction, and length of the movement with their opposite arm. Seven movement speeds (0.1-0.4 m/s) and five movement lengths (7.5-17.5 cm) were tested. Participants completed 10 trials per combination of speed and length, for a total of 350 movements. We quantified static and dynamic components of proprioception using the following metrics: End Point Error (EPE), Initial Direction Error (IDE), and Peak Speed Ratio (PSR). EPE was calculated as the difference in distance from the position of the active arm to the passive arm at the end of the movement. IDE was calculated as the angular difference between the position of the active and passive arm at peak hand speed. PSR was calculated as the peak speed of the active arm divided by peak speed of the passive arm. We found that the speed and length of the individual robotic movement profile influenced the degree of subject-produced proprioceptive accuracy. As expected, EPE increased as movement speed and length increased. IDE was influenced more by speed than by length of the movement. IDE errors linearly increased as a function of increased movement speed; however, IDE was consistent across most movement lengths and only decreased at the largest movement lengths. Further, we found that participants' ability to match the speed of movement was characterized by over-estimation at the lowest speed (0.1 m/s) and under-estimation at the highest speed (0.4 m/s), with a linear decrease in PSR as speed increased. Our results suggest that errors in proprioceptive estimates can be influenced by speed and length of movement, and that typical values for these estimates may exhibit bias depending on the characteristics of the "ideal" movement.

3-B-18 Does failure induce strategy changes in a pressure application task?

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A robust finding in reward-based motor learning is that humans increase variability following a failure. It is unclear how participants modulate this variability. One possibility is that participants might directly change the parameter that they are rewarded on, which we term 'task changes.' Another possibility is that participants might change their movement strategy; which we refer to as 'strategy change'. In this study, we assess whether failure influences strategy changes or task changes, as well as how their behavior evolves over time. We addressed these questions in a pressure application task. Participants were asked to performing a rubbing motion on a Wacom tablet. We instructed them to find the pressure that obtained a reward while rubbing visual targets. On subsequent days, participants perform 5 sessions that each contained 300 trials. The target pressure is chosen randomly from the full range of Wacom pressure detection. Pressure errors are defined as the absolute difference between the actual pressure and applied pressure. Movements were rewarded when the pressure error was either less than a fixed criterion of 5% of the Wacom pressure range or the 30th percentile of the past ten errors. A new target pressure was generated when 7 out of 10 movements hit the fixed criterion. This was communicated to the participant by a color change of the target. Strategy changes were defined as significant differences in the distribution of movement directions on trial and the distribution of movement directions on the subsequent trial. This was tested with a Kuiper test, which is a circular equivalent of the Kolmogorov Smirnov test with a significance level of 0.01. Task changes were defined as changes in the mean pressure during the rubbing movement. Early preliminary data (N = 4) suggest that failure induced task changes but did not induce strategy changes. We did find reduced strategy changes over time following failure and reward. In contrast, task changes following failure increased over time, whereas task changes that followed reward did not. Taken together, our results suggest that failure differently affects task changes and strategy changes.

3-B-20 Temporal modulation of somatosensory processing during reaching

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Somatosensory sensitivity is reduced on a limb that is moving compared to when the same limb is in complete rest. This sensitivity reduction is typically reflected in the suppressed perception of tactile inputs presented on that limb. Though a highly robust phenomenon, the origins and the function of tactile suppression remain a matter of debate. We hypothesize that this suppression stems from an interplay between (a) a sensorimotor prediction that estimates future sensory states of the moving limb and (b) the need to process the associated sensory feedback: when the prediction is more reliable, the inherently uncertain sensory feedback is down-weighted, and thus sensory input from that limb is suppressed. If this is the case, then suppression should be temporally modulated throughout a movement similar to how sensory feedback gains are tuned. According to the optimal feedback control framework, positional and velocity feedback gains are greater around halfway the movement and substantially decrease as the hand approaches the target. Thus, if suppression depends on the modulation of feedback processing, then suppression should be reduced, or even vanish when feedback gains increase (e.g., around the onset of the movement's deceleration phase). To examine this, human participants reached toward their other hand in the absence of vision. To measure somatosensory processing, a probing tactile stimulus of variable intensities was presented on the moving index finger at different moments during the movement. Participants were asked to respond whether they detected this stimulus or not. The suppression of this probing stimulus was strong in the early reach and interestingly vanished around the time of maximal speed, before substantially growing again as the hand approached the target. Similar temporal tuning was evident also when performing movements of larger amplitudes that shifted the absolute time of maximal speed later in time. In addition, the release from suppression on the moving hand was temporally coupled with enhanced somatosensory processing on the static, target hand. These results reveal a dynamic tuning of somatosensory processing during reach and suggest that the phenomenon of tactile suppression is dependent on the modulation of associated sensory feedback, suggesting an interplay between predictive and feedback signals.

3-B-21 Neocortical control and integration of movement order and timing during sequence planning and execution

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Both neurophysiological and neuroimaging data have shown that neural and haemodynamic activity patterns in primary motor, premotor, and parietal cortices hold information about the identity of trained motor sequences during production. Specifically, high-level sequence features (finger order and timing) has been found in bilateral premotor and parietal regions, whereas the integration of features has been associated with activity patterns in contralateral M1. However, the evolution of sequence-related activity patterns across the planning and execution phases remains unknown. In the current preregistered study (https://osf.io/g64hv) we recorded fMRI whilst participants produced trained finger sequences from memory on a force transducer keyboard after a short preparation period. To tease out BOLD activity patterns related to planning from execution in rapid behavioural designs, No-Go trials were introduced to acquire planning-related activity from the preparation period, whilst sampling execution data from the production period in separate trials. Two finger press orders were generated randomly for each participant and paired with two inter-press-interval sequences orders (1200ms, 810ms, 350ms, 650ms; and 350ms, 1200ms, 650ms, 810ms). Within each set, the first finger press was matched across trained sequences to avoid the first press driving the decoding of sequence identity during planning. Our pilot dataset revealed that transferable patterns related to independent finger order and timing of the sequences dominated the planning period in contralateral PMd and M1, but transitioned towards unique integrated patterns during execution within the same brain regions, particularly in contralateral M1. This preliminary data suggests flexible encoding of high and low-level sequence features within cortical premotor and motor regions that is driven by trial phase and little evidence for a fixed mapping of brain regions to high and low-level features, as suggested previously. The results from this study will help to unveil the dynamical evolution of movement order and timing signals across brain regions for skilled sequence production.

C – Posture and Gait

3-C-22 Association of motor cortical representation and hip muscle activation during gait initiation in older adults

Presenting Author: Jo Armour Smith

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Background Gait initiation is a dynamic task that requires anticipatory postural adjustments (APAs) in the lower limb and trunk musculature to shift the center of pressure (COP) laterally and posteriorly while maintaining postural stability. In older adults, APAs in the lower limbs during gait initiation are later in onset and lower in amplitude than in young adults. It is unclear how APAs in the trunk/hip musculature are affected by aging. The neural correlates of alterations in APAs with aging are also unknown. The purpose of this study was to compare APAs in the trunk/hip musculature during rapid gait initiation in healthy older and younger adults and to determine if APA characteristics are associated with representation of trunk/hip muscles in motor cortex. Methods Thirteen young adults (YA, average age 25.8±2.1 years, 8 females) and nine active, community dwelling older adults (OA, average age 72.8±8.3 years, 8 females) participated. They were instrumented with EMG electrodes on gluteus medius (GMED), lumbar erector spinae (LES) and external oblique (EO) on their dominant side. Participants performed 6 trials of initiating gait with the dominant limb as quickly as possible in response to an auditory cue. Individual muscle latency relative to the onset of COP displacement, and peak and root mean square (RMS) EMG amplitude during the APA were calculated. Reaction time (cue to start of the APA) and movement time (start of APA to toe-off of the stance limb) were also calculated. Cortical representations of GMED, LES and EO were mapped using single-pulse transcranial magnetic stimulation (TMS). Volume of each muscle representation was calculated from motor evoked potentials elicited during sub-maximal contractions. Mixed model ANOVA were used to test for main effect of muscle, group and group by muscle interaction, with t-tests for post-hoc comparisons. The correlation between representational volume and EMG characteristics for each muscle was calculated. Results Reaction time and movement time did not differ between the OA and YA groups. There was also no significant group difference in latency for any muscle. RMS amplitude and peak amplitude during the APA were significantly lower in GMED in OA ($p = 0.005$ and 0.025 respectively). There was a significant correlation between volume of GMED cortical representation and RMS amplitude of GMED activation during the APA ($r = 0.475$, $p = 0.030$). Conclusion The temporal characteristics of rapid gait initiation are maintained in active older adults. However, the amplitude of gluteus medius activation is reduced and this behavioral change is accompanied by reduction in muscle representation volume in motor cortex.

3-C-23 Greater cortical beta-power evoked during reactive balance recovery may indicate reduced automaticity of balance correcting muscle activity

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In response to a destabilizing event, balance correcting behavior consists of an initial, automatic, brainstem-mediated motor response (Horak 2011) followed by longer latency muscle activity that may also be cortically-mediated (Maki 2007). The brainstem-mediated muscle activity is driven by sensory information encoding balance error, i.e. deviations from upright standing, and can be fit to a pseudolinear combination of delayed center of mass (CoM) kinematics via a sensorimotor response model (SRM) (Welch and Ting 2008). Recent findings show that sensorimotor cortical beta-power (13-30Hz oscillatory brain activity) evoked during reactive balance recovery may provide a neurophysiologic biomarker of cortical engagement, as it increased with balance task difficulty within individuals and is larger in individuals with lower balance ability (Ghosn 2020). Moreover, the evoked muscle activity and beta-power share a similar time course (Ghosn 2020), leading to the hypothesis that perturbation-evoked beta-power and muscle activity are driven by similar sensory information. Here we predicted that both beta-power and muscle activity evoked during reactive balance responses would be reconstructed using the SRM. 18 healthy young adults (Age: 26±5, 10F) underwent a series of backwards support surface perturbations delivered at unpredictable timing and magnitude while body kinematics, electroencephalography, and electromyography were recorded. Beta-power, measured at a central midline electrode (Cz), and muscle activity of the medial gastrocnemius (MG) were reconstructed as a combination of weighted and delayed CoM kinematics (acceleration, velocity, and displacement relative to the base of support). The SRM reconstructions support our hypothesis that sensorimotor beta-power follows the same sensory inputs that drive automatic balance-correcting muscle activation, particularly in conditions evoking increased beta-power. Across both perturbation magnitudes and individuals, SRM reconstruction accuracy of beta-power ranged from $R2=0.00$ to 0.84, with a positive association between quality of fit and the magnitude of perturbation-evoked beta-power ($\Delta\beta$) ($R2=0.59$, $p<0.001$). Conversely, the MG SRM reconstruction accuracy (range: $R2=0.06$-0.94) was negatively associated with $\Delta\beta$ ($R2=0.17$, $p=0.002$). These results suggest that muscle activity can be attributed to brainstem-mediated sensory feedback when cortical activity is low, but deviates from the SRM model of brainstem-mediated sensory feedback control when cortical activity during balance control is high. As such, the amount of sensorimotor beta-power may index changes in the automaticity of balance control and help to dissociate brainstem- and cortically-mediated contributions to balance correcting muscle activity in healthy and possibly balance-impaired individuals.

3-C-24 Visual-motor control during dynamic single-limb balance tasks in female athletes after anterior cruciate ligament reconstruction

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Athletes involved in a primary anterior cruciate ligament injury (ACL) and ACL reconstruction (ACLR) showed to be highly predisposed in experiencing a second noncontact ACL impairment after returning to sport. Recently it is inferred that the loss of sensory afferent input from the joint to central nervous system, caused by LCA injury and further aggravated by the reconstruction process, may implicate a possible visual-motor control dysfunction with an enhanced demand for visual feedback to plan the movement and maintain an efficient neuromuscular control. The development of visual-disruption technology, such as stroboscopic glasses, that obstructs vision without completely obscuring it, has enable to the assessment of visual-motor control during dynamic movements more closely mimicking athletic maneuvers in sport. This study explores the effect of stroboscopic visual feedback disruption (SVFD) on postural control during single-limb dynamic balance tasks in female athletes with ACLR. Fourteen female athletes with ACLR and 14 matched healthy control performed three dynamic balance tasks: Drop Landing, Forward Jump and 90° Jump Cut, under normal and SVFD conditions. Balance tasks were performed on the Kistler force platform. The Senaptec Strobe glasses imposed the SVFD. For Drop Landing task, peak of vertical ground reaction force (GRF) and loading rate were measured; for Forward Jump task, dynamic postural stability index (DPSI) and centre of pressure (COP) were calculated; for 90° Jump Cut, vertical and lateral peaks of GRF and vertical/lateral ratio (Lat/Ver Max) were measured. Peak Vertical of GRF were expressed relative to subject's body weight. Preliminary data show that ACLR may induce alterations on postural control in all the three tasks investigated. SVFD can influence postural control during dynamic balance tasks in athletes with ACLR and healthy control. Finally, under the SVFD condition, postural control during the drop landing was found to be reduced more in athletes with ACLR suggesting possible sensorimotor adaptations occurring after ACL reconstruction.

3-C-25 Body dynamics influence decision-making

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There is evidence that the cost of action can influence decision-making (e.g. Klein-Flugge, Kennerley, Saraiva, Penny, & Bestmann, 2015). However, most studies in this field examine sequential decision-making, where the cost or reward of choice options are known before initiating any action. This contrasts with many daily tasks where we make decisions while already being in motion. For instance, imagine a soccer player dribbling the ball while deciding to bypass an opponent to the left or right side. In such situations, the cost of choices changes dynamically, and decisions and corresponding actions must be integrated with the concurrent body dynamics. More specifically, with concurrent walking, there seems to be a cost difference for making a directional change based on the current foot in contact with the ground. A left foot at the ground enables a more stable lateral step toward the right side in contrast to a more unstable cross-over step towards the left side and vice versa (Moraes, Allard, & Patla, 2007). However, whether and when these body dynamics and associated costs of concurrent action influence choices, especially for whole-body movements like walking remains an open question. Therefore, we implemented a walking paradigm, in which participants walked under time pressure towards a central obstacle and then bypassed it to collect rewards displayed on a left or right positioned target (Y-fork). Before walking towards either target, participants had to step with one foot into a designated zone in front of the obstacle. The step into the zone dictated the stepping strategy to make a directional change towards either target (lateral step or cross-over step). The stepping behavior towards the zone was manipulated by prescribing the foot position at the start and thereby the first step before starting a trial (left or right foot in front). The reward options were displayed one to three steps before reaching the designated zone. Results showed that the foot position at the start influenced participant's choices. Participants were biased to walk towards the side which enabled a lateral step given their habitual step length even at the expense of receiving less reward. However, the earlier the rewards were displayed, the more often participants adapted their stepping strategy before reaching the obstacle. Participants more frequently changed their step length and thereby altered the presumed step into the zone, or they adapted their foot location and orientation for the step into the zone towards the direction of their decision. Together, we conclude that body dynamics and associated costs of concurrent action are part of decision-making. This seems to be especially true when the time for decision-making is short. With enough time participants can adapt their body dynamics presumably to weaken its effect on decision-making and receive more rewards for less cost.

3-C-26 Spatiotemporal gait asymmetry is not a driving factor of greater metabolic cost in models with unilateral muscle weakness

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Introduction Many different neuromuscular impairments develop in people post-stroke, such as muscle weakness, spasticity, and hyperactivity, and these impairments typically affect one side of the body more than the other. As a result of these impairments, people post-stroke walk slower than controls, display spatiotemporal asymmetries, and walk with a greater metabolic cost of transport (COT) [1,2]. Understanding how neuromuscular impairments affect gait is important for developing neurorehabilitation interventions to improve mobility. Musculoskeletal modeling and predictive simulation provide an opportunity to simulate isolated neuromuscular impairments, and thereby develop predictions for how gait performance may change in response to impairment. Here, we quantified the spatiotemporal asymmetries and changes in metabolic COT that emerge from predictive simulations of walking when muscle strength is unilaterally reduced as would be observed post-stroke. Methods We used a 2-D musculoskeletal model with 11 degrees-of-freedom and actuated by 18 muscles (base; adapted from [3]) within OpenSim and Moco to generate predictive simulations [4]. We modified the base model by uniformly reducing the peak isometric muscle forces in all muscles on the left limb by 20, 40 and 60%. We generated predictive simulations that minimized the sum of integrated muscle excitations cubed over a stride for five different speeds (0.25, 0.50, 0.75, 1.00 and 1.25 m/s) for all muscle strength conditions. We calculated asymmetry indices for step length, step time, and stance time, and computed the metabolic COT for each solution based on the Umberger 2010 probe in

OpenSim. Results and Discussion The optimal gait for the base model at each speed was a symmetrical walking pattern. The asymmetrical models resulted in asymmetrical spatiotemporal gait patterns, with the magnitude and direction of each type of asymmetry varying with the level of weakness and the gait speed. These results indicate that the expected level of optimal spatiotemporal asymmetry depends on both the strength capacity of the individual as well as the walking speed. Within each speed, there were subtle differences in metabolic COTs (<10%) across the asymmetrical strength models. However, the predicted optimal speed based on COT was 1.25 m/s for the base and 20% reduced strength models, but 1.00 m/s for the 40% and 60% models. Our results suggest that it is plausible that people post-stroke would adopt slower, asymmetric gaits if they optimized their gait strategy for reducing muscle effort. Our metabolic COT results indicate that step length and step time asymmetries likely do not play a critical role in driving a greater metabolic COT for people post-stroke. References [1] Finley JM & Bastian AJ, Neurorehab Neural Re. 31, 2. 2017. [2] Sanchez N & Finley JM, Neurorehab Neural Re. 32, 8. 2018 [3] Rajagopal, A et al., IEEE Trans. Biomed. Eng. 63, 10. 2016. [4] Dembia, CL et al., PLoS Comput. Biol.

3-C-27 Nonhuman primate postural responses to platform perturbations resemble those of humans

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Nonhuman primates such as rhesus monkeys provide a robust animal model of the human brain for research and device development. One such device currently being tested in monkeys alongside human clinical trials is the vestibular prosthesis, which stimulates vestibular afferents to restore function in the case of bilateral vestibular loss (BVL). It has been demonstrated that vestibular stimulation with the prosthesis led to improvements in balance, gait, and quality of life. In order to further quantify these improvements and examine the vestibular system's contribution to postural control systems in the brain, study in a monkey model is required. Because monkeys are habitually quadrupedal, it is essential to determine whether monkeys exhibit similar postural control strategies to bipedal humans in response to support surface perturbations. Humans generally exhibit two main strategies: at low frequencies (<0.3 Hz), humans tend to fix the body relative to the platform, riding along with its motion (platform-fixed), while at higher frequencies they maintain a steady head position while compensating with the lower body (head-fixed). Patients with bilateral vestibular loss tend to exhibit greater sway overall and particularly at lower frequencies. Here, we tested whether postural strategies exhibited in standing humans during support surface perturbations persisted in a nonhuman primate model, the rhesus macaque. Three monkeys, two normal and one with BVL, were habituated to a behavioral chamber mounted on a hexapod motion platform and trained to maintain a perching position commonly seen in nature. The platform delivered rotational perturbations in roll and yaw, and translational perturbations in the mediolateral direction. Perturbations included six frequencies of sinusoid rotations (0.25-10 Hz) as well as those constructed from a pseudorandom ternary sequence (PRTS), with fixed peak velocities of 5 and 10 degrees/s or cm/s. The animal's motion was monitored using markerless video tracking (DeepLabCut), a force plate, and an IMU mounted on the animal's head. As observed in humans, normal animals demonstrated a platform-fixed postural strategy at low frequencies and a head-fixed postural strategy at high frequencies. However, humans undergo this transition at 0.3 Hz, monkeys exhibited a transition around 1 Hz; likely due to limb length. These results were consistent across stimulus amplitudes, between sinusoidal and PRTS conditions, and between the two normal monkeys. Also mirroring BVL patient responses, the BVL animal exhibited greater sway across frequencies and in particular at lower frequencies. Together, these results suggest that monkeys can be used as a model of human posture to be used in testing of the vestibular prosthesis as well as studying vestibular contributions to posture-related circuits in the brain.

3-C-28 The foot trajectory in the frontal plane when crossing over an obstacle with a non-horizontal top edge

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When we cross an obstacle during walking, the foot trajectory is controlled to avoid the obstacle. In most previous studies, motor control during obstacle crossing has been discussed based on the vertical foot clearance, and the mediolateral foot control has been paid little attention. This may be related to the fact that the previous studies used a flat obstacle where the mediolateral shift of the foot does not affect the foot clearance. In this study, we used an obstacle with a non-horizontal top edge (i.e., trapezoidal-shaped in the frontal plane) to hypothesize that the mediolateral foot trajectory was also controlled to ensure foot clearance. Sixteen healthy young volunteers were asked to step over an obstacle during walking along a walkway. The shape of the obstacle was rectangular or trapezoidal in the frontal plane. The obstacle's top edge was horizontal (rectangle in the frontal plane) or tilted (trapezoid in the frontal plane). The height of the horizontal obstacle was 15 cm. The height of the left and right sides of the tilted obstacle was, for example, 15 cm and 10 cm (15-10). Similarly, we tested 15-12, 15-14, 15-16, 15-18, 15-20, 10-15, 12-15, 14-15, 16-15, 18-15, and 20-15 obstacles in addition to the horizontal (i.e., 15-15) obstacle. Ten trials were repeated for each obstacle. The right limb was always the lead limb. The foot trajectory was evaluated using the mediolateral and vertical displacements of the marker placed on the big toe, which were defined as the distances between the marker location at the timing of the takeoff and that at the instance when the marker crossed the plane that includes the obstacle. The positive value for the mediolateral foot displacement denotes rightward, and the positive value for the vertical foot displacement denotes upward. The vertical foot clearance, defined as the vertical distance from the big toe marker and the obstacle, was also calculated. These outcomes were calculated for the lead (right) limb and the trail (left) limb and compared between obstacle conditions using repeated-measures ANOVA. A significant main effect of obstacle was observed on the mediolateral placement of the lead limb ($F(6,90) = 24.09$, $p < .001$, $\eta2 = 0.62$). Comparing with the horizontal obstacle (15-15) condition (mediolateral displacement of the lead limb: 5.27 ± 23.10 mm), the lead limb was moved leftward (-21.93 ± 49.51 mm) when the subjects crossed the 15-10 obstacle, whereas it was moved rightward (45.27 ± 42.43 mm) when the obstacle was 15-20. Note that the obstacle's height for the lead limb was the same (15 cm). In short, the foot was moved leftward for the right-up-left-down trapezoidal obstacle, and vice versa. Similarly, it was confirmed that the trailing limb was also moved on the lower side of the obstacle. These results support the hypothesis that the mediolateral position of the foot was controlled to avoid the obstacle.

3-C-29 Motor module generalizability between unperturbed and perturbed walking after stroke

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Introduction: Impairments in muscle coordination often occur after stroke and lead to balance and mobility deficits. These deficits may result, in part, from an inability to properly coordinate muscles due to reorganization of muscle coordination patterns (i.e., motor modules) compared to unimpaired individuals. Previous research has suggested that the number of motor modules observed during reactive balance that generalize to walking may be an important factor for well-coordinated walking, as relationships between generalization and walking performance have been previously demonstrated. However, we still do not know if motor modules observed during normal walking in post-stroke individuals generalize to responses from unexpected perturbations while walking. By determining the extent of generalization, we may be able to gain insight to potential differences in the neural control of unperturbed walking and balance corrective responses in these individuals. Therefore, we tested the hypothesis that corrective responses would be composed of modules shared with unperturbed walking and others that were unique to balance recovery. Methods: Sixteen participants post-stroke walked on a split-belt treadmill at their self-selected walking speed. During the trials, random accelerations to the treadmill belts on either the paretic or non-paretic side were administered at foot-strike. Kinematic and kinetic data were recorded using full body motion capture and treadmill force-plates, along with electromyography (EMG) from seven muscles on each leg. We used Non-Negative Matrix Factorization (NNMF) to compute the motor modules, where the number of modules was chosen such that the 95% confidence interval of the variance accounted for (VAF) in the original EMG had a lower bound exceeding 90%. Modules were identified as shared using Pearson correlation coefficients. Results: The average number of motor modules recruited was 3 (SD: 0.65) for non-paretic and 3 (SD: 0.6) for paretic baseline, perturbation, and recovery strides. For strides segmented from non-paretic foot-strikes, baseline modules generalized to 44% (SD: 35%) of perturbation modules and 79% (SD: 30%) of first recovery modules. For strides segmented from paretic foot-strikes, baseline modules generalized to 41% (SD: 39%) of perturbation modules and 84% (SD: 24%) of first recovery modules. Discussion: Our hypothesis that corrective responses would be composed of modules shared with unperturbed walking and that others would be unique to balance recovery was supported. Modules extracted during recovery strides tended to be composed of modules seen during unperturbed walking, while those extracted during perturbation strides tended to be more unique to that event. Considering that a subset of modules extracted were not observed during unperturbed walking, the work presented here demonstrates that recovery from perturbation is not simply mediated by scaling patterns that are used for unperturbed walking.

3-C-30 Minimization of mechanical work reveals scaling of optimal gait asymmetry with speed ratio during split-belt walking

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Several empirical and theoretical studies of steady-state and adaptive walking have provided evidence that many features of walking resemble what would be expected if humans optimized energetic cost. For example, when walking on a split-belt treadmill, where the belts run at different speeds, participants gradually learn to step further forward and spend less time on the faster belt. This is consistent with what is predicted theoretically if individuals adapt to acquire mechanical work from the treadmill to reduce energetic cost. However, it remains to be seen if these predictions from inverted pendulum models of gait extend to more human-like, multi-joint models of gait. It is difficult to determine if adaptation is driven by energy optimization without computational models, as it is not possible to have participants explore all feasible strategies throughout a high dimensional variable space against the cost landscape. To address this gap, we developed a multi-segment, mechanical model of walking, and used it to predict step length asymmetry (SLA) and step time asymmetry (STA) of energetically optimal gait patters across a range of belt speed ratios. SLA is defined as the difference between the fast and slow step length normalized by the stride length, whereas STA is the time from the slow foot strike to next foot strike subtracted from that of the fast foot strike to another. The average speed of the belts was kept at 1.0 m/s in all conditions, while the speed ratio varied over 1.5, 2.0, 2.5, and 3.0. A genetic algorithm was used to find the parameters of a set of joint-level control signals through dynamical movement primitives that minimized the positive mechanical work performed by legs. In line with the previous empirical observations of positive asymmetries in steady-state walking on a split-belt treadmill, our simulations found that minimization of positive mechanical work was always associated with positive asymmetry features, that is, longer steps by the faster legs were taken, and less time it took from the slow foot strike to the fast foot strike that it did otherwise. We also found a significant linear relationship between the optimal SLA and belt speed ratio ($R2 = 0.97$, $p = 0.001$**). Moreover, the positive mechanical work rate increased monotonically with the belt speed ratio ($R2 = 0.87$, $p = 0.01$*). The net work rate performed by the legs across the four simulated belt speed ratios were -9.82 J, -19.44 J, -25.36 J and -27.82 J, respectively. Thus, in line with empirical studies, our simulations found that the biped takes advantage of the positive work provided by the split-belt treadmill to reduce the positive work required by the legs.

3-C-31 Lower cognitive set shifting ability is associated with stiffer balance recovery behavior and larger perturbation-evoked cortical responses

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Inability to flexibly modify behavior to changes in task rules or contexts (i.e. cognitive set shifting) is associated with clinical balance impairments (Tangen 2014), fall history (Mckay 2018), and fall risk (Herman 2010), but the mechanisms underlying these associations are unclear. Our objective was to identify associations between cognitive set shifting and aspects of reactive balance recovery in older adults, including biomechanics, muscle activity, and cortical activity. A sudden balance perturbation evokes early (100ms) brainstem-mediated muscle activation, followed by later (>150ms) cortically-mediated muscle activation. Balance perturbations also evoke a cortical response (N1, 150ms) in the supplementary motor area that reflects cognitive processes such as attention (Quant 2004, Little 2015) and perceived threat (Adkin 2008) and is enhanced in young adults with lower balance ability (Payne 2020) and may provide insight into overlapping mechanisms between balance and cognitive impairments. In 19 older adults (age 71±6, 6F), we tested associations between clinical tests measuring cognitive set shifting ability (trail-making test) and balance ability (miniBEST). We then assessed reactions to 48 unpredictable forward and backward support-surface perturbations of three magnitudes. The stiffness of the biomechanical response was characterized as the maximum excursion of the center of mass (CoM) with respect to the base of support. We characterized directional specificity of perturbation-evoked tibialis anterior and soleus muscle activation (Lang 2019). We also assessed peak amplitudes of the cortical N1 (Cz-EEG) response to perturbations. Associations to cognitive set shifting were tested using Spearman rank order correlations. Although there was no association between cognitive set shifting ability and clinical balance ability (p=0.24), individuals with lower set shifting ability had smaller CoM excursions (p<0.006 in all perturbation magnitudes and directions). Individuals with lower cognitive set shifting ability had less directional specificity in the later (200-300ms) phase of balance recovery in both tibialis anterior (p<0.032 in all perturbation magnitudes) and soleus muscle activity (all p<0.014), but not during the earlier (100-200ms) automatic phase (all p>0.05). Individuals with lower cognitive set shifting ability also had larger evoked cortical N1 responses (p<0.016 in all perturbation magnitudes and directions). Our results suggest that individuals with lower cognitive flexibility ability may have stiffer behavior due to inability to flexibly modify cortically-mediated phases of muscle activity, resulting in muscle coactivation that is not specific to the direction the body is falling. The increased cortical N1 responses may provide a window into brain processes linking cognitive set shifting deficits to motor set shifting deficits that may mediate associations between cognitive and balance impairments.

3-C-32 Preliminary Investigation of Cortical Activity During Stabilized and Destabilized Gait
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Background Aging and neurological dysfunction can impair walking stability, leading to increased risk of falls. Despite extensive research, neural mechanisms underlying control of gait stability are still poorly understood. Event related potentials have been used previously as a measure of cortical activity during normal walking, in stabilized environments, and during perturbations while standing. The aim of this study is to determine the cortical activity associated with walking under stabilized or perturbed (destabilized) conditions. Methods In this preliminary step, three participants (age=27±1.4, height=173±2 cm, weight=74.3±3 kg) performed walking trials on a motorized treadmill (Motek Medical B.V) for five minutes each. The experimental conditions systematically altered the walking stability environment; constant medial-lateral perturbation (Destabilized Walk), normal walking, walking while 20% of the body weight was supported via a harness (Stabilized Walk). Kinematic data were collected from four reflective markers on the pelvis (Vicon Motion Systems Ltd). To quantify gait stability, the largest Lyapunov exponent of pelvis-approximated center of mass kinematics was calculated. Cortical activity was measured using a 64 channel Mobile EEG system (BrainProducts GmbH). Results There was a 15% decrease in center of mass stability for the Destabilized Walk and a 10% increase in center of mass stability for the Stabilized Walk compared to normal walking. The average event-related potential across subjects at premotor cortex (FC electrode of dominant side) revealed a decrease in the amplitude during midstance of the dominant foot during the Destabilized Walk condition. Conclusion These preliminary findings are consistent with earlier studies showing that the magnitude of the negative N1 peak is related to decreased stability (as a result of more intensive cognitive activity requirement) during standing after unanticipated perturbations. If these preliminary results are confirmed, information from this study may provide the basis for innovative and more effective intervention strategies to re-establish a stable gait pattern in older adults or individuals with neurological dysfunction.

D – Integrative Control of Movement

3-D-34 Proprioceptive motor style and different plane couplings of upper and lower body movements during locomotion
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The intra-individual variations during ideal-condition locomotion may reflect essential information about individuals' self-inflicted errors in the forces generated by the muscles, sensory misperceptions, and generally sensory-motor control. To what extent this variability is idiosyncratic and/or detrimental? In this work, we investigated the dynamic characteristics of movement and the associations between planes of motion (frontal, sagittal, transversal) during locomotion. New technologies such as Cartesian Optoelectronic Dynamic Anthropometer (CODA) motion analysis can contribute significantly to the capture of such dynamic changes. Eighteen healthy individuals (females:8, Age=32±11.9,range:20-58 years) with no history of any neurological orthopedic impairment, were measured while performing five different tasks: standing, walking (comfortable, at 4 km/h and race walking), and running at maximum velocity. The position of 24 markers attached on the head, shoulders, sternum, low back, right and left tibias, right and left ankles, and feet were being captured in real-time. We calculated the frontal, sagittal and transversal skeletal configurations at the moment of the heel-strikes of both legs and the sensors were grouped by body parts (Head, Trunk, Leg, Foot) and the sagittal body-parts inclinations were measured in every exercise. We also described the smoothness of body-part movements expressed by the Jerk index. Thus everybody part in every exercise is characterized by a 3-dimensional jerk value. We investigated any associations between frontal, sagittal and transversal jerk values during all exercises. During walking exercises, upper body (Head, Trunk) jerk values were significantly associated (almost proportionally) only between frontal and sagittal planes ($R>0.95$, $p<0.0001$) while lower body (Leg, Foot) jerk values were significantly associated (also almost proportionally) only between sagittal and transversal plane ($R>0.89$, $p<0.0001$). Frontal-transversal planes were not associated. During running, while upper body (Head, Trunk) jerk values still presented the same frontal-sagittal proportionality ($R>0.95$, $p<0.0001$), lower body (Leg, Foot) present high associations in all plane combinations ($R>0.58$, $p<0.01$). Our results revealed the different levels of association between planes for every body part supporting the conclusions of previous studies which suggest that postural and motor control was sub-served by different neuronal networks in the frontal, sagittal, and transversal planes. We currently perform further dynamic analyses assessing the variability, regularity, and movement optimization strategies. The combination of these dynamic markers seems to play a major role in defining the perceptive motor style of each individual. Longitudinal follow-up of the perceptive-motor style and the spatial characteristics of body parts' movements may reveal the onset of a pathological process and can help in following its rehabilitation and recovery.

3-D-35 Reaching trajectories reflect initial decision certainty when integrating multiple sources of information

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Manual reaching tasks have been used as a method to quantitatively map decision computations to motor parameters, but until recently, have largely focused on one-dimensional decisions (e.g., random dot motion direction). Here, we investigated the extent that movement reflects decision making processes via arm reaching movements when two stimulus dimensions are simultaneously discriminated. Four naive subjects performed the task using a robotic arm manipulandum. Starting at a central location, subjects viewed a briefly presented small circular display. Within the display were 100 static dots and subjects judged whether most of the dots were on the top or bottom half of the circle. In addition, subjects judged the color of the dots (along an isoluminant pink-green axis). Importantly, one stimulus dimension was always easier to discriminate than the other. The easy (high-certainty) values were taken from the extremes of the stimulus dimensions (e.g., 20:80 and 80:20 dot ratios, or 20% and 80% along the pink-green axis). The difficult (low-certainty) values were taken near the dimension midpoints (e.g., 40:60 and 60:40 dot ratios or 40% and 60% along the pink-green axis). The dot distribution was mapped to top vs. bottom targets and the color mapped to left vs. right targets. Based on the information in the display subjects had to select one of four targets, each representing the four possible outcomes of the presented sensory information. Target locations were equidistant (14.1 cm) and diagonal to the start location (45°, 135°, 225° and 315°). The task additionally included a forced reaction time component: during each trial, four tones played each separated by 500 ms, and subjects were required to move from the start location synchronously with the fourth tone. The display was presented 450 ms before the fourth tone allowing an examination of the influence of movement preparation time on the decision process. Based on previous studies that examined decisions based on one-dimensional information, we hypothesized that initial heading angles (IHAs; intended movement direction before corrective feedback processes) would reflect higher weighting of high-certainty information and be biased towards the corresponding axis. For example, movements would be biased along the horizontal axis in trials where the color was the high-certainty dimension presented. Our preliminary data show that on most trials (83% +/- 7.3), participants tended to initiate their movements towards the correct high-certainty value (e.g., leftward/rightward for pink/green and upward/downward for the corresponding dot distributions), suggesting a preferential weighting of high-certainty information. This preliminary study will be used to further dissociate low-level movement biases from perceptual biases (randomly assign the axes corresponding to the perceptual dimensions) and further examine the influence of movement preparation time on multidimensional decision making.

3-D-36 A virtual reality system for studying learning of complex motor tasks

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Learning real-life motor skills, such as those involved in many sports, often requires extensive practice. Studying complex tasks may provide new insights on motor learning but it is challenging. Virtual Reality (VR) allows to study complex motor tasks in the laboratory. We have developed an inexpensive VR system for investigating unconstrained throwing of both real and virtual balls. The system can estimate ball release position and velocity and ball arrival position on a target plane without an expensive motion capture system. To estimate ball release, the hand throwing both real and virtual balls can be tracked by taking advantage of the tracking capabilities embedded in consumer VR systems developed for gaming. For real balls, by connecting a micro-switch to a wireless controller of the VR system, we can estimate the time of ball detachment from the fingers. However, the velocity of the ball at release, i.e., when the ball motion completely decouples from the hand, cannot be estimated accurately using only the velocity of the hand at the time of switch release. Crucially, during the opening of the fingers, the ball starts moving in the hand and the actual onset of ball movement relative to the hand along the three directions of a Cartesian reference frame attached to the hand occurs at different times. Thus, to correctly estimate the ball release parameters, it is necessary to identify the time at which the ball starts moving relatively to the hand in relation to the switch release time. To do so, we have developed a calibration procedure based on a simple model of ball-hand interaction. We have validated the model with throws in which both the ball and the hand are tracked by an optoelectronic system (OptiTrack, Natural Point) as rigid bodies. The estimation of the time of ball motion onset in the different directions with respect to switch release can be used to improve the estimation of ball release with the VR system without tracking the ball. To estimate ball arrival, we have developed an automated image processing procedure for extracting the three-dimensional position of the ball bouncing on a target board from the video recorded by a camera synchronized with the VR system. We plan to use this system to investigate unconstrained throwing in three different conditions: simulated throws of virtual balls released at the time of release of a switch built into a hand-held VR controller; throws of real balls; simulated throws of virtual balls released at the time of balls release estimated with our procedure. Moreover, we plan to exploit VR to alter the dynamics of ball flight (e.g. altering gravity or drag) and hand-ball interaction (e.g. simulating balls with additional degrees of freedom) and to investigate individual throwing strategies and learning capabilities. This system will be a powerful tool for studying learning of real-life motor skills and of complex motor tasks with novel environmental and object interaction dynamics.

3-D-37 Effects of kinematic variability on hitting a target with a bull whip

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Over evolution, humans have become exquisitely adept at manipulating complex objects, ranging from chopping onions to spreading a tablecloth. However, traditionally motor control studies have focused on simplified and highly controlled motor tasks, typically excluding contact or interaction to ensure experimental control. This study chose one of the most challenging motor skills: manipulation of a flexible underactuated object--a bull whip. We studied participants' arm movements when swinging a 1.6m-long bullwhip to hit a target at ~2.2m distance with the tip of the whip. Thirteen subjects were asked to hit a distant target by manipulating a whip in a rhythmic style that kept the whip in the air across successive trials. All subjects performed the task for 5 blocks, each consisting of 30 trials. Each trial lasted ~2 seconds. Three-dimensional body and whip kinematics were tracked using a marker-based motion capture system. The key question we explored was what strategies participants use to achieve high performance in the task. Performance was quantified by target hits and by error, defined as the minimum whip-to-target distance in every trial. The 13 participants displayed a wide range of skills. Based on this breadth of performance levels, the next focus was on how intra-limb coordination of the arm prepared an accurate whip throw. Given the redundancy of the multi-joint arm and the flexible whip, principal components analysis assessed the dimensionality of the throwing movement and whip motions evolving across the throw. The arm and whip were analyzed as one system and as separate systems through PCA. We hypothesized that successful throws are preceded by lower kinematic variability around the throw onset; the latter was defined as the point in time when a subject's arm was farthest from the target. This strategy suggests that subjects aim to exploit the redundancy in the task and reduce kinematic variability in the dimensions that affect task performance. By dividing each trial into distinct time epochs - preparation, throwing, and hitting - we showed that better performing subjects displayed lower variability in the preparation and hitting stages of their throw. Furthermore,

within-subject analysis showed that all subjects performed better in trials where they reduced the kinematic variability of the whip and arm system during the preparation and hitting stages. These results suggest that reducing the kinematic variability of the whip and arm resulted in more accurate target hitting. This analysis of a highly complex motor task aimed to shed light onto how humans learn to adjust their limb coordination when interacting with a complex object. We showed that humans can manipulate an infinitely-dimensional object in a low-dimensional fashion. This study presents a first step in this new experimental paradigm that sets the stage for more hypothesis-driven analysis.

3-D-38 Electrical stimulation of the wrist biases human hand choice

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Hand choices--deciding the hand to use to reach for targets--represent continuous, daily, unconscious decisions. Left-hand choice is facilitated when single-pulse transcranial magnetic stimulation disrupts left posterior parietal cortex (PPC) activity (Oliveira et al., 2010). We also showed that the probability of left-hand choice increases when left PPC activity is suppressed and the right PPC is facilitated simultaneously by transcranial direct current stimulation (Hirayama et al., 2021). Electroencephalography and functional magnetic resonance imaging studies have shown that motor subthreshold electrical stimulation (ES) of the median and ulnar nerves of the wrist increases PPC activity. In the present study, we tested the hypothesis that ES of each wrist increases the probability of stimulated hand choice. Fifteen right-handed healthy participants (5 females, mean age=25.3 y) were recruited in this study. The participants selected one hand and reached for each target randomly presented at 9 positions as fast as possible. One block consisted of 120 reaching tasks, and participants performed 6 blocks. ES was applied to the median and ulnar nerves of the wrist, and the ES conditions were uni-manual (left-only, right-only), bi-manual, and no stimulation. Each stimulus condition was assigned three times to each target position in one block, with the order pseudorandomly assigned. The ES duration was 85 ms, applied simultaneously with, 300 ms before, or 600 ms before the target presentation at random. The ES intensity was 80% of the motor threshold. The probability of hand choice and reaction time for each condition were statistically compared. The probability of stimulated hand choice significantly increased with uni-manual stimulation than with no stimulation (Right-only: adj $p<0.01$, Left-only: adj $p<0.05$). The reaction time also significantly decreased with uni-manual stimulation than that with no stimulation (Right-only: adj $p<0.05$, Left-only: adj $p=0.085$). Meanwhile, there was no remarkable change in the probability of hand choice or reaction time with bi-manual stimulation than those with no stimulation. These results suggested that ES of the wrist prior to reaching increased stimulated hand choice. A non-human primate study showed that PPC accumulates sensory information to evaluate appropriate action selection, thus playing a critical role in this process (Cui et al., 2007). Herein, ES may have excited PPC activity of the stimulated hand choice. Furthermore, previous studies on the priming effect and selective attention have shown that prior tactile stimulation induces behavior associated with prior stimulation (Spence et al., 2000; Lang et al., 2019). Herein, increased stimulated hand use was possibly due to the ES providing tactile stimulation to each wrist, facilitating the priming effect and selective attention. Henceforth, we will investigate this finding's applicability in stroke rehabilitation to facilitate paretic hand use.

3-D-39 Variations in neuromuscular coupling and perceptions of control during precision grasp with altered visual feedback

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Neuromotor rehabilitation technologies with computerized interfaces, as with virtual reality, are increasingly prevalent. Persons with neurological disruptions, such as stroke or spinal cord injury, can train with such interfaces to repeatedly practice functional movements and reformulate neuromotor connections. It is crucial for computerized interfaces to be cognitively engaging to accelerate functional outcomes. Neurophysiological signals, including electroencephalography (EEG), may be monitored, or used as feedback to the interface. Thus, adapting the interface according to EEG signal features that are indicative of beneficial cognitive perceptions that optimize user performance. Our lab has recently demonstrated that reach and grasp performance are positively related to intentional binding (Nataraj et al., 2020, Front Hum Neurosci, Nataraj & Sanford, 2021, Front Bioeng Biotechnol). Intentional binding (IB) has been suggested as a proxy for a greater sense of agency, or perception of voluntary control (Haggard et al., 2002, Nature Neurosci). Intentional binding indicates perceived compression in time between one's voluntary actions and expected outcomes. In this study, we have conducted a preliminary investigation (n = 10) into the connections between EEG and IB during visual-guided grasping. Performance was based on a participant's ability to track a displayed time-dependent ramp with a computer trace. Height of the trace was proportional to grasp force applied on an instrumented apparatus. The "action" in this experiment was the completion of the ramp, and the expected "outcome" was a sound-beep that occurred at a variable time-interval following ramp completion. Intentional binding was estimated as the difference between actual time-intervals and participant estimation of those same time-intervals. To ensure a broader range of performance and agency, the mode in which the force trace was displayed was varied across blocks of trials. Variations included changes in speed, the addition of noise, and the inclusion of automation as described in the preceding study (Nataraj & Sanford, 2021, Front Bioeng Biotechnol). In this study, 32-channels of scalp-surface EEG were also recorded (g.tec system). Our current preliminary results indicate that there is less variance in the EEG potential with greater 'binding' at active scalp sites during the action-outcome time-interval. We aim to examine additional features of EEG signals (e.g., principal components) and correlate to both intentional binding and performance across control modes. Demonstrating relationships between physiological signals and parameters that indicate performance or perception during movement training has important implications for computerized rehabilitation applications. These device interfaces may then be better customized to induce physiological responses that produce greater engagement and performance.

3-D-40 Modulation of vestibular-sensitive neurons in deep mesencephalic nucleus to locomotion in walking monkeys

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The deep mesencephalic nucleus (DpMe) is a large midbrain reticular area that plays a key role in integrating and processing sensory, attention, and limbic inputs. Locomotion is crucial for even the most basic needs. Successfully maintaining balance during locomotion requires incorporating self-motion cues such as vestibular information DpMe cells have been shown to respond to passive vestibular stimuli, which suggests that this region plays an important role in vestibulo-motor control. However, DpMe

responses to locomotion have not yet been characterized. Here we analyzed single-unit extracellular activities from the DpMe in rhesus monkeys during passive vestibular stimulation (translations and rotation), head-fixed treadmill walking, head-fixed and head-free ground walking. 3Dgyroscopes/ 3Daccelerometers were used to record the head motion. 4 High-speed cameras were used for motion recording synchronously. DeepLabCut were used to extract the animals' 3D posture for gait analysis. We identified that DpMe cells demonstrated a significant increase in activity during head-fixed treadmill walking, head-fixed, and head-free ground walking when compared to resting activities. Notably, DpMe cells demonstrated phase-dependent modulation during walking, even in the absence of vestibular stimulation. Modulation patterns varied between DpMe cells- some cells demonstrated peak activity during the swing phase, and others during stance. Taken together these results suggest that DpMe neurons play a critical role in processing multi-sensory input during the complex sensorimotor activities generated in everyday life, such as walking. In addition, our findings also advance our knowledge of the neural circuits that coordinate gait and balance and thus have important implications for the development of novel treatments and interventions.

3-D-80 Postural instability context implicitly enhances visually-induced reflexive reaching control without explicit assistance of voluntary action

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Hierarchical motor control schemes have frequently assumed that the voluntary action system regulates lower level of reflex mechanisms so as to adjust these quick reactions according to various environments or tasks. Actually many experimental studies demonstrated that reflexive responses were modulated in accordance to the goal oriented voluntary actions following reflex responses.

Here we introduce a different example that reflexive visuomotor processing modulates a quick manual reaction without any assistance of voluntary reaching adjustments, and then will explain this modulation by the variance change of self-motion estimation in the Bayesian inference. In the first experiment, participants were asked to stand on the stable or unstable (moving) platform in the context phase (5 s) with watching the screen on which grating pattern was filled. After the context period, they were asked to make reaching movement toward the target flashed on the screen. During reaching in some trials, grating pattern started to move rightward or leftward to induce the reflexive manual response in the direction of visual motion (named MFR: manual following response). When we compared the MFRs for two context conditions, the MFR was significantly greater for the unstable postural context than for the stable postural context. In the second experiment, we additionally introduced random visual motion context (2 postural and 2 visual conditions). While the postural fluctuation was greatest in the context of unstable posture with inflicting random visual motion, the MFR was greatest after the context of unstable posture with inflicting static visual pattern. These results deny the account that the MFR modulation is simply associated with the degree of postural fluctuation, rather suggest that the coherency between visual motion and body fluctuation is important in enhancing MFR. Importantly, there was no assistive voluntary reaction enhancing MFR because the voluntary adjustment during reaching was in the opposite direction to the MFR for correcting the deviation caused by MFR.

If we assume that the MFR is driven as a compensatory response to the estimated self-motion using visual motion, the observed MFR modulation can be well explained by the change in prior probability distribution of the estimated self-motion as follows. The unstable postural context increases variability of self-motion, which acts as a change in prior probability to estimate self-motion from applied visual motion during reaching movement. Bayesian theorem predicts that posterior probability of the self-motion estimated from visual motion shifts in the increasing direction, which is compatible to the experimental results. This examination suggests that the implicit visuomotor control mechanism can modulate reflexive adjustment during reaching by accessing a functional representation of the body states reflecting environmental context, rather than by being subservient to the voluntary motor control.

E – Disorders of Motor Control

3-E-41 The fatigue caused by functional electrical stimulation of deltoid muscle does not reduce its effect on the glenohumeral distance

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Functional electrical stimulation (FES) has been shown to improve arm function and reduce shoulder subluxation in people with paresis and muscle weakness due to stroke (Auchstaetter et al. 2016; Faghri et al. 1994). FES is typically delivered transcutaneously to elicit muscles contractions and produce motion. The limitations of this technique within assistive technologies are muscle fatigue (Doucet et al. 2012), force controllability (Lynch and Popovic 2008), and the unknown interactions between therapeutic effects on arm function and subluxation. In this study, we quantified how fatigue affects shoulder rotation and the shortening of the glenohumeral distance by FES of deltoid muscles. We recruited six healthy volunteers (age mean ± s.d.=21.3 ±3.4 yr., weight 73.8±11.8 kg, height 163.8±8.1 cm, 3 male, 3 female). The volunteers sat with their arm by their side while their anterior or medial deltoid muscles were stimulated (neuromuscular electrical stimulation system Ewave by Zynecs Medical) to elicit a shoulder flexion or abduction of about 40 deg. Current was injected through two 5x5 cm electrodes positioned over the belly of the muscle. The stimulation pattern was designed to assist with reaching movements. Biphasic pulses (pulse width = 300 µs) were delivered at 30 Hz. During the 5 s "on" and 5 s "off" duty cycle the current amplitude was ramped up for 1 s, stayed at maximum for 2 s, and ramped down for 2 s. The maximal current amplitude was between 17 and 21 mA across participants. During the experiment lasting up to 2 hours, shoulder abduction or flexion with FES was video recorded and the glenohumeral distance was visualized with ultrasound every 10 min. Additionally, the forces generated during the maximal voluntary contraction of shoulder muscles were assessed using a handheld dynamometer three times during the experiment, pre-session, mid-session, and post-session. The videos were used to measure the maximal angle caused by each duty cycle. The recorded ultrasound video clips were used to obtain two measures during FES: 1) the maximal change of the distance between the glenoid fossa and the head of the humerus, and 2) the maximal change of the glenohumeral height using procedures described in Lahham et al. (2016). All measurements were taken by three researchers, two were blinded raters. Results show that FES caused fatigue observed as the gradual decline in the abduction or flexion angle of about 5 deg in an hour and shoulder forces post-session compared to pre-session. We further observed that FES of deltoid muscle reduced the glenohumeral distance in all participants, but that this effect did not decline throughout the duration of experiment despite fatigue. Our results suggest that FES may be effective in a combined treatment aimed at both reducing shoulder subluxation and facilitating arm function, even in presence of fatigue.

3-E-42 Post-stroke upper-limb training to recover reciprocal activations

Presenting Author: Ana Bengoetxea

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After a stroke, spasticity remains one of the most disabling symptoms. Spasticity is clinically defined as a set of associated symptoms arising from different neurophysiological characteristics, one of them being the loss of reciprocal inhibition. According to the hypotheses that discrete movements are segments of cyclic movements, that cyclic movements emerge as a results of reciprocal activation of antagonistic muscles, and that these reciprocal activations are in turn modulated through neural oscillators, we hypothesize that training cyclic movements would help to recover the reciprocal activations lost after stroke. Moreover, spasticity increases with the stretching of spastic muscles during joint rotations induced by movements. Every concentric isotonic contraction produces the stretching of antagonist muscles due to shortening of the agonists in a proportional manner. In order to sidestep the stretching of spastic muscles, we theorized that isometric contractions would avoid the increase of tonus resulting from stretch reflex hyperexcitability present after stroke, in patients with upper limb neurological sequelae. We hypothesized that practicing cyclic movements in an isometric condition would train reciprocal activations conducted by neural oscillators without increasing muscular spasticity due to the mechanical stretch. In this context, we have implemented a training methodology based on cyclic isometric activations against resistance. We have performed a longitudinal training program with a single chronic stroke patient, severely impaired. The training was performed 3 days per week over 3 months. The training was stopped abruptly due to the Covid19 lockdown, but was restarted after 4 months of halt, for a subsequent period of 4 months. Through the whole training process exercises included: shoulder flexo-extension, elbow flexo-extension, lower-arm prono-supination, wrist flexo-extension in neutral lower-arm position and in lower-arm pronation, and finally fingers flexo-extension in lower-arm neutral position. Agonist-antagonist activity was alternated 1s each during 1min. Once per week EMG data from 14 muscles of the upper limb were recorded during the realization of the exercises to assess the effects of the training by comparing the quality of activations. We recorded additionally to our stroke patient, 2 healthy volunteers and used it as a reference activation pattern. Principal component analysis (PCA) was applied to identify the EMG rhythmic activities and distribution of muscles contributions. Our results showed that the rhythmic activation component , became apparent with training even for wrist and fingers muscles, which were compromised by palsy. These results suggest that this type of training might help to control upper limb neural oscillators, but questions concerning the transfer to functional activity still remain to be answered.

3-E-43 Impact of essential tremor on saccadic adaptation

Presenting Author: Florence Blondiaux

Authors: Florence Blondiaux[1], Louisien Lebrun[1], Bernard Hanseeuw[1], Frédéric Crevecoeur[1]

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Essential Tremor (ET), one of the most common movement disorders, is characterized by involuntary oscillations of the limbs, mainly during movement. Although its origin remains unclear, there is a consensus on a neurogenic cause originating from a dysfunction of the cerebello-thalamo-cortical loop. A recent neuroimaging study reported reduced connectivity between the cerebellum and other brain regions, providing additional evidence for an implication of cerebellum in the generation of the tremor. To gain further insight into whether cerebellar functions are altered in ET, we sought to investigate the performances of patients affected by ET in a saccadic adaptation task, which is known to rest on the integrity of the cerebellum. We hypothesized that if the tremor is linked to cerebellar deficits, then a deficit in saccadic adaptation could be observed. We recruited 33 participants (18 ET patients (13 F) and 15 healthy aged-matched controls (9 F)) to perform a standard saccadic-adaptation task. They were first assessed with standard clinical evaluation (Fahn-Tolosa-Marin tremor rating scale) to confirm their inclusion in the study. During the task, a visual target presented laterally (eccentricity: 20 degrees) jumped vertically during the saccade (5 degrees). The target shift was typically not perceived but it resulted in a final error in the vertical direction that participants learned to anticipate with practice. After adaptation, the final position of the saccade became closer to the goal target after the jump. Participants performed a series of 5 blocks of 60 saccades. The protocol included oblique and horizontal saccades without any jump for control analyses (60 trials in total). There was no significant difference between the two groups during the baseline trials. Regarding the adaptation trials, ET patients showed reduced adaptation captured by the extent of vertical component of the saccade and by the peak vertical velocity of partially adapted saccades. Mixed models analysis of these two parameters revealed strong interaction between groups and the trial indices, revealing slower adaptation for the ET group ($p < 0.001$). The curvature of saccades from ET patients after adaptation also differed from the control group, showing an adaptation mainly towards the end of the saccade, in contrast with the control group who showed more gradual change in saccade curvature within each movement. These results show impairments in saccadic adaptation, for which no effect of the tremor itself was expected. Indeed, participants did not exhibit any nystagmus or eye oscillation, and their behaviour during fixation prior to saccades was similar to the control group. We suggest that these results support the hypothesis of a cerebellar origin of ET and could represent a new quantitative behavioural marker of the disorder.

3-E-44 Predictive impairments compromises motor skills in children with autism spectrum disorder

Presenting Author: Sabrina Bond
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The predictive impairment hypothesis by Sinha et al. (2014, PNAS) proposes a unifying computational account for ASD. Although the hypothesis is promising theoretically, more direct empirical evidence is required. Motor coordination constitutes an excellent domain in which to test this hypothesis. Although not part of the diagnostic criteria for ASD, motor coordination difficulties are often observed in the condition. For instance, many children with ASD find it challenging intercept dynamic objects such as catching a ball. We conducted a comprehensive study of naturalistic ball catching to examine features of predictive control. Fine-grained kinematic analysis of interceptive action and postural adjustments reveal reduced anticipatory control in autism. To discount alternative coordination deficits causing interception problems, three control tasks tested reaction time, movement speed, or balance control. This study is also distinguished by its use of precise spatio-temporal motion capture technology for characterizing a pediatric clinical population. The experimental protocols and the data acquisition/analysis methodologies developed will likely be useful for future studies of predictive abilities in ASD, and also patients undergoing motor behavior therapies.

3-E-45 Causal effects of cerebral palsy on energy expenditure in children
Presenting Author: Pavreet Gill

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Children with cerebral palsy (CP) expend more than twice as much energy while walking when compared to their typically developing peers [1]. Consequently, they fatigue faster, hindering their ability to be physically active and lowering quality of life [2][3]. The mechanisms underlying this high energetic cost of walking are still uncertain and there are numerous proposed causes. Several studies have investigated the effects of a single variable on energetic cost, such as gait kinematics [4] or co-contraction [5], but they often neglect other causal relationships in CP. Potential causes of high energetic cost, such as poor strength or motor control, do not occur in isolation of each other in CP. Here, we (1) propose a model to untangle the individual and combined effects of potential variables that may contribute to high energetic cost and (2) identify the impact of each underlying effect. Here, energetic cost is the net non-dimensionalized volume of oxygen per unit time. First, we modeled our causal assumptions using directed acyclic graphs (DAGs). DAGs represent causal relationships and let us critically examine if a variable is a confounder of a specific causal path [6]. We must adequately adjust for confounders and sources of bias to strengthen any stance of causation we may take. Informed by prior literature, we modeled the relationship between energetic cost (outcome) and spasticity, strength, selective motor control, dynamic motor control, and deviation in gait kinematics (exposures), as well as, age, height, mass, and walking speed. We used this causal model to determine covariate adjustment sets and then, with Bayesian additive regression trees (BART), modeled energetic cost as a function of each exposure. BART generates an ensemble of regression trees to flexibly capture non-linear relationships and estimate causal effects for each exposure variable [6]. The magnitude of these effects determine the contribution of each exposure to energetic cost. This analysis was done with the R package bartMachine with data collected at Gillette Children's Specialty Healthcare. We included 1639 children with CP aged 18 or younger who were classified as level I, II, and III within the Gross Motor Function Classification System. We used random forests to impute missing data. The results indicate that (1) gait kinematics had the greatest effect on energetic cost, followed by (2) selective motor control, (3) dynamic motor control, (4) spasticity, and (5) strength. The latter three exposures had effect sizes half that of gait kinematics. These results suggest that abnormal gait kinematics may affect energy expenditure more than other proposed factors in children with CP. [1]Campbell & Ball. Orthop Clin North Am 1978.[2]Bell & Davies. Am J Clin Nutr 2010.[3]Varni et al. Dev Med Child Neurol 2005.[4]Noorkoiv et al. Phys Ther 2019.[5]Unnithan et al. MSSE 1996.[6]Greenland, Pearl & Robins. Epidemiology 1999.[7]Chipman, George, McCulloch. Ann of Appl Stat 2010.

3-E-46 Subthreshold vibration influences the temporal structure of standing in persons with transtibial amputations
Presenting Author: Zachary Meade

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Objective: To determine the influence of subthreshold vibration, specifically pink and white noise, on clinical measures of somatosensory perception, gait, and balance. Design: A crossover design with randomized order of interventions implemented during one three-hour session. Setting: University of Nebraska at Omaha Biomechanics Research Building. Participants: 20 individuals with a transtibial amputation. Interventions: Continuous subthreshold (imperceivable) vibration was delivered to the thigh, proximal to the prosthetic socket with a null condition (no vibration) and two different signal spectra: pink, and white noise. Main Outcome Measures: Perception to light touch (as measured by Semmes-Weinstein monofilament test), perception to vibration (Biothesiometer vibration test), linear standing characteristics (center-of-pressure (COP) velocity, and root-mean-square (RMS)), nonlinear standing characteristics (SDA and COP-VAF), step length, step width, and step time. Results: Using linear mixed effect models we found no differences in vibration perception or light touch perception, and no differences in perturbed walking across vibration conditions. We found that white noise amplifies the RMS of COP displacement in the eyes closed condition in the mediolateral direction compared to pink and no vibration. Pink and white noise also demonstrated an increased time to minimum in COP-VAF analysis. Lastly, we saw an effect of mass that caused an increase in zero time for pink noise. Conclusion: Subthreshold vibration had no influence on the perception of light touch or perception of vibration. Pink and white noise had no effect on measures of the magnitude of postural sway but did impact measures of the temporal structure of postural sway during quiet standing as demonstrated by COP-VAF analysis. Limitations of this study include its small sample size and heterogenous cohort. Longer term data collection with a larger sample size is needed to determine the value and application of this intervention.

3-E-47 Dissociating sensorimotor recovery and compensation during exoskeleton training following stroke

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The quality of arm movements typically improves in the sub-acute phase of strokes for individuals with stroke-induced upper extremity impairment. Here, we used whole arm kinematic analysis during exoskeleton-aided reaching movements to distinguish whether these improvements are due to true recovery or due to compensation. 53 participants with post-acute stroke performed ~80 reaching movement tests during 4 weeks of training with the ArmeoSpring exoskeleton that reduced the effects of gravity on the arm. All participants showed improvements in end-effector movement smoothness. Four ArmeoSpring angles, shoulder horizontal rotation, shoulder vertical rotation, elbow rotation, and forearm rotation, were recorded and analyzed. We first characterized healthy joint coordination patterns by performing a sparse principal component analysis on the four joint velocities during the reaching tests performed by young control participants. We found that two dominant joint correlations (shoulder horizontal + elbow rotation and shoulder elevation + forearm rotation) explained over 95% of variance of joint velocity data. We identified two clusters of stroke participants by comparing the evolution of these two correlations in all tests. In the 'Recoverer' cluster (N = 19), both joint correlations

converged toward the respective correlations for control participants. Thus, Recoverers relearned how to generate smooth end-effector movements while developing joint movement patterns more similar to those of control participants. In the 'Compensator' cluster (N = 34), at least one of the two joint correlation patterns diverged from the corresponding correlation of control participants. Compensators relearned how to generate smooth end-effector movements by discovering various new compensatory movement patterns less similar to those of control participants. There was no difference in clinical impairment level between the two groups either at the onset or at the end of training as assessed with the Upper Extremity Fugl-Meyer scale, but the Recoverers showed significantly faster improvements in end-effector movement smoothness (p=0.001) than the Compensators at the start of training, suggesting that there may be a relationship between joint coordination patterns and the speed of improving end-effector performance. Our analysis can be used to inform neurorehabilitation clinicians on how to provide movement feedback during practice and suggest avenues for refining exoskeleton robot therapy to reduce compensatory patterns.

3-E-49 Neuronal activity of globus pallidus correlates with effectivity of deep brain stimulation in cervical dystonia

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Cervical dystonia (CD) is the most common form of dystonia, which characterized by altered head position and involuntary head movements. CD is frequently refractory to medical management and in such cases surgical treatment with deep brain stimulation (DBS) of globus pallidus internal (GPi) has been successful. The mechanism of DBS in treatment of dystonia is unclear. Overarching goal of our research is to examine mechanistic underpinning of dystonia and how DBS affects it. Here we asked whether there exist differences in the firing patterns within the GPi of the same dystonic patient and whether regions of GPi where DBS results in favorable therapeutic response differs in their electrophysiological characteristics compared to those where the therapeutic response is absent. We analyzed pallidal single unit activity recorded by means of microelectrodes (MER) during bilateral DBS surgeries in 17 CD patients (34 hemispheres). We then classified (a-posteriori) the single units amongst those located in DBS responsive and non-responsive locations within GPi. Amongst total of 564 GPi neurons, 336 cells were in DBS responsive regions, while 228 cells were in DBS non-responsive regions. We performed classification of GPi cells to tonic, burst and pause patterns using hierarchical clustering approach. The burst neuron had relatively larger proportion in responsive regions (74%) compared to non-responsive regions (68%). Pause neurons also had decreased proportion in responsive regions (10%) compared to non-responsive areas (14%). Tonic neurons had similar proportion. The difference in the neuronal distribution was insignificant. Wherein we showed that burst and pause cells characterized by significantly ($p<0.05$) lower coefficient of variance and burst spike percent in responsive area. Then we compared parameters of pallidal neuronal activity in responsive area between patients with weak, moderate and excellent clinical outcomes. Patients with excellent clinical effect characterized by higher proportion of pause cells (13%) compared to patients with moderate (8%) and weak (5%) outcomes. We also found a consistent significant (ANOVA, $p<0.01$) decrease of firing rate, burst index and alpha oscillations of GPi burst cells in patients with excellent to weak outcomes. Overall, our data showed that neuronal parameters of GPi responsive area correlate with clinical outcomes in CD patients. The results will further lead to determination of electrophysiological biomarkers to improve efficiency of deep brain stimulation. The study was funded by the Russian Science Foundation (project 18-15-00009).

F – Adaptation & Plasticity in Motor Control

3-F-50 Harnessing built-in somatosensory signals for optimal motor control of an extra robotic finger

Presenting Author: Elena Amoruso

Authors: Elena Amoruso[1], Lucy Dowdall[1], Mathew Kollamkulam[1], Obioha Ukaegbu[2], Tammy NG[2], Harriet Dampsey-Jones[1], Dani Clode[1], Tamar Makin[1]

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Acting efficiently in the world depends on complex interactions between the motor and somatosensory systems, forming a closed control loop for the sensory consequences of motor commands. When controlling artificial limbs, this closed loop control is profoundly impaired. Here, we tested the contributions of an incidental form of somatosensory input as a surrogate source of proprioceptive feedback for robotic limb control. On Day 1, participants learned to control a robotic extra finger (The ThirdThumb, Dani Clode Design), worn on the hand and controlled by pressure sensors attached underneath the big toes - allowing the control of Thumb flexion/extension and adduction/abduction. On Day 2, we measured four learning outcomes - acquisition (initial ability to perform the task), retention (performance on the following day), automaticity (performance under varying cognitive load) and flexibility (performing different tasks using similar movements). To modulate somatosensory contributions to the Thumb's motor control during learning, we used injections of local anaesthetics to attenuate touch and proprioceptive inputs from both toes in a test group (N=20). Learning outcomes were compared against a control group (N=20), who received sham injections. Both groups similarly acquired the motor skills necessary to operate the Thumb, indicating that the reduced somatosensory feedback did not impact participants' overall ability to train to use the Thumb. However, participants with reduced surrogate feedback showed impaired learning relative to the control group, as indicated by impaired automaticity, flexibility and retention learning outcomes. For example, anaesthetised participants were more affected by the addition of a cognitive load to a dextereous motor task, and showed worst retention of hand-Thumb coordination. Motor learning was not impacted by the somatosensory deprivation when tasks involved collaboration with the biological fingers, indicating that the brain could 'close the gap' of the missing proprioceptive inputs by alternative means, including other body parts involved in the motor task. However, while motor performance appeared matched in such circumstances, an analysis of the toes movement as recorded by the pressure sensors indicated that participants deprived of sensory feedback used arguably less efficient motor strategies (e.g. increased use of bilateral movements). Overall, our findings suggest that motor learning is enhanced when users can rely on the incidental proprioceptive signals emerging from the control of the artificial limb. Importantly, even when the performance advantages afforded by the incidental feedback are minimal, they provide opportunities for automaticity and optimisation that are not available to users relying on alternative sensory cues. Augmentative and assistive technologies should consider the multiple available avenues to provide proprioceptive feedback, beyond bespoke device somatosensory signalling.

3-F-51 Re-optimization processes for forearm-weight increase in reach-to-grasp movement

Presenting Author: Luna Ando

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In a daily life, we often experience arm weight changes in such cases when using tools or lifting of objects. Most of the studies of motor adaptation in a force-fields have investigated adaptation processes to force applied in the horizontal plane, but not to gravitational force. In this study, we thus investigated the re-optimization processes for forearm-weight increase in trajectory planning of reach-to-grasp movement. Previous studies suggested that the height of movement trajectory increases to reduce effects of signal-dependent noise on the planned trajectory in the gravitational direction. Based on this idea, we predicted that movement trajectory will be higher when participants re-optimized the forearm-weight, in reach-to-grasp movement performed on a desk. In addition, signal-dependent noise increases with fatigue. It is therefore predicted that movement trajectory will be higher as the arm gets exhausted. In the experiment, right-handed participants performed reach-to-grasp movement on a desk. They were asked to grasp the target object located 30 cm in front of the starting point, and transport and place it 10 cm right of target position with their right-hands. The participants performed eight blocks, and one block consisted of 50 consecutive trials (400 trials in total). First, a block was performed with no weight, as a baseline. Next, six blocks were performed with a 200 g weight attached around their forearm, with one-minute breaks between the blocks. Finally, a block was performed with the weight removed. In all movements, reflective markers were attached to the participants' thumb, index finger, and wrist, and their three-dimensional positions were recorded using an optical motion capture system. We used maximum height as the kinematic measure. Maximum height was defined as the maximum height (cm) of the wrist marker from the desk. To examine the changes in maximum height over time, we calculated the mean of maximum height for each block. In addition, we defined aftereffects as the difference in maximum height between the mean of the last 5 trials of the first no-weight block and the first one trial of the no-weight block after the 200 g blocks. In addition, aftereffects were calculated to confirm whether the participants adapted to the forearm-weight increase. The results showed that maximum height was higher in the 200 g blocks than in the no-weight blocks. In the 200 g blocks, maximum height tended to be higher in the later blocks. The high movement trajectory observed in the later of 200 g blocks supports the hypothesis that the height of movement trajectory increases to reduce effects of signal-dependent noise on the planned trajectory in the gravitational direction. In addition, there were positive aftereffects in the trial immediately after the weight was removed. This result suggests that the participants adapted to the forearm-weight increase.

3-F-52 The acute effects of strength and skill training on the neural circuits of the contralateral limb

Presenting Author: Antonio Capozio

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Unilateral strength and skill training lead to increase in strength and performance in the contralateral untrained limb, a phenomenon known as cross-education or bilateral transfer. It was proposed that transfer of strength and skill might share similar neural substrates (Ruddy & Carson, 2013). Recent evidence suggests that the neurophysiological changes underlying cross-education can be observed after a single session and include bilateral increase of corticospinal excitability (Leung et al. 2015).

Nevertheless, there is still controversy over whether transfer of strength depends on bilateral activation of the primary motor cortex and/or on the role of spinal circuits in mediating it (Hendy & Lamon, 2017). The aims of this study were to: (1) measure increases in strength observed in the untrained limb after a single session of strength training; (2) measure changes in performance in the untrained limb after a single session of force-matching training; (3) compare changes in spinal and corticospinal neural excitability between the two training sessions. Ten participants (Age (SD) = 23.5 (4.6); F = 4) completed a session of strength training and a session of skill training in a randomised order. For strength training, participants completed isometric wrist flexion maximum voluntary contractions (MVCs) with the left arm. For skill training, participants traced a trajectory on the screen by producing forces matching 25% or 50% of their maximal isometric wrist flexion with the left arm. In both conditions, participants received online visual feedback of their performance. Neurophysiological measures were collected from the untrained (right) arm and included: corticospinal excitability measured by TMS at 100% motor threshold (MT); H-reflex evoked in the FCR muscle at an intensity of 10% of Mmax (HM10%); TMS-conditioning H-reflex at multiple conditioning-test intervals. A single session was successful in increasing force-tracking performance in the untrained limb ($F_{1,9} = 9.017$, $P = 0.015$). However, there was no significant increase ($F_{1,9} = 3.069$, $P = 0.114$) in contralateral strength after a session of strength training. For corticospinal excitability, the two-way RM-ANOVA showed a significant effect of TIME ($F_{1,9} = 15.224$, $P = 0.004$) but no significant effect of CONDITION ($F_{1,9} = 0.117$, $P = 0.740$) or TIME × CONDITION interaction ($F_{1,9} = 0.007$, $P = 0.936$). There were no changes in the amplitudes of the H-reflex across TIME ($F_{1,8} = 1.176$, $P = 0.310$) or CONDITION ($F_{1,8} = 0.821$, $P = 0.391$). Similarly, TMS-conditioned H-reflex did not differ after training among conditions ($F_{1,9} = 0.019$, $P = 0.895$). We suggest that cross education of skill and strength could be modulated at the acute stage by increases in the excitability of the ipsilateral motor cortex. In addition, data showed that spinal circuits of the untrained side have a limited role in mediating the cross-education of skill and strength.

3-F-53 Improvements in balance control in yoga may depend on method of virtual instruction in novice practitioners

Presenting Author: Andrew Cho
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Yoga is a widely practiced form of exercise known to have many health benefits. Due to the COVID-19 pandemic many yoga programs have transitioned to strictly virtual learning platforms. There are a multitude of ways to conduct yoga classes virtually, including live sessions or on-demand video. Existing research in classroom-based education details how a blended model including synchronous (instructor and learner practice in real time) and asynchronous (learner practices on own time) modules is optimal for learning outcomes. However, the efficacy of each distance learning paradigm on motor learning parameters acquired during a fitness class has yet to be explored. The purpose of this study was to compare various distance learning methodologies in novice yoga practitioners' ability to improve balance control. We hypothesized that a mixed learning model that includes both synchronous and asynchronous delivery would lead to the greatest improvements. Fifty-three participants between the ages of 18-65 were recruited to participate in a virtual 8-week yoga program. Participants met over video conferencing before and after the intervention to complete a series of balance tests to assess the retention of three postures. These included single-leg stance with eyes closed (to assess generalization of learned balance), eagle pose (to challenge anterior-posterior balance), and tree pose (to challenge medial-lateral balance). Videos were recorded during these postures and analyzed using two-dimensional motion analysis software to track center of mass (COM) position. Marker coordinate data were used to compute COM excursion, velocity, and total distance traveled. The intervention consisted of a two-class per week yoga program where participants were randomly assigned into synchronous, asynchronous, and mixed groups. Synchronous participants attended two live yoga sessions offered by trained instructors, while asynchronous participants completed two pre-recorded sessions on their own time. Individuals in the mixed group completed one of each session every week. Preliminary results indicate that while all participants showed improvements, those who followed the mixed model demonstrated slower COM velocity, reduced total COM excursion, and reduced total distance traveled after intervention--all suggesting the greatest improvement increase in balance control and indicating that distance learning of yoga may be most effective when instruction includes both synchronous and asynchronous components. We postulate that these outcomes are due to the mixed group receiving the combined benefit of live feedback and real-time error corrections through synchronous practice, while also experiencing the added autonomy and internalization of error corrections provided through asynchronous practice. Ensuing research should further investigate these topics on a neurophysiological level and study whether other populations such as older adults respond in a similar way.

3-F-54 Analysis of cognitive and muscular fatigue during last-moment reach correction

Presenting Author: Florencia Garro

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Previous studies on movement preparation and execution have shown a relationship between neural populations in the motor cortex [1]. During the preparatory phase, a particular pattern across neurons is produced, which regulates how neural activity (and therefore muscle activity) evolves during the movement execution [2]. Cognitive fatigue indicates a feeling of tiredness or exhaustion, and a disengagement from the task [3], while muscular fatigue is the decline in the ability of muscles to generate force [4]. We want to explore how these factors affect neural patterns during movement preparation and execution. Changes in lower alpha and theta band power have been reported with increasing levels of fatigue and changes in beta activity are associated with compensatory efforts to maintain performance levels. In addition, changes in the amplitude of ERP components associated with error calculation are also significantly reduced in states of mental fatigue [3]. In this study we investigate the effects of fatigue on the underlying motor control patterns, which could help to identify the mechanisms of fatigue compensation. For this, we explore the neural activity modulation during a repetitive reach task in which we introduced last-moment corrections, executed in a robot-assisted experimental paradigm using visual cues. 12 right-handed healthy participants were instructed to execute a random sequence of reaching tasks within targets located in the vertices of a 15 cm side equilateral triangle. Three different types of force fields were applied to the hand, in which the viscosity constant was modulated by a handle planar manipulandum (KINARM End-point Lab). The plane where the robot moved was covered, and hand position was displayed by a pointer on a screen placed above it. During each trial, a fixed movement preparation time was provided. In order to introduce last-moment reach corrections, three types of catch trials were randomly presented: (1) the force field was unexpectedly removed, (2) the target jumped to another position just before the planned movement onset and (3) a combination of (1) and (2). EEG data was recorded from 128 channels at a sampling rate of 1 kHz and 24 bits of depth(actiCHamp, BrainVIsion LLC). In addition, four surface EMG channels were included, placed on the pectoralis clavicular head, the posterior deltoid, the biceps long head, and the triceps lateral head. A T1-weighted structural MRI image was acquired for source localization of EEG data. Preliminary results of time-frequency analysis of a ROI subset in the left hemisphere showed task-dependent modulation of the brain signals of interest. Further analysis will elucidate how this modulation is affected by muscular and cognitive fatigue during motor tasks. Ref: 1.G.F. Elsayed, et al., Nat. Commun. 2016 2.M.M. Churchland, et al., J. Neurosci. 2006 3.Q. Peng, et al.,Engineering 2019 4.T Romain, et al., J Electromyogr. Kines. 2009

3-F-55 Cortical preparatory activity reflects visuomotor retention deficits after punishment feedback during motor learning

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Purpose: Cortical motor preparation underpins visuomotor adaptation (VMA). Reinforcement feedback (i.e. reward and punishment) has demonstrated dissociable effects on learning and retention of VMA. However, it is currently unclear how reinforcement feedback alters cortical motor preparation during the performance of a VMA task. This research aimed to determine whether reinforcement feedback changes cortical motor preparation during the learning and retention of VMA. Procedures: Participants (age range: 19-32, males: 18, females: 24) were randomly placed into one of three groups [Reward (n=14), Punishment (n=14), Control (n=14)] and performed 680 trials of a VMA task under five conditions [Baseline (80 trials), Adaptation (200 trials), No Vision (200 trials), Washout (100 trials), and Readaptation (100 trials)] with a Wacom pen and tablet. Adaptation (learning phase) and No Vision (retention phase), featured an incongruent position between the cursor and the target, with the cursor trajectory rotated 30-degrees counterclockwise to the target, requiring participants to adapt their movement to hit the target. During Adaptation, after each trial, feedback based on error magnitude was provided in the form of a positive number (Reward), negative number (Punishment) or two vertical lines (Control). Positive and negative numbers represented monetary gain and loss, respectively. No Vision featured no reinforcement or visual feedback. EEG was recorded in all task conditions from 28 electrodes to measure movement readiness potentials (MRP) amplitude, time locked to trial initiation as an index of cortical motor preparation. Learning rate and percent adaptation achieved was calculated to measure behavioral performance. Results: All groups (Reward, Punishment, and Control) displayed similar learning rates ($F(2,39)=0.11$, $p=0.89$, ANOVA) and adaptation achievement ($F(2,39)=0.91$, $p=0.41$, RMANOVA) throughout the Adaptation condition, suggesting reinforcement feedback does not alter task learning. However, the Punishment group did not maintain the same level of motor performance during the retention phase (46.02 ± 8.46%), while Reward (65.19 ± 6.23%) and Control (67.45 ±5.62%) groups preserved their performance ($F(2,39)=4.24$, $p=0.02$, RMANOVA) (Figure 1). Moreover, Punishment significantly decreased MRP amplitude during both learning and retention phases compared to Reward ($F(2,35)=6.62$, $p=0.01$, RMANOVA) and Control ($F(2,35)=4.14$, $p=0.04$, RMANOVA). No significant differences were found between Reward and Control groups ($F(2,35)=0.01$, $p=0.949$, RMANOVA). Conclusions and Implications: In conclusion, punishment feedback not only impairs retention of visuomotor learning, but also alters the neural processes associated with motor preparation. These results are useful in rehabilitation efforts, especially for those that experience neurological diseases that affect motor function.

3-F-56 Robust but specific enhancement of somatosensory-motor skills through an active haptic training in expert pianists

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Somatosensory perception plays essential roles in skillful behaviors. Recently, we demonstrated that the active haptic training (AHT) with a finger enhances both experts' active somatosensory perception and motor skill in terms of accuracy of keystrokes by pianists. However, it remains unclear what mechanisms underlie the effect of the somatosensory training on the motor skill. Specifically, probing the transfer of the trained abilities provides ways of understanding at which domain the training-related changes occurred in the sensory-motor system. Here, we tested whether effects of the AHT on a single finger are transferred to the untrained fingers and the untrained movement contexts. A total of 71 expert pianists participated in this study. The pianists in the training group performed the AHT so as to improve the proprioceptive ability of either the right index (n=15) or ring fingertip (n=13). The AHT consisted of a repetition of discriminating a piano-key weight. After each trial of the task, the pianists received feedback on correctness of their answer. By contrast, the pianists in the control group performed the AHT using either the right index (n=15) and ring fingertip (n=13) but did not receive feedback on the answer following each trial. Before and after the training, two behavioral measures were assessed; a weight discrimination threshold (PT) and a motor precision that is an index of how accurately the pianists can produce a predetermined keystroke velocity. Each of the two tasks had three keystroke conditions; (1) single keystrokes by the right index or (2) ring finger, and (3) alternate strikes of two keys by the two fingers. In all conditions, the target keystroke velocity was 30% of the maximum keystroke velocity. We further performed an additional experiment that assessed an intensity discrimination threshold of a passive keystroke before and after the AHT, in which 15 pianists participated. In the training group, both the weight PT and motor precision improved following the training session only when these tasks were performed by the trained finger. In the control group, we found no significant differences in the two behavioral measures between the pre- and post-training sessions in all of the conditions. Furthermore, the AHT yielded no significant change in the intensity discrimination threshold of a passive keystroke. Our results indicate specific effects of the AHT on the somatosensory perception and motor precision at the trained finger and movement context. We speculate that the pianists learned an optimal movement strategy that provides fine-tuned somatosensory information on the key weight during the keystrokes (e.g., touch with the most sensitive zone of the fingertip, change the fingertip force direction to strike the key) through the AHT, as further exemplified by no change in the passive somatosensory perception. The fine-tuned somatosensory information can enhance both the perception and the somatosensory motor skils.

3-F-57 Reach-to-grasp movement in a viscosity force field

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In the literature of the motor control of reach-to-grasp movement, very limited studies have used a force field paradigm. The present study used a viscosity force field, where the resistance force was applied to the participant's wrist against the movement direction (not rotating force), to investigate the time course of adaptative kinematic changes in reach-to-grasp movement. Ten right-handed young adults participated in the experiment. They performed reach-to-grasp movements for a cylindrical target with a 2 cm diameter and 2 cm height located on 26 cm away from a start point. The experiment consisted of 30 trials of pre and post movements with a null force field (NF) and 100 trials with a viscosity force filed (FF) (14Nm/s). The participants were instructed to perform the movements in their natural speed. Reflective markers were put on the tips of thumb and index finger and the wrist, and their 3D positions were sampled at 60 Hz by an optical motion capture system (Smarttrack, ART, inc.). Grasping aperture was calculated using the thumb and index finger position. The average performance of the last 5 trials of the pre-NF block was used as a baseline and compared with the average of the first 5 trial of the FF block. Regression coefficients were calculated to evaluate the adaptive change in the FF block. The results showed that (1) movement time evidently increased (about 300 ms) at the early FF phase from the baseline. It slightly decreased as the trials proceed while was still longer than the baseline; (2) MGA, MGA timing (% of the movement time), and plateau duration (% of the movement time), which is the relative length of the period where the aperture is larger than 90 % of MGA, did not change at the early FF phase. However, they gradually decreased, postponed, or lengthened as the trials proceeded, respectively. These findings indicate that the controls of reach and grasp movements were well coordinated regardless of the large increase of reach effort and movement time due to the applied external force against the reach. In addition, the results suggest that adaptive changes occurred in the FF block, although it is still unclear whether the changes were attributed to the applied force.

3-F-58 Auditory and somatosensory memory and speech motor learning

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Motor learning requires that one maintains sensory information about prior movements. In the case of speech motor learning, improvements in performance are likely reliant on both auditory and somatosensory memory, however their contributions to learning are presently unknown. To evaluate their role, we examined whether sensory memory performance explains differences between subjects in speech motor learning. We hypothesized that individual differences in auditory and somatosensory memory can predict speech motor adaptation. We carried out a speech motor adaptation task and somatosensory and auditory memory tasks using a within-subject design. We examined whether there was a correlation in performance between adaptation and memory tasks. As the stimulus utterances, we focused on a vowel /ɛ/ since this vowel can be changed acoustically to the vowels /e/ or /a/ simply by manipulating the first formant frequency, and those acoustical change can be related to vertical movement of speaking. For the speech motor learning task, we used an experimental model of speech adaptation that involved altered auditory feedback. In this procedure the first formant of the produced speech sound was altered in real-time and the altered sound was played back to speakers through headphones. The speech task was to produce the syllable /tɛ/ which was altered so as to sound like /te/. Participants were expected to change their produced syllable towards the vowel /ta/ so as to maintain the feedback sound as /tɛ/. In the auditory memory test, discriminable variants of the vowel /e/ were tested. In the somatosensory memory test, the orofacial skin was gently stretched in vertical direction.

Somatosensory and auditory memory capacity were tested in separate sessions, but using the same experimental procedure, in which participants were required to identify whether a test stimulus had been presented earlier in a memory set of stimulations. As shown in previous work, we found that the magnitude of speech motor adaptation varied across the participants. Differences in adaptation were correlated with individual differences in somatosensory memory performance, but not auditory memory performance. The results suggest that even though speech is largely auditory in nature, adaptation itself may be more reliant on somatosensory inputs and memory processing.

3-F-59 Motor control and adaptation in a novel redundant motor task manipulating a tool with both hands

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The motor system controls a redundant musculoskeletal system to achieve a motor task. A unique solution is likely to be obtained by an optimization process. However, it remains elusive how the motor system sticks to use this solution when correcting errors. The ordinary planar arm reaching task is not useful to deal with these problems because there is no redundancy between the task goal (the hand position (2D)) and the controlled variables (shoulder and elbow joints (2D)). Here, we develop a stick manipulating task to investigate the redundancy problem: the subject manipulated a stick with both hands to reach the stick's tip to visual targets. In this task, the dimension of controlled variables is 3 (right (or left) hand position (2D) + stick's angle (1D)), which can naturally create a redundant condition. Subjects moved the stick's right tip (a cursor) from a starting position to a target (stick length = 40 cm, the movement distance = 10 cm) that appeared in one of nine directions (40, 30, ..., -40 deg; 0 deg means horizontal direction) (baseline phase; 360 trials). The left hand controlled the left end of the stick and the distance between hands was always constrained to 15 cm. During subsequent 240 trials (adaptation phase), the target appeared in only a 0-deg direction, and rotational perturbations were introduced to the cursor and/or the stick's angle. The subjects learned to move the cursor while tilting the stick, contributing to minimizing the motor effort. Using the baseline phase data, we identified the inherent relationship between the stick's tip movement direction and the stick's tilting angle (T-A map). To examine how the stick tip direction and tilting angle changed during visuomotor adaptation with reference to the T-A map, the subjects performed the visual rotation task where the movement direction of the cursor was gradually (1 deg/trial) (Exp. 1, N = 20) or suddenly (Exp. 2, N = 14) rotated by 30-deg relative to the actual movement. Their movement patterns finally converged onto the T-A map learned in the baseline phase, but the convergence process varied across subjects, and some subjects showed new movement patterns that deviated from the T-A map. Next, Exp. 3 was performed to test whether task-irrelevant errors are corrected when imposing the stick's angle rotation around the cursor (N = 8). Interestingly, although this perturbation did not produce any task goal error, the subjects corrected the stick's angle, and rather this correction often induced the cursor error. Does this correction in task-irrelevant dimension assist or interfere with the cursor's visuomotor adaptation? In Exp. 4, both the cursor and the stick rotation were simultaneously introduced (N = 8). Counterintuitively, the perturbation of the stick rotation neither accelerated nor decelerated the adaptation. These results indicate a complex interaction between the task-relevant and task-irrelevant error while learning the redundant goal-directed movement.

3-F-60 The effect of time: Overcoming residual errors in visuomotor adaptation

Presenting Author: Lisa Langsdorf

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One famous law-like description of human behavior is the speed-accuracy tradeoff. This inverse relation between the accuracy of an action and the time taken to produce it has been shown to shape behavior across multiple domains, especially in motor control and decision-making. In the present study, we sought to investigate whether the phenomenon of an incomplete asymptote of adaptation in typical visuomotor adaptation paradigms might be a consequence of this speed-accuracy tradeoff. Based on studies from decision-making, we hypothesized that when tasked with adapting their reach direction +45° to counteract a -45° rotation of their visual feedback, participants try to balance the urge to complete a trial as fast as possible while at the same time manage to complete a "good enough" performance. The most common explanation for the resulting underperformance pertains to computations in an implicit, low-level system balancing error-based adaptation and trial-to-trial forgetting. However, this view has been challenged by findings that participants are capable to overcome their residual errors if the error distribution at asymptote is manipulated, giving rise to an alteration of the individual's learning policy (1). Sensorimotor learning is driven by an implicit learning mechanism and a qualitatively distinct explicit learning component (2,3). This explicit component reflects volitional compensatory strategies based on explicit knowledge of the respective visuomotor transformation. One way in which such explicit strategies might be implemented in rotation adaption is by a parametric mental rotation of an individual's aiming direction. Under the assumption that it is in fact due to hasty motor planning and therefore prematurely interrupting the mental rotation processes, that cause the incomplete asymptote, we tried shifting this balance through artificially prolonging response time, intending to abolish, or at least attenuate consistent undercompensation. Across three experiments, we find evidence supporting this hypothesis: An obligatory waiting period before movement initiation resulted in complete compensation. This effect was specific to prolonging response time, since adding delay after movement termination to match intertrial interval length did not affect the asymptote. Furthermore, emphasizing explicit re-aiming strategies and concomitantly increasing response time also led to complete adaptation. Those findings suggest that incomplete adaptation is, in part, the result of an intrinsic speed-accuracy tradeoff, perhaps reflecting effortful cognitive control operations that require attentional re-orienting from the visual target to the goal. 1 Vaswani, P. A., et al., (2015). J. Neurosci. 2 Hegele, M., & Heuer, H. (2010). Conscious. Cogn. 3 Taylor, J. A., Krakauer, J. W., & Ivry, R. B. (2014). J. Neurosci.

3-F-61 Proportional myoelectric control: Can we adapt to overcome limitations of cheap sensors?

Presenting Author: Julia Manczurowsky

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Proportional myoelectric control is a control option for human-machine interfaces, such as prosthetics and exoskeletons used in rehabilitation to restore motor function. This approach is non-invasive and effective for users who are limited in their movement capability. However, learning proportional myoelectric control can be more challenging than other control methods, such as force or torque

control. A widely cited reason is the relative noisiness of electromyographic (EMG) measurements. However, recent work questions this conjecture, showing that the variability of EMG is not necessarily a limiting factor in myoelectric control (Johnson et al., IEEE Trans Neural Syst Rehabil Eng, 2017), and individuals can adapt to an artificial increase in myoelectric noise to regain baseline performance levels (Hasson et al., Front Hum Neurosci, 2016). Together, these results suggest that with adequate user training, low-quality EMG systems, which tend to be relatively noisy, could be used without a performance penalty. This study tests the hypothesis that individuals controlling a virtual arm with a low-quality (LQ = more noisy) EMG system can adapt and achieve a performance level similar to when they use a high-quality (HQ = less noisy) EMG system. In the experiment, participants practiced a goal-directed task with an EMG-driven upper-limb musculoskeletal model programmed in Simulink (Mathworks) using LQ and HQ EMG systems. For LQ EMG, consumer-grade hardware was used (MyoWare). The LQ EMG sensors had pre-gelled disposable snap-electrodes and on-board signal conditioners that output analog EMG linear envelopes (LEs) that were digitized by a 10-bit analog-to-digital converter (Arduino). For HQ EMG, a research-grade, wired EMG system was used (Delsys Bagnoli). The HQ EMG system used silver bar electrodes with pre-amplifiers that output a raw (band-pass filtered) signal, and a separate signal conditioner used leaky integrators to produce analog LEs that were digitized with a 16-bit converter (National Instruments). Electrodes were placed on the biceps and triceps brachii, and the LEs served as inputs to lumped Hill-type flexor and extensor muscle models, which produced forces to actuate and move the virtual arm. In the task, subjects had to move the virtual arm to a small target position 40 degrees of flexion away in minimum time (demanding speed and accuracy). The protocol consisted of five blocks of 40 trials with the LQ and HQ conditions (10 blocks total) with block order randomized. Data collection is ongoing. If the hypothesis is supported, it would suggest that the human nervous system can learn to compensate for noisy sensors in myoelectric control. On the other hand, an inability to adapt would suggest that other aids such as augmented feedback may be required with low-quality EMG hardware to promote performance. Information related to either outcome would be useful for users of prosthetics and exoskeletons.

3-F-63 Consolidation of motor memories after training with increased motor variability depends on congruence between imposed variability and pre-existing coordination strategy

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Motor memories undergo a period of consolidation before they become resistant to the practice of another task. However, the role of motor variability in consolidation is not well understood. Specifically, when the task has redundancy, motor variability can be introduced along different dimensions - in a 'task space' that affects task performance, or in a 'null space' that does not affect task performance. Here, we used haptic perturbations to introduce variability in these different dimensions and examined their effect on motor memory consolidation. The task used was a bimanual shuffleboard task, where participants held a bimanual manipulandum (KINARM) and made a discrete throwing motion to slide a virtual puck towards a target. The task was redundant in that the distance traveled by the puck was determined only by the sum of the left and right hand speeds at the time of release (with a perfect score achieved at VR+VL = 1.5 m/s). We used an A-B-A paradigm to examine motor memory consolidation. During the first 400 trials of practice, all participants learned the same task with no haptic perturbations. Subsequently, depending on group assignment, we used haptic perturbations to introduce motor variability in different dimensions (task space/null space), and in different amounts (low/high). In the task space variability groups, perturbations were introduced along the task space (i.e. on any given trial, both hands were either sped up or slowed down simultaneously), whereas in the null space variability groups, perturbations were introduced along the null space (i.e. one hand was sped up while the other was slowed down). The magnitude of variability in each dimension was controlled by the change in magnitude of the viscosity. Participants performed this modified task for 400 trials and then returned 24 hours later to perform the original task without haptic perturbations for 400 trials. We found that regardless of the amplitude of variability, increasing variability in the task space resulted in significantly better consolidation compared to variability in the null space. Further analysis showed that the benefit of task space variability on consolidation was due to the fact that it was congruent with the pre-existing coordination strategy used in the task, in which the variability was preferentially distributed along the task space. These results show that the effects of variability on motor memory consolidation depend on the interplay between the imposed variability and the pre-existing coordination strategy, and highlight the need to consider coordination as a critical element in motor memory consolidation of tasks with redundancy.

3-F-64 Neuromechanical adaptation of the lower body to simulated hypogravity

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INTRODUCTION: When falling from a drop or jump, people and other animals preactivate their leg muscles in preparation for landing. This preactivation occurs prior to ground contact, indicating that it relies on a prediction of the time and force of landing. People are skilled at such predictions, as they readily alter preactivation characteristics to accommodate different jump heights and vertical accelerations. The ability to accurately predict the time and force of landing indicates an implicit understanding of the physics affecting the jump, including the acceleration due to gravity. We aimed to affect these gravity-based predictions by exposing participants to simulated hypogravity in a targeted jumping task. We hypothesized exposure to hypogravity would result in predictable after-effects, including a reduced preactivation time and lower preactivation magnitude, reflecting an expectation of lower gravity. METHODS: Ten participants (6 female; Age: 21.8 ± 4.0 yrs; Height: 1.74 ± 0.11 m; Weight: 615 ± 98 N) gave informed consent prior to participating in this Georgia Tech IRB approved study. They each performed targeted countermovement jumps before (Pre), during, and after (Post) exposure to simulated hypogravity. A 0.5G environment was simulated using constant force springs mounted above the participant and attached at their hips. Muscle activity (Vastus Lateralis (VL), Lateral (LG) and Medial (MG) Gastrocnemius, and Soleus (SOL)), kinetics, and kinematics were collected on both legs for each jump. Preactivation timing was calculated as the time prior to landing when build-up of muscle activity began. Preactivation magnitude was calculated as the integrated electromyographic activity between preactivation onset and contact with the ground. RESULTS: Following hypogravity exposure, preactivation onset timing was reduced (compared to Pre) in 6 of 8 muscles by about 18-58%. This reduction suggests the expectation of a longer airtime due to hypogravity. Preactivation magnitude was significantly reduced by about half (31 - 55%) in 7 of 8 muscles. A 50% reduction is reasonable as the hypogravity exposure was targeted at reducing participants' body weight by half. This reduction in preactivation magnitude likely represents the expectation of a lower muscle load during landing. DISCUSSION: Taken together, our results indicate that people adapt pre-landing muscle activity to match the requirements of hypogravity exposure and that this adaptation persists following a return to typical gravity. Thus, it appears that motor control strategies that rely on a prediction of the effects of gravity can update this prediction based on motor experience with a novel gravity level. The paradigm developed here will facilitate further investigation on how the neuromuscular system predicts the effects of gravity and how such predictions are used to control movement.

3-F-65 The effect of time-dependent force perturbations on the learning of a surgical pattern-cutting task

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In robot-assisted minimally invasive surgery (RAMIS) surgeons use robotic manipulators to control the movements of instruments, which are inserted into patients' bodies via small incisions. RAMIS offers many advantages over open surgery but to reap the benefits of RAMIS, surgeons must be well trained to use the robotic systems. Currently, there are no training guidelines for RAMIS. Motor learning theories are important sources of knowledge for developing RAMIS training guidelines, but there is a gap between the current knowledge, which is based on simple movements, and the knowledge needed to train RAMIS surgeons, who perform complex motor tasks. To fill this gap, we investigated the effect of time-dependent perturbations on the learning of a surgical task. In our experiment, the participants completed a pattern-cutting task using the da Vinci Research Kit (dVRK). In this task, the participants used curved scissors to cut a circle drawn on a gauze while they were exposed to force perturbations that alternatingly pushed their hands inwards and outwards in the radial direction. We chose a time-dependent perturbation because surgeons encounter various time-dependent perturbations, such as the periodic movement of the heart. To develop RAMIS training protocols, we need to understand whether and how surgeons learn to deal with such perturbations, and their effects on performances. Our task has a clear desired path, and the perturbations increase the error between the desired and the actual movement. We hypothesized that the motor system would adjust motor commands and reduce error with training. If surgeons do succeed in improving performances during exposure to the perturbations, it is interesting to understand the learning mechanisms behind the improvement, and it is important to test whether this learning impairs their ability to cope with other conditions (such as an environment without perturbations). Thirty participants took part in the experiment: (1) a control group that trained without perturbations, and (2) a 1Hz group that trained with 1Hz periodic force perturbations. We monitored their learning using metrics that quantified task performance, and metrics that allowed us to follow different approaches of the participants. We found that participants in the 1Hz group learned how to cope with the perturbations and improved their performances during training but did not adapt to the perturbations - we did not observe aftereffects of adaptation. When the perturbations were removed, both groups reached a similar performance level, indicating that learning how to deal with the perturbations was not at the expense of learning how to perform the task better. Our results lead the way toward developing training protocols that will incorporate time-dependent perturbations, which could improve the way surgeons acquire RAMIS skills. Additionally, this study is an important behavioral step toward understanding motor learning in real life tasks.

3-F-66 Difference in event-related desynchronization between bimanual motor imagery and unimanual motor imagery

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Bimanual movements have been reported to be effective for rehabilitation of stroke patients. However, few studies have examined the effects of bimanual motor imagery on brain activity and motor learning. This study investigated how the motor imagery of bimanual movement differs from that of unimanual movement in the effects on brain activity by using ERD (Event-related desynchronization) recorded from motor-related areas. When one mentally simulates a physical action, called motor imagery, ERD decrease of α wave appears in the motor-related areas. The size of the ERD is thought to reflect the quality of the motor imagery. Right-handed healthy students participated in the experiment. Participants mentally simulated the action of rotating two balls (45 mm in diameter) on their palm without physical movements (ball rotation imagery task). In the task, they alternately performed the imagery of rotating the two balls unimanually (left and right hands) or bimanually. One trial consisted of a rest period (Period of prohibition of physical activity) of 6 seconds, a preparation period of 2 seconds, an imagery period of 7 seconds, and a break period (Period to relax) of 5 seconds (20 seconds in total). Participants watched visual cues displayed on the computer screen during the task. The experiment consisted of 4 blocks, and 1 block consisted of 5 trials each of right hand imagery, left hand imagery, and bimanual imagery. The 2-minute break was inserted between blocks. OpenBCI was used for the measurement of EEG. Ultracortex Mark IV, the headset of the system, was made by a 3D printer. Additional purpose of this study was to verify whether stable ERD can be measured using an low-cost EEG measurement system. Eight channels of EEG data were recorded with the OpenBCI system. The locations of the electrodes were Fp1, Fp2, FC1, FC2, C3, C4, O1, and O2 according to the 10-10 international system. The reference and ground were placed at A1 and A2, respectively. EEG data were sampled at 250 Hz and pre-processed with the 1 Hz-40 Hz FIR band pass filter and notch filter (60 Hz) to remove the noise and offset. ERD was calculated by subtracting the amplitude of the α wave band (8 Hz to 13 Hz) averaged for 6 seconds in the rest period from that averaged for 7 seconds in the imagery period. The right-hand imagery showed the largest ERD among the three imagery conditions, and large ERD was recorded not only in C3 but also in C4 in the condition. The left-hand imagery showed a smaller ERD than the right-hand imagery. In the bimanual motor imagery condition, the ERD was small in the earlier blocks, but the ERD on both sides of C3 and C4 was big in the late blocks. This finding revealed that motor imagery of dominant hand affected left and right hemispheres of cerebrum compared to motor imagery of non-dominant hand and bimanual. This suggests that bimanual motor imagery may be more difficult than unimanual motor imagery.

3-F-67 Integration of artificial motor feedback 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 internal model that optimally combines vestibular and visual signals with sensory predictions based on motor efference copies (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 yield an indirect motor signal that the brain integrates in self-motion estimation. 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 control 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 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 is able to integrate the sensory consequences of an indirect motor signal and sensory feedback to accurately estimate self-motion.

3-F-68 Auditory feedback variability in speech is actively regulated but does not affect subsequent auditory-motor learning

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Inter-trial variability in human motor performance is ubiquitous. However, it is still unclear how variability is regulated and whether it influences motor learning. Studies in limb motor control have shown that motor variability is regulated when variability in the visual feedback is artificially manipulated (van Beers, 2009; Wong et al., 2009), but the effect of variability on motor learning remains controversial. On the one hand, it has been suggested that variability facilitates both reward-based and error-based motor learning through mechanisms of action exploration (Wu et al. 2014). On the other hand, subsequent studies have challenged this view and shown that artificially introduced variability reduced learning in a visuomotor rotation task (Therrien et al., 2018). Here, we start exploring these questions in the context of sensorimotor control for speech. We present results from a study where we experimentally reduced or magnified variability in the auditory feedback signal and examined how these manipulations affected speech production and speech motor learning in a subsequent auditory-motor adaptation task. Twenty-eight subjects first participated in a pretest during which they produced the three target words "tech," "tuck," and "talk" with unaltered auditory feedback. The subject's median formant frequencies (F1 and F2) for each target word were calculated. Subsequently, subjects completed two conditions of a Variability-Adaptation task, which was composed of a Variability task followed immediately by an auditory-motor Adaptation task. The Variability task included three conditions: control, reduced and magnified. Auditory feedback was unaltered in the control condition. In the reduced condition, variability in the auditory feedback was decreased by fixing the F1 and F2 in the feedback to the pretest median frequencies. In the magnified condition variability was exaggerated by increasing to 250% the difference between the formant values produced and the median formants of the same target word. All subjects underwent the control condition. Half of the subjects received the reduced condition as their experimental condition, while the other half received the magnified condition. In the Adaptation task, all subjects heard altered feedback of their current production with both F1 and F2 shifted up by 250 cents. Subjects in the reduced condition of the Variability task showed gradually increasing motor variability in their produced speech, whereas no decrease in variability was observed in the magnified condition. Importantly, auditory-motor adaptation was not affected by either variability manipulation. Overall, results suggest that motor variability in speech is actively maintained based on auditory feedback, but that speech motor learning is robust to short-term changes in sensory variability.

3-F-69 Unconscious bias on the explicit component of human motor learning

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The present study aimed to reveal unconscious aspects of the explicit component in visuomotor adaptation by investigating two groups with possibly different ways of thinking or behavior. While previous psychological research suggested the strong influence of cultural background on human mindset and behavior, the effect of the unconscious bias has not been addressed in the field of human motor learning. In other words, the universality of motor learning regardless of cultures, at least in its mechanism, has been tacitly assumed. We tackled this topic using a visuomotor adaptation paradigm, which has been extensively used in the motor learning literature. We investigated explicit and implicit components of motor learning based on the paradigm proposed by Taylor et al. (2014), where participants' verbal reports are used to estimate the explicit component. Twenty-four Norwegian and twenty-four Japanese participated in a center-out reaching task with 45˚visuomotor rotation. The task was composed of two baseline blocks, an adaptation block, a catch block (with no visual feedback), and a washout block (with visual feedback). The participants verbally reported aiming direction before they start reaching in the adaptation block. To assess the time course of visuomotor adaptation, we calculated directional error, hit rate, and movement time. We estimated the explicit component as the aiming angle and calculated the implicit component by subtracting the aiming angle from the reach angle. In addition, the aftereffects and the residual aftereffects, which is defined as the difference in the error between the baseline and averages of the last 8 trials of the catch or washout blocks, were calculated. The residual aftereffects were assumed to indicate how strongly the forward model for the visuomotor rotation remains. In both Japanese and Norwegian groups, the angle error and the movement time significantly decreased at the early period of the adaptation block compared to the late period, and the hit rate increased in the late period. These results showed that the apparent performance was similarly improved in both groups. Interestingly, while the reported aiming angle was significantly larger in the Japanese group than in the Norwegian group throughout the adaptation block, there was no significant difference in the aftereffects and the residual aftereffects between two groups. These results suggest that even though the overall amount of adaptation is not different between the Norwegian and Japanese participants, the ratio of the explicit component to the implicit component would differ because of the effect of unconscious bias such as cultural differences in explicit strategies. Furthermore, the present study suggests that implicit components calculated based on participants' verbal report and the behavioral index describe implicit learning from different perspectives.

G – Theoretical & Computational Motor Control

3-G-70 Improved estimation of trial-by-trial adaptation rate using stochastic signal processing

Presenting Author: Dan Blustein

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The measurement of motor adaptation has been a topic of interest within the field of movement neuroscience over the past two decades. Elegant experiments have provided detailed insight into the temporal dynamics of learning, the role of memory in learning, and how noise from different sources affects motor outputs. Often these laboratory-based studies require interventions such as perturbations, error clamps, or set breaks. Here we focus on trial-by-trial adaptation, which can be measured without manipulations using movement data from the steady-state condition after parameter-based adaptation has stabilized, i.e., when mean error is near zero. This experimental paradigm allows for the assessment of naturalistic movement data without laboratory interventions. Motor noise biases the traditional regression-based analysis of trial-by-trial adaptation, particularly because it masks the motor intent on a subsequent trial. Researchers have identified this as an issue and proposed a Yule-Walker-based solution that appears to work on simulated data [1]. Here we present an alternative method that uses stochastic signal processing to statistically filter out the noise effects from the estimation of trial-by-trial adaptation. We confirm that traditional adaptation rate estimates are biased. With increasing control noise, conventionally calculated adaptation estimates counterintuitively increase. We would expect the opposite: reduced adaptation in a noisier system. We demonstrate this bias using simulated data generated by a hierarchical Kalman filter model and empirical data collected using a simple computer-based cursor movement task with mouse control. In simulated data, the novel analytical solution we propose closely matches the true adaptation rate, i.e., the ratio between the change in motor command and the perceived error. Using empirical data, the true adaptation rate is inaccessible, so we use a paradigm in which measurable trial-by-trial control noise is added, such that we can calculate a "silver-standard" to validate our approach. The silver standard also uses the change in measured error rather than perceived error. This silver standard closely approximates the true adaptation rate in simulation and serves as a measurable empirical baseline for comparison. Our analytical solution closely matches the results of the silver standard across a range of conditions and does not require knowledge of the noise added on each trial. Our findings point to an important new method that can be used to analyze unperturbed and unconstrained movements. Compared to the previously described Yule-Walker approach [1], we find our approach produces less variable results (SD = 0.075, from 0.12) and requires fewer trials to minimize estimation bias (<200 trials, from 400). The versatility of the method will allow for movement analysis in a wide range of contexts beyond the laboratory. [1]Ahn, Zhang, & Sternad. (2016). PLoS ONE. doi:10.1371/journal.pone.0158466

3-G-71 A mesoscopic characterization of sequential movement-related states in premotor and motor cortices: A machine learning approach

Presenting Author: Michael DePass

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Movements have been decoded from spikes and local field potentials (LFPs) recorded from primate motor cortex during movement planning and execution. However, little is known about mesoscopic signals, such as LFPs, regarding their potential to provide network-like spatial characterizations of neural dynamics during sequential movement planning and execution tasks. Specifically, it remains to be seen whether the aggregate nature of LFPs makes them suitable for constructing informative characterizations of recorded areas with respect to their spatial and spectral distributions during neural states associated with activity related to movement preparation and execution. To investigate this, we analysed LFPs obtained from microelectrode arrays implanted in the pre-motor and motor cortical areas on both hemispheres, and recorded during specific phases of a reach and grasp task by a non-human primate. For each trial, the reach and grasp action was divided in five sequential motor states. The first two representing motor preparation, the next two execution, and the final representing reward retrieval (0.25s samples were extracted for each state). The orientation of the grasped handle was also varied from trial to trial (0º or 135º). A computational framework involving multinomial logistic regression (MLR) was then developed to analyse the LFP-ensemble recordings and produce network-like characterizations of each motor state based on either electrode power or functional connectivity for eight frequency bands ranging from 4-500Hz. We then identified the most relevant features of each neuro-motor state via recursive feature elimination (RFE). Our work produced two main results: first, that electrode power in the multi-unit frequency band (200-500Hz) yielded the highest discrimination accuracy (0.87) across the five movement-related states, and that pair-wise correlation significantly degraded the classification (0.51; over a chance level 0.2). Second, accuracy decreased with frequency band. Finally, our results also show that high-frequency LFP activity and functional connectivity may be used to classify not only movement related states, but also arm orientation during performance. Furthermore, we produced discriminative support networks to characterize our movement related neural states, highlighting differential neuronal population activity at above-gamma frequencies. The discriminative support networks exhibited minimal overlap between neuro-motor states as well as a high degree of heterogeneity on small spatial scales. These findings suggest that novel machine learning techniques may be used with LFP-ensemble data features to accurately classify and characterize complex movement-related neural states. Furthermore, they suggest a significant contribution of above-gamma frequencies, encoding these states.

3-G-72 The time course of neural population activity is constrained

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Behavior unfolds over time, as does the neural activity that governs movement. It is unclear if the consistent time courses of neural trajectories observed during overt movements are due to constraints imposed by the underlying neural circuitry, or if they are simply related to controlling the limbs through time. If the time course of activity is constrained by neural circuitry, we would expect the constraints to be present even in the absence of overt movement, and to be robust to pressure to change. Here, we leveraged a brain-computer interface (BCI) to probe the ability of Rhesus monkeys to volitionally alter the time course of their neural population activity in primary motor cortex (M1) without making arm

movements. Animals performed BCI tasks in which their recorded neural activity was used to control the position of a computer cursor. One benefit of using a BCI is that we can provide the animal with feedback of their neural activity in different 2D projections. We first identified a 2D projection of neural population activity designed to yield proficient control. Using this "intuitive" BCI mapping, animals moved a cursor repeatedly between a pair of onscreen targets (A and B). We observed that while the cursor trajectories were largely overlapping between the two conditions (A->B and B->A), the underlying neural trajectories were non-overlapping in the 10D neural activity space. This shows that there are distinct A->B and B->A time courses of the neural trajectories in the absence of arm movements. Next, we wanted to test if the monkeys could produce the time-reversed sequence of these neural trajectories. We identified a "rotated" BCI mapping: a 2D projection of neural activity where the trajectories were maximally non-overlapping. Using this rotated mapping, we encouraged the animals to generate time-reversed sequences of the observed cursor trajectories by imposing a path boundary through which animals were required to move the cursor to hit an onscreen target. Specifically, we defined a boundary along one condition's cursor trajectory (e.g., A->B) and then asked animals to move along this path starting from the other target location (e.g., move from B->A along the A->B path). To further challenge the animals to modify their activity, we gradually decreased the boundary's diameter over the course of each experiment. We found that animals were largely unable to modify the time course of their neural population activity, despite incentives to do so. Our findings suggest that the underlying network imposes strong constraints on the time course of population activity in M1. This supports the view that neural trajectories extracted from population activity during motor control reflect underlying network mechanisms.

3-G-73 Learning to simultaneously control multiple end-effectors by isometric force and electromyographic activity in the muscle-to-force null space

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Electromyographic (EMG) signals allow the study of motor learning by altering the mapping between the muscle activity and the force generated by a virtual end-effector. For example, overcoming a virtual remapping of the pulling directions of shoulder and elbow muscles that makes existing muscle synergies incapable of generating forces at the hand in all directions (incompatible virtual surgeries) requires learning new muscle patterns that do not generate force, i.e., spanning the redundant muscle-to-force null space. However, it is not clear whether the control of null space can be learned with practice. If so, voluntary modulation of EMG activities in the null space could be used simultaneously with force generation to control multiple effectors. To test the feasibility of this approach, we investigated the concurrent control of the displacement of a virtual end-effector by isometric force and its rotation by null space control. In a virtual environment, 8 participants were instructed to reach 8 ellipsoidal targets arranged on a planar circle with a cursor of the same shape and to maintain it inside them for 1 s. The cursor was displaced from a central rest position proportionally to the isometric force applied to a force transducer through a hand-forearm orthosis. Simultaneously, participants were instructed to rotate the cursor around one axis of the ellipsoid to match the orientation of the target by controlling, in real-time, the projection of the vector of EMG signals recorded from 15 shoulder and arm muscles onto the null space of a linear muscle-to-force mapping. We compared different null space projections as control signals for the rotation and we selected the projection onto the principal components that explain 80%

of EMG data variation during voluntary stiffening of the shoulder and elbow in an initial calibration block. Participants then performed 12 blocks of the reaching task with cursor rotation. On average participants were able to reach the target and match its orientation already in the first block in 72 ± 26 % of the trials, and the performance improved in the last block to 93 ± 11 %. However, holding performance was much lower, never exceeding a success rate of 43 ± 31 %. A generalized linear mixed effect model analysis showed that both reaching and holding performance significantly improved with practice ($p < 0.001$). Remarkably, we observed large differences in the individual performances and different individual strategies in the temporal coordination of cursor displacement and rotation. These results indicate that simultaneous control of isometric force and EMG activity in the null space is feasible and it could be used to control multiple end-effectors, with potential applications to augmentation of human motor capabilities. However, parameters of the control interface affecting performance and learning, e.g. the size of targets, should be customized according to individual null space control capabilities.

3-G-74 Cognitive control of motor synergies

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In difficult movement tasks, such as retrieving an object from a cluttered environment, humans are inventive problem solvers, but at the other end of the movement spectrum in most everyday repetitive movements such as walking, sitting, and reaching, humans exhibit large degrees of regularity. In the quest to understand the human movement system, it would be essential to know if general movements have regularities across subjects as it would provide an essential scaffold in the development of more detailed dynamic movement models. A Bayesian perspective argues that this repeatability arises because such movements are committed to memory with precedence based on the probability of use. Related studies show that the kinematics of a movement is directly related to its dynamics, thus raising the possibility that regularities in the energetic cost of a movement may be indicative of regularities in the kinematics. This project aims to learn the principles behind large-scale arbitrary movements, particularly regarding variations between different subjects. Given a goal-directed task, do the movements appear similar across subjects, or are movements very individualized? To solve this problem, a full-body virtual-reality tracing task was developed to elicit a series of human movement sequences. At each trial, subjects were given no instructions on how to comport themselves during the tracing process. Specialized aggregation methods were provided for data analysis that extracted similarities of posture sequences in the face of kinematic variations. The exciting and unsuspected result was that both the movement's posture sequences and kinematic variations showed striking commonalities across subjects. This regularity of movements across different subjects implies there must be some general principles for humans generating motions. A generally accepted view is that humans' self-selected trajectories should be economical in energetic cost. To test this hypothesis, a forty-eight degrees of freedom dynamic computational model capable of simulating, analyzing, and synthesizing humanoid movements was created. One creative idea is that the joint connections are not treated as perfectly rigid constraints but rather as very stiff springs that hold body parts together like tendons and muscles. The model allows computing instantaneous power from the product of net joint torque and joint angular velocity. The work performed at each joint was determined by numerically integrating the instantaneous powers over the entire tracing task. In this way, the energy cost of human motions can be computed given motion capture data. Finally, the cost of original virtual tracing movements and perturbed movements were computed and compared using the human dynamic model. The energetic cost always exhibits a U-shape while tracing using different postures sequences, with the minimum of the U-shape curve consistent with the original posture traces, which our subjects self-selected.

3-G-75 Complex transformation from feedback response to feedforward motor command

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When the motor system encounters an error during a reaching movement, it corrects the movement within a trial (online correction by feedback response) and in the next trial (offline correction by motor learning). Consistent with the feedback error learning hypothesis (Kawato et al., 1987), a recent study has shown that the motor command for the online correction serves as a teaching signal for the offline correction (Albert & Shadmehr, 2016). However, there remain several unsolved issues. First, the kinematics of online corrections varied with the perturbation pattern, but those of offline corrections lost the specificity (Fine & Thoroughman 2008). Second, even when only the endpoint error was presented (i.e., online correction is absent), the offline correction existed (Wei & Kording, 2009). Here, we reinvestigated the link between both corrections using the force channel method combined with the visual cursor shift (Dimitriou et al., 2013). This method is ideal because the temporal pattern of perturbation (onset, duration, offset) can be precisely manipulated, and the motor commands for both corrections can be directly compared by force against the channel. Experiment 1 elucidated how the temporal pattern of online correction was translated to that of offline correction. Participants (N=10) moved a cursor toward a front target 20cm away with their unseen hand. In the perturbation trial, the cursor was shifted laterally by /- 3cm in various movement ranges (1~17cm). In the next probe trial, the visual feedback was absent. The force channel method was used to measure both online and offline corrections. The online corrections were simply modulated with the perturbation: they started ~150ms after the perturbation onset and lasted and decayed with the duration and offset. The offline corrections were also modulated specifically with the perturbation patterns, but their temporal patterns differed from those of online corrections, suggesting the complicated mechanisms of transformation from online to offline correction. Experiment 2 elucidated the influence of the endpoint error (N=10). In the perturbation trial, the cursor was shifted by /-3cm at 1cm distance, and the cursor shift near the endpoint (at 17cm distance) was maintained, removed (/-3cm→ 0cm), or reversed (/-3cm→-/ 3cm). The online corrections were almost identical, but there was a slight modulation during the holding period between the endpoint conditions. Importantly, however, this subtle difference had a significant impact on the offline corrections. The removal of cursor shift attenuated the offline corrections, and the reversal of cursor shift almost nullified the contribution of online corrections on offline corrections. Thus, the present study demonstrated the presence of highly complex mechanism transforming the feedback response and the endpoint error information to produce the feedforward motor command.

3-G-76 Muscle spindle gamma drive and spinal reflex gain cause dissociable kinematic outcomes in neuromechanical simulations of the knee-jerk reflex

Presenting Author: Giovanni Martino

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A number of neuromuscular impairments manifest in clinical assessments as increased joint resistance to passive motion. Spasticity is described as velocity dependent hyperreflexia, a neural contributor to hyper-resistance. However, the mechanisms underlying spasticity and its consequences on movement are still unclear. Two neural mechanisms that can cause hyperreflexia are considered here: increased muscle spindle sensitivity due to increased gamma drive (γ-drive); and increased sensorimotor gain due to increased spinal reflex excitability (SR-gain). We recently developed a novel multiscale biophysical model of the muscle spindle that can simulate the effect of γ-drive and predict muscle spindle instantaneous firing rate of in vivo experimental data (Blum et al. 2020). Our objective was to test whether integrating a biophysical model of a muscle spindle with a biomechanical model of the lower limb would allow the contributions of increased γ-drive vs increased SR-gain in the knee-jerk reflex (KJR) to be dissociated. We hypothesized that increasing γ-drive vs SR-gain would generate different simulated kinematic responses of the leg to the KJR. The biophysical model of a muscle spindle was simulated to interact in a closed-loop with a single-link, torque-driven model of the lower limb with passive damping. Muscle spindle sensory signals were modeled by simulating muscle cross-bridges in intrafusal muscles and converting the resultant force and yank to simulated muscle spindle Ia sensory signals. Increasing γ-drive modulates the number of available actin binding sites, increasing the force in the intrafusal fiber and sensory signal per unit of stretch. Increasing SR-gain modulates the amount of torque produced per unit of muscle spindle sensory feedback. KJR was simulated by imposing a stretch of the tendon that elicited an initial reflex torque of 12Nm in the baseline condition, based on published data (Mamizuka et al. 2007). KJR kinematic responses were evaluated based on the amplitude of the leg's first swing excursion and the total number of oscillations. Simulations of the KJR suggest that kinematic outcomes due to increased γ-drive versus spinal reflex gain are dissociable. Either γ-drive or SR-gain could be increased to match the first swing excursion observed in spastic individuals (Mamizuka et al. 2007). However, increasing γ-drive also decreased the number of oscillations whereas increasing SR-gain did not. Although our neuromechanical simulations suggest that the number of total oscillations may reflect the extent to which hyper-reflexia is cause by increased γ-drive or SR-gain, no prior studies have reported KJR kinematics beyond the first leg oscillation. Our data suggest that mechanistic modeling of muscle spindle sensory feedback in conjunction with kinematics measures could provide a clinically feasible method to dissociate mechanisms of hyperreflexia in spasticity and other motor disorders.

3-G-77 Visual information is insufficient to interact with complex dynamic objects
Presenting Author: Rashida Nayeem

Authors: Rashida Nayeem[1], Salah Bazzi[1], Reza Sharif Razavian[1], Mohsen Sadeghi[1], Dagmar Sternad[1]
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Humans dexterously interact with a myriad of complex objects. An example is picking up a cup filled with coffee: the hand applies forces not only to the cup, but also to the sloshing liquid, which creates complex forces back on the hand. Dynamic behavior in such objects can evolve rapidly, and it is difficult to correct the unpredictable interactions in real-time given long latencies and noise in the neuromotor system. Further, when transporting a complex object from rest, the dynamics inevitably passes through a transient state, which may be even less predictable. As the complexity of this transient is dependent upon the initial conditions, a first study examined whether humans choose initial conditions to shorten transients prior to reaching a steady state. A follow-up study examined the role of haptic feedback in such interactions. Participants transported a 'cup of coffee' with a rolling ball inside a 2D-semicircular cup that represented the liquid. A model of the cup-and-ball was rendered in a virtual environment where subjects moved the object on a horizontal line via a robotic manipulandum that transmitted haptic feedback. Subjects were encouraged to explore the object dynamics to find the best initial conditions prior to starting a rhythmic movement. In our first study visual and haptic feedback about the cup-and-ball was fully provided. In the following study visual and haptic feedback were manipulated in four different conditions. In three conditions, the position of the cup was directly controlled by the subject via the robot, but the interaction forces from the ball were transmitted in different ways: 1) invisible ball: ball movements were visually occluded but its forces fed back to the subject; 2) massless ball: the ball's movement was visually displayed, however its mass was set to zero; 3) fully provided: both visual and haptic feedback about the ball were present. A fourth condition eliminated haptic feedback from the ball force to the hand, while it remained in effect on the virtual cup. Results showed that when haptic and visual information was present, subjects converged to a subset of initial conditions that shortened transients and achieved a steady state that was predictable. Simulations with a simple impedance controller and inverse dynamics calculations confirmed that the initial conditions that subjects preferred led to shorter transients and to less complex, more predictable interaction forces. This behavior continued to be observed, even if the ball was visually occluded, if haptic information was provided (condition 1). When haptic feedback was withheld (conditions 2 and 4), subjects failed to find optimal initial states and the subsequent dynamics was highly irregular and chaotic. These results support that humans can identify a mapping between initial states that simplifies subsequent dynamics. But only if provided haptic information. These results have implications for virtual interactions such as telesurgery.

3-G-78 Control of complex objects: Impedance control around an optimal reference trajectory

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For decades, point-to-point reaching in the horizontal plane has served as a testbed to gain insight into human motor control. Except when adaptation to force-fields was examined, these experiments studied free unconstrained movements. However, interactions with objects create sensorimotor challenges that go beyond simple reaching, particularly when the objects have intrinsic dynamics. This research examines physical interactions with a non-rigid object, inspired by carrying a cup of coffee. Safe control of such a complex object needs to predict, preempt, or compensate for self-generated perturbations from the liquid that act back onto the hand. Major computational frameworks that have accounted for key features in human movements are stochastic optimal feedback control (OFC), kinematic smoothness (minimum-jerk), and impedance control for physical interaction. This study tests these models for interactions with non-rigid objects and introduces a new control framework for modeling such interactions. In a virtual environment interfaced with a haptic robotic manipulandum, participants transported a cup with a ball inside on a horizontal line to a target. The ball rolling inside the circular cup represented the sloshing liquid in the cup and was simulated as a pendulum suspended from a cart in the virtual environment. For comparison, the ball was also fixed inside the cup, rendering a solid object; as the object only added mass to the movements, this condition was equivalent to free reaching. Subjects performed 100 trials in each condition in block 1. Block 2 was the same, but subjects encountered an additional resistive impulse-like perturbation mid-way to enhance the challenge. As expected, moving the rigid object exhibited a smooth bell-shaped velocity profile. However, when moving the cup with the moving ball, the cup trajectory significantly deviated from the bell-shaped velocity profile due to the internal dynamics of the ball. Further, the perturbation significantly disrupted the cup and ball trajectory exhibiting characteristic deviations. To account for the observed behavior, we constructed models with three different modeling components: minimum-jerk cup trajectories, OFC, and arm impedance (stiffness/damping). All models could replicate human behavior in the rigid object condition. In the non-rigid object condition, minimum-jerk trajectories, with or without arm impedance, could not realistically replicate data. OFC without arm impedance predicted a two-peak cup velocity profile for the non-rigid object that deviated from the data; its response to perturbation was also stiffer than participants' response. Only an OFC that included arm impedance could reproduce data in all test conditions. In this new model, OFC flexibly produced the reference trajectory for arm impedance in place of a preplanned profile. These results demonstrated that both the object and the arm dynamics should be included in OFC to replicate key behavioral features.

3-G-79 Natural statistics of gravitational and inertial head acceleration in humans: implications for modeling spatial orientation

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In daily life, the nervous system must estimate the organism's state from sensory and motor information that is often incomplete, indirect, noisy, or otherwise imperfect. In the specific case of estimating spatial orientation, the otoliths of the vestibular system are stimulated by the sum of linear acceleration due to both self-motion and gravity, and the nervous system must decompose this signal into gravitational and inertial components. Multiple approaches have been proposed to model this process including frequency segregation, Bayesian estimation, observer models, and others. Most of these approaches incorporate parameters that represent prior knowledge about the statistics of head orientation and motion, but empirical measurement of these statistics during natural behaviors outside the laboratory has been limited. Statistics of total linear acceleration and angular velocity have been measured using inertial measurement units (IMUs), but head orientation (i.e. the gravitational component of linear acceleration) is generally not reported. It is difficult to reconstruct orientation of the head relative to gravity based on IMU data without additional magnetometer measurements and sensor fusion via Kalman filtering. Even after filtering, these estimation methods can be noisy and subject to drift. Here, we present head orientation data collected using a mobile head-tracking system that implements visual-inertial simultaneous localization and mapping (VI-SLAM), a method that is robust to the error and drift that affects IMU-only systems. In this study, 8 clinically normal participants wore the Intel RealSense T265 tracking camera on the head during 5 hours of normal, everyday activity. The camera was connected to a lightweight laptop worn in a backpack. The distribution of pitch and roll angles measured across all participants and conditions was centered close to upright, but pitch showed higher variance than roll and the pitch distribution was skewed towards downward pitch. Distributions for inertial acceleration were centered near zero and showed high kurtosis. Distributions were similar for axes in the horizontal plane, but the distribution for inertial acceleration along the head-vertical axis showed much greater variance and was strongly skewed. These distributions provide empirical data to constrain parameters of Bayesian, and particle filter models. Power spectra of gravitational and inertial

components for all axes exhibit a crossing point at about 1Hz; gravitational components had greater amplitude below, and inertial components had greater amplitude above this crossing point. This crossing point provides an empirical measure to inform frequency segregation models. Implications for physiological processing of vestibular signals are also discussed.

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