The 13th KCMCW

Karniel Computational Motor Control Workshop

Ben-Gurion University of the Negev

Computational motor control is a multidisciplinary research field in which mathematics, engineering, biology, medicine and the cognitive neurosciences play important roles. This workshop brings together world leaders in the field of computational motor control, including Israeli researchers and distinguished guests. The goal is to learn about the current state of the field and to identify the challenges and research directions that will lead to scientific and medical breakthroughs in the next decades.

The workshop is named after Professor Amir Karniel who passed away on June 2nd 2014 at the age of 47. Amir, a leading researcher in the field and head of the biomedical engineering department, was a dear mentor, colleague and teacher. Amir was a man of vision and a pioneer in motor control research in Israel and internationally. He organized this workshop, together with Professor Opher Donchin, from its founding, in June, 2005, until the 10th workshop in June, 2014.

The organizers:

Dr. Lior Shmuelof – conference chair

Prof. Opher Donchin – program chair

Dr. Ilana Nisky

Avia Lavon

Liran Krisi

Program committee:

Dr. Lior Shmuelof, Ben-Gurion University of the Negev

Prof. Opher Donchin, Ben-Gurion University of the Negev

Dr. Ilana Nisky, Ben-Gurion University of the Negev

Dr. Shelly Levy-Tsedek, Ben-Gurion University of the Negev

Prof. Sandro Mussa-Ivaldi, Northwestern University

Prof. Tamar Flash, Weizmann Institute of Science

Prof. Hagai Bergman, Hebrew University

Dr. Andrey Broisman, Ministry of Science and Technology

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Ben-Gurion University of the Negev – Faculty of Health Sciences

Zlotowski Center for Neuroscience

New Biotechnology – NBT

Workshop Program

Tuesday, March 14

Lab visits- 11:00-13:00

Physiotherapy

- The laboratory for Rehabilitation and Motor Control of Walking, Simona Bar-Haim
- Cognition Aging and Rehabilitation laboratory, Shelly Levy-Tzedek
- Schwartz Movement Analysis & Rehabilitation Laboratory, Itzik Melzer

Biomedical engineering

- Biomedical Robotics Laboratory, Ilana Nisky
- Motor Learning Laboratory, Opher Donchin

Cognition

- Brain and Action Laboratory, Lior Shmuelof

Labs tour will start from Student Center (near bank Hapohalim) at 11:00

Lunch 13:00 – 14:00

Purim festivities 14:00 – 15:30

Session1 - The theory of motor control

Chair: Miriam Reiner, Technion, Israel

- 15:20 – 15:30 Opening Remarks Lior Shmuelof, BGU, Head of the organizing committee
- 15:30 – 16:00 Max Berniker, University Illinois Chicago, USA
  "“Seeing” the motor system through “blind” reaches"
- 16:00 – 16:30 Anatol Feldman, Montreal University, Canada
  "Minimization principles and motor equivalency in the control of movements"
- 16:30 – 17:00 Tamar Flash, Weizmann Institute of Science, Israel
  "Compositionality and timing of upper limb and locomotion movements"
- 17:00 – 17:10 Discussion

Evening Special Talk

- 17:10 – 18:00 reception at 58 building, room -101
- 18:00 – 19:00 – Eitan Globerson, The Jerusalem Academy of Music and Dance, Israel

  "The neuro-pianist"

Festive dinner 19:30

Wednesday, March 15

- 08:20-08:50 Registration, Poster placement and coffee
- 08:50-09:00 Greetings by Andrey Broisman, Director of Applied Science and Engineering, Israel's Ministry of Science, Technology and Space

Session 2 – Flow of motor information

Chair: Opher Donchin, Ben-Gurion University of the Negev, Israel

- 09:00-09:30 Ilana Nisky, Ben-Gurion University of the Negev, Israel
  "Living in the past – how our brain copes with delayed information?"

- 09:30-10:00 Jason Friedman, Tel-Aviv University, Israel
  "Using arm movements to inform our understanding of decision making, and vice-versa"
- 10:00-10:30 Nicholas Hatsopoulos, University of Chicago, USA
  "Spatio-temporal patterning in motor cortex required for movement initiation"
- 10:30-10:40 Discussion
- 10:40-11:20 Coffee break

Session 3 – Motor control and aging

Chair: Shelly Levy-Tzedek, Ben-Gurion University of the Negev, Israel

- 11:20-11:50 Naftali Raz, Wayne State University, USA and Max Planck Institute for Human Development, Germany
  "Longitudinal studies of cognitive consequences and correlates of the brain aging: Only Time will tell"
- 11:50-12:20 Daniela Aisenberg, Rupin Academic Center, Israel
  "The aging brain: decline and potential improvements of cognitive performance"
- 12:20-12:50 Joseph Galea, University of Birmingham, UK
  "Motivating motor learning in stroke patients and healthy older adults"
- 12:50-13:00 Discussion
- 13:00-13:30 Lunch
- 13:30-14:30 **Posters**

Session 4 – Keynote session

Chair: Eilon Vaadia, Hebrew University of Jerusalem

- Greetings Lior Shmuelof, BGU, Head of the organizing committee
- Greetings Prof. Rivka Carmi, President of Ben-Gurion University of the Negev
- 14:40-15:10 Jennifer Raymond, Stanford University, USA
  "Neural learning rules in the cerebellum"
- 15:10-15:40 Prof. Amir Karniel Memorial Young Researcher Lecture Samuel McDougle, Princeton University, USA
  "Analog computations drive strategic re-aiming of an intended movement"
- 15:40-16:10 Jeff Wickens, Okinawa Institute of Science and Technology, Japan
  "Contributions of dopamine and acetylcholine to the enigmatic motor functions of the basal ganglia"
- 16:10-16:20 Discussion
- 16:20-16:40 Coffee break and posters

Session 5 – The impaired motor system

Chair: Meir Plotnik, Sheba Medical Center, Israel

- 16:40-17:10 Tamar Makin, UCL, UK
  "Natural and artificial limb representation in amputees"
- 17:10-17:40 Vincent Cheung, The Chinese University of Hong Kong, China
  "Stroke rehabilitation through motor modules"
- 17:40-17:50 Discussion
- 17:50-18:00 Best poster awards sponsored by NBT

19:00 Dinner at "Avaz Hazahav" restaurant

Thursday, March 16

Hike in the Negev

Abstracts

Talks

Session 1 – 14.3.17

15:20-17:10

The theory of motor control

Chair: Miriam Reiner

Technion, Israel

“Seeing” the motor system through “blind” reaches

Max Berniker

Department of Mechanical and Industrial Engineering, University of Chicago, USA

The study of reaching behaviors has influenced our understanding of a broad range of fields from biomechanics to electrophysiology, and even our notions of how the nervous system encodes knowledge in general.

Despite the success and prominence of this work, the basic experimental approach may have unintentionally introduced a systematic bias. That is, while reaching movements should be informed by our limb's dynamics, varying across individuals and moving along efficient, curved arcs, experiments find that straight reaches are the norm. The conclusion seems to be that the brain's objective is to make straight movements, independent of the required effort and dynamics. Here we introduce preliminary data that challenges this conclusion. It is known that the standard experimental protocol, dominated by visual cues and feedback, influences subject behavior. Therefore we examine unperturbed reaches, and reaches made in a force field, across conditions where we systematically attenuate visual feedback. As expected, reaches made with continuous visual feedback of targets and hand location, are straight across reaches and subjects. Reaches made in a “blinded” condition, where neither the target nor hand location is visible, vary across subjects and are often arced. We suggest that the standard paradigm for examining reaching movements may mask the motor system’s inherent objectives and sense of efficiency.

Minimization principles and motor equivalency in the control of movements

Anatol G. Feldman

Neuroscience, University of Montreal; Center for Interdisciplinary Research in Rehabilitation (CRIR), Montreal, McGill University, Quebec, Canada

The understanding of minimization (optimality) principles is quite different in physics and robotics. In physics, systems obey the principle of least action: motion is produced along the trajectory associated with minimal action; $\delta \int p \, d \, q=0$. By obeying this physical laws, natural systems, including stones, move optimally without any "efforts" or "computations" based on cost functions. According to Einstein, the nature does not care much for our computations, "it solves all problems empirically". Optimality is an empirical, non-computational property of natural systems. By inversing causation of natural laws, teleology states that stones have a hidden capacity to choose and actualize an optimal trajectory to fly. We do not need to attribute the action of mind ("computation") where there is none. However, in robotics and artificial intelligence that are based on computations, mathematical inversions of causation of physical laws are possible: optimal movement trajectories can be computed according to some cost function and kinematics and kinetics can be adjusted to drive the effector along an optimal trajectory. The method relies on emulations of physical laws – internal models of the robot interacting with the environment. However, computational programs that are natural for robotics are physically and physiologically unrealistic for biological movement control. To illustrate this point, consider the optimal feedback control theory of Todorov and Jordan (2002). Computed optimal muscle forces need to be actualized. Forces represent the output of motoneurons (MNs) and muscles. In order to actualize forces, appropriate synaptic inputs should be delivered to the inputs of MNs. However, the input-output relationship is fundamentally irreversible because of threshold properties and intrinsic capacity of firing of MNs, etc. so computation of forces is useless: the theory is unrealistic since it is inverts causality inherent of physiological properties of MNs. In addition, the theory runs into the classical posture-movement problem. Intentional movements are usually associated with shifts in balance in a spatial domain. According to physics, the place where balance can be established is not defined by forces, torques or EMG patterns. They defined by system parameters. Therefore: direct specification of computed muscle forces or EMG patterns would be met with resistance of posture-stabilizing mechanisms. Biological optimality is thus accomplished empirically, without any computations. An example: an elegant smoothness criterion by Flash and Hogan. Mathematically, movement jerk is minimized. However, the system does not compute the jerk to make movement smooth. Smoothness is natural, emergent property of neuromuscular elements. I will illustrates, with experimental support, that optimal behavior without any computations can be identified at any level of neural control of posture and movements, starting from the level of a single MN. Movement equivalence may be one of manifestations of such globally empirical, non-programmable optimality of actions.

Compositionality and timing of upper limb movements

Tamar Flash[1], Matan Karklinsky[1], Irit Sella[1,2], David Ungarish[1,2], Nicholas Hatsopoulos[3,4] Naama Kadmon-Harpaz[1]

[1] *Department of Computer Science and Applied Mathematics,* [2] *Department of Computer Science and Applied Mathematics, Weizmann Institute of Science, Rehovot, Israel,* [3] *Department of Organismal Biology and Anatomy,* [4] *Committee on Computational Neuroscience, University of Chicago, Chicago, IL, USA*

In the first part of this presentation I will describe recent studies aimed at investigating the principles underlying global timing during the generation of complex movements such as reaching, drawing and locomotion. Particularly, how humans select total movement duration is an open question. In one recent study we examined this question by using a theoretical approach based on the idea that the invariance of least action principles to temporal and spatial transformations gives rise to conservation laws (see Huh and Sejnowski, 2016). Using Noether's theorem, we examined different symmetries of optimization models such as the minimum jerk and minimum acceleration models, deriving their conservation laws. We then tested the validity of these conservation principles by examining empirical data taken from human reaching and drawing movements.

Another study dealing with motor timing was aimed at investigating how humans select the durations of movement segments during complex hand motions. Specifically, we examined how the internal timing of hand drawing trajectories is affected by the geometrical properties of their distinct parts. In addition to local effects of geometry on movement timing, we found global effects whereby the geometrical features of one movement segment affect other segments' durations, indicating global movement planning. This global-planning effect was successfully modeled using the minimum jerk algorithm.

The last part of this talk is dealing with movement compositionality at the neural activity level. A complex action can be described as the composition of a set of elementary movements. Identifying the compositional structure and its neural representation is a key objective of understanding action execution. Accumulating evidence suggests that the neural populations in the motor cortex act as dynamical entities, in which transitions between distinct neural states facilitate different epochs of movement generation, such as movement preparation and execution. Recently we extended this view suggesting that transitions between neural states also correlate with transitions between movement segments, allowing the identification of the temporal structure underlying the movements. To detect state transitions in the network activity we modeled and analyzed the firing patterns of an ensemble of neurons in the primary motor cortex of two macaque monkeys by using a hidden Markov model. The obtained neural segmentation was then projected onto the behavioral movement output. Our findings reveal dynamical structures in the neural activities associated with distinct decompositions of the executed movements.

Talks

Session 2 – 15.3.17

9:00-10:40

Flow of motor information

Chair: Opher Donchin

Ben-Gurion University, Israel

Living in the past – how does our brain cope with delayed information?

Ilana Nisky

Biomedical Engineering Department, Ben-Gurion University of the Negev, Israel

During everyday interaction with the external world our brain graciously deals with a task that control engineers find very challenging – closed-loop control of movement and contact forces with outdated (delayed) information. Sensory signals are characterized by different transmission delays, and movement planning and execution require processing time, and hence, our brain “lives in the past” and continuously deals with delayed feedback. Therefore, understanding movement coordination, object manipulation, and perception in the presence of delayed feedback is critical for understanding fundamental constructs in human motor control: forward models and sensory integration. In addition, understanding how humans deal with delayed feedback is important for improving the control of teleoperation and telepresence devices that are widely used in our tech-savvy world in a variety of applications such as interpersonal communication and medicine .

I will discuss our recent findings about the effects of delay in force feedback on perception and action. Delay in force feedback appears to be represented in the brain using current and delayed motion primitives. Different combinations of these primitives are used for perception of mechanical properties of objects, for the control of grip force during object manipulation, and in adaptation. I will also tell how studying interaction with delayed elastic objects helped us to identify a specific role of the Posterior Parietal Cortex in perception of stiffness. I will conclude my talk with a glimpse on the implications for the design of teleoperation systems.

Using arm movements to inform our understanding of decision making, and vice-versa

Jason Friedman

Department of Physical Therapy, Tel Aviv University, Israel

Arm movements are the workhorse of computational motor control, used in countless studies to help us understand how we produce movements, how we learn new movements and adapt to changes in the environment, and how we use feedback to control our movements. Arm movements can also be used as a way of studying cognitive processes related to decision making. Movements and decision making are necessarily intertwined - before we can produce any movement, we need to make a decision about when to start moving, how to move, what to move and for how long to move. During execution of the movement, decision making is still involved in ensuring the movement is correctly performed and necessary adjustments are made. As these decision processes can be concurrent with the production of a movement, by decomposing arm movements made in response to stimuli we are able to understand the temporal dynamics of the decision process. In a series of experiments, we required subjects to indicate their choices by reaching out and touching a target. In these studies, the subjects were required to start moving their arm before a final decision was made. I will give several examples of how we can interpret the kinematics of these arm movements to help understand the cognitive processes involved, including for masked priming, face recognition using high and low spatial frequency information, and decision making in situations of conflict between the stimuli and location (the Simon task).

In addition, studying decision making tasks when arm movements are used as the response can provide us insights into questions of motor control. For example, we can study the question of when movements consisting of multiple submovements are made, how do we decide when to make the second (and subsequent submovements), based on the available evidence? I will also describe how we can use these tasks to look at biases in producing arm movements, biases in decision making, and the relationship between the two.

Spatiotemporal patterning in motor cortex during movement initiation

Nicholas G. Hatsopoulos[1,2], Karthikeyan Balasubramanian1, Matthew D. Best[2], Aaron J. Suminski[1]

[1] *Dept. of Organismal Biology and Anatomy, University of Chicago, Chicago*

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Voluntary movement initiation involves the modulation of large populations of motor cortical (M1) neurons around movement onset. Despite knowledge of the temporal dynamics of cortical ensembles that lead to movement, the spatial structure of these dynamics across the cortical sheet are poorly understood. Here, we show that the timing in attenuation of the beta frequency oscillation amplitude, a neural correlate of corticospinal excitability, forms a spatial gradient across M1 prior to movement onset with a defined beta attenuation orientation (BAO) from earlier to later attenuation times. We show that a similar propagating pattern is evident in the modulation times of populations of M1 neurons. Using various spatiotemporal patterns of intracortical microstimulation, we find that movement initiation is significantly slowed when stimulation is delivered against the BAO suggesting that movement initiation requires a precise spatio-temporal recruitment pattern in M1.

Talks

Session 3 – 15.3.17

11:20-13:00

Motor control and aging

Chair: Shelly Levy-Tzedek

Ben-Gurion University, Israel

Longitudinal studies of cognitive consequences and correlates of the brain aging: Only Time will tell

Naftali Raz

Institute of Gerontology and Department of Psychology, Wayne State University, Detroit, USA

Max Planck Institute for Human Development, Berlin, Germany

Brain and cognition change with age but the rates of change vary among individuals as well as across brain regions and cognitive domains. The mechanisms of these differential changes remain unclear. Multiple factors associated with vascular and metabolic risk, inflammation, stress, accumulation of reactive oxygen species and beta-amyloid modify the course of aging. I will review longitudinal studies of normal aging and cognition in the context of vascular, metabolic, and inflammatory risk factors and discuss plausible mechanistic accounts of these phenomena.

The aging brain: decline and potential improvements of cognitive performance

Daniela Aisenberg

Department of Clinical Psychology-Gerontology, Ruppin Academic Center, Israel.

It is well known that cognitive functions decrease with healthy aging. In both behavioral and imaging findings, we have showed that young participants are slower to report a feature, such as color, when the target appears on the side opposite the instructed response, than when the target appears on the same side. Target location, even when task-irrelevant, interferes with response selection. This effect is magnified in older adults. Nevertheless, lengthening the inter-trial interval, suffices to normalize the congruency effect in older adults, by reestablishing young-like sequential effects. Looking at the neurological correlate of age related changes by comparing BOLD signals in young and old participants performing a visual version of the Simon task, revealed that regions in attentional, control and visual-motor networks showed larger BOLD responses following incongruent than congruent targets. BOLD modulations by target congruency were more widespread in older than young adults. Comparing BOLD responses in sequential effects showed that old participants, showed large BOLD responses to incongruent than congruent targets, irrespective of the congruency of the previous target. This contribute to our understanding that aging may interfere with the trial by trial updating of the mapping between the task irrelevant target location and response.

In attempt to influence elders' performance we examined whether social priming could affect the cognitive process of inhibition. Seniors were assigned to three groups and performed the Simon task, which was followed by 3 different manipulations of social priming (i.e., thinking about an 82 year-old person): 1) negative—characterized by poor cognitive abilities, 2) neutral— characterized by acts irrelevant to cognitive abilities, and 3) positive—excellent cognitive abilities. After the manipulation, the Simon task was performed again. Results showed improvement in aging effects after the positive manipulation, (decreased Simon and interference effects, and young-like sequential effect). This was also tested using fMRI, showing significant change in BOLD response of the resting-state networks (RSN). Future exploration of RSN related interventions, such as Mindfulness, is now in process.

Reward and Punishment enhance motor adaptation in stroke

Joe Galea

School of Psychology, University of Birmingham, UK

A common assumption regarding human error-based motor learning (motor adaptation) is that its underlying mechanism is insensitive to reward- or punishment-based feedback. Contrary to this hypothesis, I will present 3 studies which highlight the dissociable effects of reward- and punishment-based feedback on motor adaptation. First, I will show a double dissociation whereby punishment accelerates learning to a novel visuomotor displacement and reward leads to greater memory retention. Second, I will present data which uses pharmacology to show the positive influence of reward on memory retention is dopamine-dependent. Finally, I will show that motor learning in stroke patients can be accelerated by both reward and punishment-based feedback. These findings reject the assumption that motor adaptation is independent of motivational feedback, raise new questions regarding the neural basis of negative and positive feedback in motor learning and highlight the importance of motivational feedback in stroke rehabilitation.

Talks

Session 4 – 15.3.17

14:20-16:20

Keynote session

Chair: Eilon Vaadia

Hebrew University, Israel

Neural learning rules in the cerebellum

Aparna Suvrathan, Hannah Payne, and Jennifer Raymond

Department of Neurobiology, Stanford University School of Medicine

Neuroscientists have generally viewed learning as being implemented by a few, generic synaptic plasticity rules, with the specialization for specific behavioral tasks arising from the circuit architecture. In contrast, we recently discovered that the synaptic plasticity rules themselves can be precisely tuned to functional requirements. More specifically, we found heterogeneity in the learning rules implemented by different subsets of parallel fiber-to-Purkinje cell synapses in the cerebellum. These synapses undergo associative synaptic depression in response to conjunctive activation with climbing fibers, which signal behavioral errors during cerebellum-dependent learning. In the cerebellar flocculus, the timing requirements for the induction of this associative synaptic plasticity precisely compensate for the ~120 ms delay in the error signals carried by the climbing fibers during oculomotor learning. Moreover, tuning for the same, behaviorally relevant climbing fiber delay was observed in the flocculus for long-term and short-term plasticity, and in vivo as well as in vitro. In other regions of the cerebellum, which support a broader range of behavioral functions, plasticity at different parallel fiber-to-Purkinje cell synapses was tuned to different delays between parallel fiber and climbing fiber activation. Our results suggest that the rules governing synaptic plasticity at the cerebellar parallel fiber-to-Purkinje cell synapses are tuned to solve the temporal credit assignment problem.

Analog computations drive strategic re-aiming of an intended movement

Sam McDougle

Department of Psychology, Princeton University, USA

Models of visuomotor learning have focused on the implicit calibration of a forward model, but less attention has been paid to the contributions of an explicit "aiming" component to visuomotor learning. In this talk, I will first highlight the various important roles of explicit learning in visuomotor rotation tasks, and then provide evidence that the process of re-aiming an intended movement may rely on the cognitive mental rotation of the movement goal or plan. In the first set of experiments, we show that explicit learning makes up much of the learning curve, is fast and flexible, and guides the generalization of aftereffects. In a second set of experiments, we explored a mechanism that may underlie aimed movement planning.

Re-aiming a movement isn't unlike re-orienting an object in your mind, a cognitive act which has been studied for decades. If a form of mental rotation underlies the aiming process in VMR, it follows that the magnitude of an imposed rotation perturbation in a VMR task should predict RT. Furthermore, if re-aiming a movement involves mental rotation of the movement plan, subjects should make predictable intermediate movements when they are forced to reach before they have fully "rotated." We tested both of these hypotheses across two experiments: In the first experiment, subjects performed a one-trial learning experiment with shifting rotation magnitudes. As predicted, we found that larger rotation magnitudes yielded longer RTs in a linear fashion. In a second, forced-response-time task, subjects had to execute movements to targets in a short time window, while simultaneously countering a 90˚ rotation. As predicted, subjects consistently performed intermediate movements (i.e. between 0˚ and 90˚) when their RT was limited. At larger RT windows, subjects' movement directions increased linearly toward the 90˚ solution angle. Combined, these results suggest that explicit aiming in VMR — an operationalized analog of "cognitive" motor control — may require the mental rotation of an imagined goal location or movement trajectory.

Contributions of dopamine and acetylcholine to the enigmatic motor functions of the basal ganglia

Jeff Wickens, Sho Aoki, Stefan Zucca, Aya Zucca

Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan.

Anatomically, the striatum – the main input nucleus of the basal ganglia – receives input from almost the entire cortical mantle. Axon branches of cortical pyramidal neurons make monosynaptic connections on the dendritic spines of the striatal output neurons, forming a single layer neural network. The striatal output neurons are inhibitory in their projections to downstream basal ganglia nuclei, and also make lateral inhibitory connections with each other. This lateral inhibition network generates a competitive dynamic. The corticostriatal synapse has a dopamine- and activity-dependent synaptic plasticity mechanism that may be involved in reinforcement learning. Consistent with this striatal output neurons display activity related to learned association of sensory input and actions. Thus we imagine that these corticostriatal synapses represent learnt, adaptive, situation-action associations, or crudely, stimulus-response connections. Recent work extends this basic stimulus-response reinforcement idea, by investigating the role of the striatal cholinergic interneurons. We found that disrupting cholinergic interneurons in the dorsomedial striatum caused increases in perseverative errors in an extra-dimensional set-shifting task requiring a change in response strategy. This suggests that cholinergic interneurons may be important in enabling a switch from one behavioral rule to another. To investigate the cellular mechanisms involved we are using in vivo whole cell recordings together with optogenetic manipulation of cholinergic interneurons in mouse striatum. Preliminary results indicate that silencing of cholinergic interneurons causes inhibition of spiny projection neurons. We propose that cholinergic interneurons play a role in switching from an old rule to a new rule. They may do this by momentarily suppressing subsets of striatal output neurons connections, allowing other subsets to become competitively active.

Talks

Session 5 – 15.3.17

16:40-18:00

The impaired motor system

Chair: Meir Plotnick

Sheba Medical Center, Israel

Natural and artificial limb representation in amputees

Tamar Makin

Institute for Cognitive Neuroscience, University College London, United Kingdom

As the brain is shaped by experience, real life constraints on behavior should provide a powerful driver for brain organisation and plasticity. Arm amputees will adapt fundamentally altered patterns of motor behavior to compensate for their disability, e.g. using a prosthetic limb. Here we demonstrate, using fMRI and behavioural tests, how changed motor control due to hand loss, and the adoption of a prosthetic limb to substitute hand function, profoundly impacts sensory and cognitive processing. We find that habitual prosthesis usage in daily life – as opposed to visual exposure only – shapes communication between sensory and motor areas, thus facilitating visual processing. We also discovered that natural limb experience (i.e. age at limb loss) sharpened the boundary between hands and tools, while artificial limb usage blurred it. Our results provide insight into the mechanisms of embodiment, which may aid substitutionary, assistive and augmentative technological implementation.

Stroke rehabilitation through motor modules

Vincent C. K. Cheung

School of Biomedical Sciences, The Chinese University of Hong Kong, Hong Kong, China

Stroke is a leading cause of adult disability worldwide. The efficacy of most assistive technologies for reversing post-stroke motor impairment, especially for chronic survivors, has remained limited. A new technology that facilitates recovery at the level of general motor control beyond that achievable by standard care must be based on true biological mechanisms of control. We propose that one theory of how the CNS coordinates muscle activations can be the basis of a new rehabilitation strategy. There is strong evidence from recent optogenetics studies suggesting that CNS activates groups of muscles together as neuromotor modules - the rudimentary building blocks of movement. The CNS produces complex muscle patterns by flexibly combining several modules together. Here, we aim to use this modular framework to understand the complex muscle-pattern changes that underlie motor recovery in stroke survivors, and harness this knowledge to develop a new rehabilitation. Electromyographic activities (EMGs) from upper-limb muscles of stroke survivors were recorded, before and after intervention; motor modules were identified from the EMGs using specialized algorithms. Preliminary results from chronic survivors indicate that enhanced motor recovery is associated with the activation of a specific muscle synergy in the affected arm after rehabilitation - a “marker” of post-training recovery. Our results raise the possibility of providing rehabilitative training by facilitating the emergence of the marker module through muscle-signal feedback provided to the subject. Overall, our research may be a step towards developing a stroke rehabilitation with specific targets of intervention that is likely to significantly improve general motor control of the arm.

Posters

Co-adaptive learning improves performance in a Multi-day Motor Imagery BCI training

A. Abu-Rmileh, E. Zakkay, L. Shmuelof, O. Shriki

Department of of Brain and Cognitive Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel

Background: Motor imagery (MI) based brain computer interfaces (BCI) detect changes in brain activity associated with imaginary limbs movements, and translate them into device commands. MI based BCIs require training, during which the user gradually learns how to control relevant patterns of brain activity with the help of feedback. Machine learning techniques are frequently used to boost BCI performance and adapt the decoding algorithm to the user's brain. Thus, both the brain and the machine need to adapt in order to improve performance.

To study the role of co-adaptive learning in the BCI paradigm and the time scales involved, we investigate the performance of two groups of subjects in a 4-days MI experiment. One group (n=9) performed the BCI task using a fixed classifier based on MI data from day 1 (control group). In the second (experimental) group (n=9), the classifier was regularly adapted based on brain activity patterns during the experiment days. The experiment used a video-game based feedback training environment to increase subjects' engagement. In both groups, subject specific features were extracted for classification and feedback.

Results: Our results show a significant difference between the groups which was primarily driven by decreases in performance in the control group with training. The experimental group showed an improvement in performance, albeit with a higher inter-subject variability. The results support the idea that a co-adaptation strategy could positively affect the BCI performance. The results also point to a large inter-subject variability in producing and controlling the brain features required to accomplish the task, suggesting that optimization of co-adaptive learning could benefit from subject-specific adaptation protocols.

Conclusions: Subject-specific feature extraction, adequate adaptation protocol and engaging training interface are important factors for improving the overall system performance of a BCI system over multiple days.

Measure of motor planning as a possible marker for ADHD

Anat Dahan and Miriam Reiner

The Virtual Reality and Neuro-cognition Laboratory, Faculty of Education in Technology and Science, Technion – Israel Institute of Technology, Israel

It has been shown that individuals who are diagnosed with ADHD have atypical motor development and behavior. Few studies have looked at the aspect of preparation for movement. In the present study, we used a paradigm introduced by Gehz (1997) to separate between motor performance after two motor planning intervals. We compared motor execution following two planning conditions for control and for ADHD subjects. We compared the difference in execution following the two conditions, and compared these differences between the two groups.

Movements were performed and recorded in an ecologically valid environment that allows natural and free hand movements, using a 3D virtual environment, and a haptic Phantom robotic arm with haptic feedback and possibility of force and high resolution hand position measurements (desktop 6DOF Phantom by Sensegraphics).

We compared motor execution for control subjects under two conditions: short and long planning intervals. Several aspects of execution were compared to see the effect of the planning interval on the consequent movement. One of the parameters that stood out was the time of reaching a larger that zero velocity threshold, i.e. time of actual start of movement. It seems that the movement does not begin until the brain has some form a movement plan ready.

We further compared the execution of ADHD subjects to that of control subjects. It appears, that for ADHD subjects, there was a significantly smaller difference in the movement start time between the two planning conditions. Moreover, the start time in both conditions was delayed relative to the control long –planning condition. This may be an indication a movement plan was not ready in both conditions.

Further differences were revealed between the two groups, in the velocity pattern the smoothness and jitter of the movement.

Catching heuristics are optimal control policies

Boris Belousov[1], Gerhard Neumann[1], Constantin A. Rothkopf[2], Jan Peters[1]

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Two seemingly contradictory theories attempt to explain how humans move to intercept an airborne ball. One theory posits that humans predict the ball trajectory to optimally plan future actions; the other claims that, instead of performing such complicated computations, humans employ heuristics to reactively choose appropriate actions based on immediate visual feedback. In this paper, we show that interception strategies appearing to be heuristics can be understood as computational solutions to the optimal control problem faced by a ball-catching agent acting under uncertainty. Modeling catching as a continuous partially observable Markov decision process and employing stochastic optimal control theory, we discover that the four main heuristics described in the literature are optimal solutions if the catcher has sufficient time to continuously visually track the ball. Specifically, by varying model parameters such as noise, time to ground contact, and perceptual latency, we show that different strategies arise under different circumstances. The catcher's policy switches between generating reactive and predictive behavior based on the ratio of system to observation noise and the ratio between reaction time and task duration. Thus, we provide a rational account of human ball-catching behavior and a unifying explanation for seemingly contradictory theories of target interception on the basis of stochastic optimal control.

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Contributions of geometric properties of the arm to non-uniform precision of arm position sense in normally sighted and visually impaired people

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The reasons for the non-uniform precision of arm position sense in horizontal workspace are poorly understood. Given the non-linear geometric transformation from hand position to joint angle changes, we hypothesized that (1) geometric arm properties would contribute to the non-uniform precision of arm position sense and (2) this contribution would be similar in individuals with normal and impaired vision given their similar arm geometry. To test the first hypothesis, we conducted a Jacobian-based geometric analysis of a two-segment kinematic model of the human arm. The analysis revealed precision ellipses of hand position for any arm configuration. The predicted precision ellipses were non-uniform in the horizontal workspace, their size increased with distance from the body, and they were oriented nearly orthogonal to the arm stiffness ellipses reported in the literature. To test the second hypothesis, we measured precision of arm position sense in right-handed individuals with normal (n=10) and impaired (n=7) vision using joint and hand position matching tasks. No difference in precision between the tasks was found. Visually impaired individuals had lower precision of arm position sense than normally sighted, however, orientations of experimental precision ellipses did not differ between the groups. The experimental and predicted precision in the radial direction and closer to the body was higher than in the azimuth direction and farther from the body. We concluded that geometric properties of the arm substantially contribute to the non-uniform precision of arm position sense in both sighted and visually impaired individuals and that visual experience benefits position sense.

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Lateralized modulation of self-generated visual stimuli

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Introduction: Sensory stimuli triggered by voluntary action are perceived differently and evoke differential neural activity in sensory regions compared to identical stimuli triggered by an external source. Such modulations are suggested to occur through corollary discharges sent from the motor system to sensory regions prior to stimulus arrival. Given the strong laterality of the motor system, it is plausible that the magnitude of such sensory modulation will also exhibit a laterality effect, depending on the identity (right/left) of the stimulus-triggering hand. Indeed, in the auditory domain, we have recently provided evidence in support of such a mechanism (Reznik et al. 2014). The aim of the current study was to further probe this model in the visual domain.

Results: 24 subjects judged the relative brightness of self-generated visual stimuli to identical stimuli triggered by the computer. Self-generated stimuli were triggered using either the right or left hand and presented either in right or left visual field. At the group level, some subjects reported experiencing the self-generated stimuli as brighter on most trials and others as darker relative to identical visual stimuli generated by the computer. However, examining the absolute modulation magnitude (i.e. proportion of trials), demonstrates that it depended on the relation between stimulus-triggering hand and stimulated visual field (right/left). In the left visual field, perception of stimuli triggered with the left hand (ipsilateral to the visual field) was more strongly modulated than perception of stimuli triggered with the right (contralateral) hand ($p<0.05$ one tailed). In the right visual field, no such effect was found ($p=0.35$).

Conclusions: our behavioral findings in the left visual field are in accordance with the model proposed based on findings in the auditory domain- predicting stronger modulation in sensory regions residing in the same hemisphere as the motor cortex commanding the stimulus-triggering hand. Using fMRI, we are now examining the neural mechanism behind these behavioral findings.

Dissociating implicit and explicit learning using a computational modelling approach

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Motor adaptation plays a major role in motor learning. This study will focus on the distinction between implicit adaptation and explicit adaptation. Implicit adaptation happens gradually and subconsciously, whereas explicit adaptation involves the conscious application of a strategy.

Preliminary research has identified several factors that influence motor adaptation. However, it remains unknown whether these factors mainly affect the implicit system, the explicit system, or both. In order to get more insight in the effects on each learning system, it is necessary to separate the implicit and explicit system. This separation has previously been made in an experiment in healthy subjects. In this research, we investigate whether it is also possible to separate implicit and explicit learning using computational modelling.

We used a two-rate state space model with different retention rates (A) and learning rates (B) for the implicit and explicit system to simulate data for 100 subjects. We set Aimplicit to be a random number between 0,990-0,995, Aexplicit between 0,950-0,990, Bimplicit between 0,100-0,200 and Bexplicit between 0,200-0,300. For qimplicit (state noise) and qexplicit we set random values between 0,000-0,100 and 0,000-0,500 respectively. The observation noise was given a random value between 0,000-0,200. The simulation started with a baseline phase of 450 trials, followed by an adaptation phase of 768 trials, in which the perturbation consisted of a summation of multiple sinewaves with an amplitude of 10 degrees and frequencies of 1, 2, 4, 8 and 16 cycles within 768 trials.

Analysis revealed that this model was able to separate implicit and explicit learning. The results show that implicit learning predominates over explicit learning in response to low frequencies, whereas for high frequencies the opposite is seen. Besides, we were able to show a positive correlation between learning of the implicit and explicit system in driven frequencies (i.e. frequencies that are present in the perturbation signal) (median rdriven=0,8457, IQR=0,1102). Strikingly, in undriven frequencies, a negative correlation between the implicit and explicit system is seen (median rundriven=-0,8670, IQR=0,0898), indicating that one of the two systems compensates for the other. In order to determine which system responds to the other system, we computed the optimal number of trials that the implicit system lagged the explicit system. The median number of optimal lags was 2, indicating that the implicit system responds to the explicit system in undriven frequencies.

Adaptation to a Visuomotor Delay Affects Drawing Symmetry

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To successfully move in the world and interact with dynamic objects, it is very important to accurately control the timing and location of our arm. Previous studies of adaptation to delayed information reported an association between space and time. These studies showed that breaking the simultaneity between the proprioceptive and other sensory inputs results in a deformation of motion.

Here, we aimed to shed more light on the effect of sensorimotor delay on state representation and the control of arm movements. While performing reaching movements to both left and right targets, participants were exposed to a visuomotor delay perturbation to one side of the task space, to both sides, or to neither side. We examined changes in the internal representation of hand-cursor dynamics by asking the participants to draw a circle without visual feedback on randomly selected trials.

We show that when the participants were exposed to the single-sided delay perturbation while performing reaching movements, their hand reach trajectories exhibited end-point movement deviation only when the movements where toward the side with the perturbation. In addition, we saw transfer of adaptation to a blind circle drawing task: the circles were asymmetrically elongated. Interestingly, this hypermetria in participants' drawings did not depend on the side where the delay was applied, but rather on the side where the drawing was initiated. This indicates that the altered internal representation due to the unilateral delay affected movements toward both sides when the visual feedback was omitted. Interestingly, when we applied delay in both sides of the task space, only the left side of the drawn circles was elongated. Overall the laterality in the exposure to this perturbation, resulted in different effects on the control mechanisms of participants' movements.

Our study shows that delay perturbations can cause asymmetrical movements across space. This is important for understanding the mechanisms underlying adaptation to delayed feedback, and may explain various forms of movement disorders that distort temporal or spatial movement coordination, such as hemispatial neglect.

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Interactive Generation of Calligraphic Trajectories with Stochastic Optimal Control

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Many computer aided design applications require the definition of continuous traces, where the most common interface is to edit the control points of some form of interpolating spline. We study how tools from computational motor control can be used to extend such methods to encapsulate movement dynamics, variations and coordination. Here we describe a methodology for the interactive and procedural definition of motion trajectories using stochastic optimal control.

The system is based on a probabilistic formulation of Model Predictive Control (MPC) [1] and provides users with a simple interactive interface to generate multiple movements and traces at once, by visually defining a distribution of trajectories rather than a single path. By exploiting this representation, a dynamical system is then used to generate curves stochastically. The resulting traces are natural looking and reflects similar dynamics of the movement that would be made by a human when drawing.

The input to our method is a sequence of states defined as multivariate Gaussians with full covariances, which allow the manipulation of the curvilinear evolution as well as the variability of trajectory segments. The output is a trajectory that is consistent with the minimal intervention principle [9], and minimises a tradeoff between control effort and tracking accuracy. We demonstrate how Gaussians with isotropic covariance can be used for computing approximations of Bezier curves [4], as well as for generating paths that minimise high derivatives of position, such as jerk [5], snap [3] or crackle [2]. An increase in variance produces a smoothing effect, which can be interpreted as a form co-articulation [8], while full covariances allow the user to define coordinations and directional trends in the trajectory evolution.

We propose our method as a general-purpose tool for motion synthesis and robotics applications. In addition, we support the hypothesis that the observation of a human made artistic trace triggers the mental recovery of the movement underlying its production [6,7], and that this recovery affects aesthetic appraisal [10]. As a result, we emphasise the advantages of the proposed methodology for the computational synthesis of hand drawn curves, and demonstrate its applications for the generation of traces that are visually and dynamically similar to instances of human made graffiti art or calligraphy.

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Representation of self-generated sensory consequences in motor cortex

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Every motor act we perform is inevitably coupled with sensory consequences. Both pulling the strings of a harp and aimlessly waving our hands in the air produce a wide spectrum of self-generated, expected and non-expected alike, sensory feedback – auditory, somatosensory and proprioceptive. The modulatory effect of voluntary action execution on sensory perception has been studied extensively during the past years. From human and animal studies, accumulating evidence implies that during voluntary action execution, motor cortex sends 'efference copies' of the expected sensory consequences to sensory regions thus creating sensory "corollary discharges" that modulate both behavioral and neural responses to otherwise identical stimuli perceived in a passive fashion. However, despite the theoretical assumption that during voluntary action execution, "efference copies" should represent their expected sensory consequences, the representation of such consequences in motor pathways is scarcely known.

The aim of the current study was to examine how sensory consequences of voluntary actions are represented in motor pathways. To this end we acquired whole-brain fMRI data from healthy subjects (n=14) while manipulating the expected modality of sensory consequences – either auditory or visual – triggered by voluntary button presses. Using our recently developed approach to estimate differences in spatial activity patterns our results point that during execution of voluntary actions, activity in primary motor cortex (M1) and supplementary motor area (SMA) represents their expected sensory consequences. Finally, our results show that the motor modulation of fMRI activity during active compared with passive conditions was greater in the auditory and visual cortex contralateral to the executing effector (i.e., right hand). Namely, fMRI activity in the left auditory cortex was modulated to a greater extent during active sound generation compared with passive listening and the fMRI activity in the left visual cortex was modulated to a greater extent during active generation of visual stimulus compared with its passive perception.

Verifying computational models of motor adaptation with event-related negative EEG responses

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For everything we do, we rely on our motor system. It is therefore no surprise that motor learning is very important in our daily lives. Motor learning can be divided in skill acquisition and adaptation. Adaptation is driven by movement errors. Our brain uses these errors to adapt our internal model to a changing environment. Adapting to a changing environment involves repeating a part of the previous movement while changing another part of it in correspondence with the error size.

When your motor output is too noisy, it is better not to adapt to it too quickly, because that would only amplify the noise. To filter out unreliable information and adapt efficiently, it is believed the brain uses a Kalman filter. According to the Kalman filter model of adaptation, a higher planning noise is associated with a higher learning rate, whereas a higher output noise results in a lower learning rate.

To investigate whether our internal model is similar to this computational model, we want to find neurophysiological evidence for this by measuring error-related negativities (ERNs) with EEG. An ERN is a negative potential, that can be found approximately 100 ms after a subject makes an error. We will perform a visuomotor adaptation experiment with healthy subjects while at the same time performing EEG measurements on the subject. We will then analyse whether there is a correlation between the amplitude of the ERN and the error size, and whether the ERN amplitude correlates with the planning noise and the observation noise. Previous research suggests that larger errors produce bigger ERNs. We want to clarify this correlation and find out how large an error needs to be to still produce an ERN. Furthermore, we expect that with a higher output noise, the ERN will be smaller. Because we trust sensory information less, we will ascribe the error more to the environment and less to ourselves. Conversely, because with a higher planning noise, we will more readily ascribe the errors to ourselves, we expect that the ERN will be larger. Confirming this correlation would provide new evidence that our brain uses a Kalman filter for motor adaptation.

Keywords: Motor adaptation, internal model, Kalman filter, error-related negativity

Representation of Visuomotor Delay as a Spatial Gain Change in Visuomotor Mapping

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Time representation is important for sensory integration and for movement planning and execution. Sensory signals are characterized by different transmission delays, and movement planning and execution require additional processing time. Therefore, to enable the organism's survival, the brain must take these delays into consideration.

Here, we examine how the sensorimotor system represents a visuomotor delay. Participants played a pong game in which the paddle was delayed with respect to the hand. A Time Representation of the delay is an estimation of the actual time lag between hand and paddle movements. A State Representation is a representation of delay using current state variables: the brain may interpret the distance between the paddle and the hand originating from the delay as a spatial shift, or as a result of a minifying gain. The lag may be also attributed to a mechanical resistance that influences paddle's movement. Unlike Time Representation, the State Representation would influence the state of the movement of the hand.

To investigate the way humans represent the dynamics between the hand and the delayed paddle, we performed a set of experiments in which we examined transfer of the delay effects to blind reaching and blind tracking tasks. Comparing the results from these experiments to simulations of the representation models enabled to dissociate between the alternatives. We found that a prolonged exposure to the delayed feedback cause participants to exhibit hypermetric movements in all transfer tasks. These results are consistent with a State-based rather than a Time-based Representation of the delay. The hypermetric movements in the tracking task indicate that the delay is not represented as a spatial shift. In addition, the delay-induced hypermetria was not influenced by movement velocity, suggesting a delay representation as a gain change in the visuomotor mapping rather than as a mechanical system equivalent.

Understanding delay representation is critical for understanding forward models and sensory integration. Our results suggest that, to overcome inherent feedback delays, the sensorimotor system utilizes information about the current state, rather than measures the actual time lag. The study is supported by the BSF (2011066) and the ISF (823/15).

The Neural Substrates of Error and Success in Adaptation to Visuomotor Rotation

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A prominent view in the computational motor control community is that adaptation to sensorimotor perturbations occurs through an error-based mechanism where sensory prediction errors lead to updates of forward and inverse internal models. Nevertheless, adaptation was recently shown to be also affected by reward signals that could directly drive changes in the motor plan. This involvement of multiple computational mechanisms in sensorimotor adaptation suggests that multiple brain networks should be active during the processing of feedback in an adaptation task. Here, we localize the areas that show sensitivity to the presence and size of errors and to success feedback.

Lying in a 3T MRI scanner (Philips), 17 participants made fast out-and-back movements with their wrist. They were instructed to position their movement reversal point at a target. After movement completion, visual feedback was given at the reversal point and a change in the color of the target informed about failure or success. Following a baseline session with no perturbations, the visual feedback rotated with respect to movement direction according to a random walk algorithm. In 20% of the trials, participants did not receive feedback. To extract activation patterns on a trial-by-trial basis, we used a slow event-related fMRI design with ITI of 6-10 seconds.

Behavioral results show that due to the random walk perturbations, participants were experiencing errors throughout the entire experiment. However, with experience, these errors became smaller than the applied rotation, indicating a trial-by-trial adaptation. We did not find indications of error-related corrections within trials. Contrasts of the error and no-feedback trials revealed a network of areas that include the PPC, primary and premotor cortices, lateral occipital areas, and areas in the anterior lobe of the cerebellum. A parametric analysis in search of areas that are sensitive to the size of errors revealed areas only in the anterior lobe of the cerebellum. Contrasts between the successful trials and the no-feedback trials revealed higher BOLD activation in the putamen and in Brodmann area 7. Isolating the neural networks that are involved in error and success processing is a vital step towards understanding the effect of feedback on learning and memory processes in the sensorimotor system.

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Voluntary step execution under single and dual task conditions, in patients with knee osteoarthritis, comparing symptomatic and non-symptomatic legs: A case controlled study

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Falls are a major cause of injury among older individuals in the western world. The risk factors for a fall are numerous. Among them are age, a previous fall, imbalance, loss of muscle strength, polypharmacy, decline in activity of daily living (ADL) function, chronic conditions, cognitive decline, joint pain, and more. Some falls result from the combination of such internal causes and additional external trigger that lead to loss of balance. A common reaction against loss of balance incident would be a protective step, to regain balance by adjusting the base of support (BoS), so that the projection of the new location of the center of mass will remain within the adjusted BoS limits. The speed of voluntary stepping was shown to be predictive of future falls. Older individuals perform slower in the voluntary step testing compared to young adults. In the presence of an attention demanding task the execution of the step was delayed, more so in older individuals as compared to young adults, with the former group increasing the initiation phase of the step by more than twice. Stepping durations were increased in stroke survivors in comparison to healthy individuals, exhibiting slower swing phase while stepping with the paretic limb.

Older adults with joint disease were found to fall more than the average rate of the healthy population in their age group (up to 50% per year compared to 30%). This might be because of the cumulative nature of the physical deterioration, and the difficulty in moving the painful limb quickly and efficiently when needed.

We aimed to explore the performance of older individuals with unilateral symptomatic knee osteoarthritis in a voluntary step test under single and dual task conditions, compared with healthy, asymptomatic age matched peers. We measured the changes in ground reaction force and center of pressure as 21 Osteoarthritis (OA) patients and 22 healthy individuals age 65 and older performed a voluntary step test in different directions, under full attention and during a dual-task paradigm. We will compare the stepping pattern of the painful limb with the non-painful one, and will describe cohort related differences. . We hypothesize that: (1)The motor phases of stepping will last longer for the OA group; (2) The painful limb will perform slower; and (3) The attention demanding task will have a larger effect on the OA group.

Assessing spatio-temporal joint coordination

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Reaching movements require coordination of various degrees of freedom in space and in time. We propose a novel method for assessing spatio-temporal coordination based on a stochastic model of joint trajectory. Most previous studies of motion coordination have analyzed temporal and spatial coordination separately using methods such as angle-angle diagrams, displacement cross-correlation, and kinematic variability analysis in the controlled and uncontrolled manifolds. A notable exception is the temporal coordination index (TCI) which is based on angle-velocity phase diagrams. While the TCI assumes joint dynamics can be modeled by a second order system, the current method makes no such assumption. In the current method, the trajectory of each joint is modeled by a two-dimensional (space and time) Gaussian Mixture Model (GMM). Model parameters are found using Expectation-Maximization, initialized by K-Means. Bayesian Information Criteria is used to establish the best fit. Inter-joint coordination is evaluated by compering joint trajectory models using a symmetric variant of the Kullback-Liebler Divergence (KLD). The method was applied in 11 healthy participants aged 48 to 76 years (mean 60.0 yrs). Each participant performed 20 reach-to-grasp movements to each of 3 targets located at arm length in different areas (ipsilateral, sagittal, contralateral). Arm movement was recorded using electromagnetic sensors (G4™ Polhemus). Joint centers (shoulder, elbow, and wrist) and angles were extracted based on an analytical arm model. For all participants, principal component analysis indicated that shoulder and elbow flexion-extension were the most contributing angles thus, KLD was calculated between the estimated GMMs of the shoulder and elbow flexion-extension of each participant (after adjusting the spatial Gaussian components to the same region). All participants but one had the same number of Gaussians in both GMMs and the mean KLD was 25.57 (SD 13.37), which indicates model similarity.

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Arm joint angle variability analysis during virtual robotic teleoperation with two master devices

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The use of teleoperated robotic systems is widely spreading in multiple fields, ranging from telemedicine to radioactive materials handling. In teleoperation, the user directly interacts with a robot that acts as a master device to control a slave manipulator; the master device translates the users' hand gestures in movements of the slave end-effector that interacts with the environment.

Teleoperation represents a complex motor control task users need to undergo an intensive phase of training to exploit the full potential of the high dexterity robots and tools that are currently used. This complexity derives from the high redundancy that characterize the human arm which translates into multiple possible joints configurations to achieve the same hand movement. Previous works analysed the joint variability using the uncontrolled manifold analysis, showing how expert tele-operators were able to exploit the arm redundancy to efficiently reduce hand movement variability with respect to novices.

In this work, we propose the use of the uncontrolled manifold analysis as a way of underlying the differences that different master devices induce in the motor control strategies adopted in the execution of three different virtual teleoperation tasks using a parallel and a serial link master device. In the three planar tasks, the users were asked to accurately follow a half cloverleaf path, to perform eight radial reaching movements starting from a central resting position and to follow the same half cloverleaf path while also orienting the cylinder-shaped tool end-effector to be tangent to the trajectory. The tasks were used to test the users' precision, accuracy during fast movements and dexterity in orienting the tool.

The arm and thorax motions of eight right-handed users were acquired using optoelectronic and electromagnetic tracking devices. The arm kinematic was then reconstructed using a user-specific model through OpenSim. The results will be used to depict the differences between the two types of master devices analysed and to understand if and how different types of tasks elicit different ways of exploiting the arm redundancy.

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The effect of long-term unexpected constant balance perturbation training on dynamic balance and functional connectivity in patients with Acquired Brain Injury

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Background: Acquired Brain Injury (ABI) is a major cause of impairment and functional disability, including deterioration of locomotion and balance. The aim of this study was to evaluate the effect of long-term unexpected constant balance perturbation training on dynamic balance, variability of Step-by-Step asymmetry and resting-state functional MRI connectivity (FC) in the cortical and sub-cortical motor control network.

Methods: In an exploratory clinical interventional trial, 28 subjects post ABI received 22 sessions of long-term unexpected constant balance perturbation training using Re-StepTM technology (Step of Mind-Israel). Before and after training we assessed dynamic balance, step-by-step asymmetry variability for all subjects and FC for 24 subjects.

Results: We found a significant improvement in dynamic balance measure (p=0.008) and a significant reduction in step-by-step variability (p=0.04), indicating that the training was effective. FC in the cortico-cerebellar motor-control network did not change following training.

Nevertheless, the behavioral and clinical measures showed inter-subject correlations with both baseline FC measures (for example, baseline step-by-step variability was correlated with baseline FC between the right and left cerebellum (rs=-0.44, p=0.03)), and with changes in FC following training (changes in dynamic balance was correlated with FC changes between right and left cerebellum (rs=-0.41, p=0.045)). In order to search for FC changes outside the cortico-cerebellar network, we applied a seed-based analysis. We found a decrease in FC between the cerebellum and the parietal cortex, an increase in FC between the primary motor cortex and the parietal cortex and the posterior lobe of the left cerebellum.

Conclusion: Long-term unexpected constant balance perturbation training improves dynamic balance control in chronic ABI subjects. The correlations between FC in the cortico-cerebellar motor-control network and the behavioral measures suggest that these areas play a role in dynamic balance. However, our results suggest that dynamic balance improvement following training is mediated by connectivity changes outside the cortico-cerebellar execution network.

Group synchronization of human movements

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We study how human groups synchronize common movements. Human or animal group movements arise from the actions of each group member, and reflect the group's social and communication patterns. The flocking patterns of birds suggest that a bird's social position in the hierarchy determines its flight direction, leading or following other birds' directions [Nagi et al., 2010]. In fish, local relations between individuals may define their direction and lead to swarming behavior [Paley et al., 2007]. Humans may use their predictive ability to synchronize when moving in a pair [Noy et al., 2011], and are capable of using different communication structures to synchronize in a group, similar to Kuramoto's model [Alderisio et al., 2016]. The spatial patterns of human group movements through a common space are still less understood [Belz et al., 2012].

Our experiment studied the basic principles guiding human group motion, in a low dimensional setting. We let 30 groups of 4 subjects play a computer game. Each subject used four arrows to move a circle inside a common square arena, while seeing the movements of the 3 other players. The experiment included 3 minutes of free play and 3 minutes of instructed synchronization. Additionally, subjects filled personality questionnaires.

First, we analyzed the leader-follower relation within each dyad; a follower is characterized by movements correlating with near past movements of a leader [Nagi et al., 2010]. Thus, we examined pairwise hierarchic relations using movement analysis. Second, we tested whether group members interact with others differently according to the distances between their circles. The distances between group members define a time-dependent communication network structure that yields a natural definition of a group's synchronicity measure [Paley et al., 2007].

We present preliminary findings; instructed synchronization between humans may depend on their relative distances. This suggests that basic principles of collective animal behavior may play a role in shaping human group interactions.

Shared patterns of learning for pursuit and saccade eye movements

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To uncover the organization of behavior we need to break it down to its components and understand the rules by which the different components are controlled. In the eye movement system this is manifested, for example, by our need to coordinate smooth pursuit and saccade eye movement. A critical question in this regard is whether the different eye movements are controlled together or separately.

We approach this question from the perspective of learning. We designed a task in which monkeys were required to learn to associate between a color of the targets and the size of the reward. In each trial, two targets of different colors, each associating with either a large or a small reward, moved simultaneously in orthogonal directions. The monkeys learned to bias their pursuit and later in the trial make a saccade towards the target that was associated with the larger reward. After the monkeys consistently made saccades to the larger reward in consecutive trials we reversed the association between color and reward size. We interleaved the learning trials with trials in which the monkey selected between two familiar targets, associated with either large or small reward.

We found that learning to bias pursuit and the final saccade to the larger reward shared the same dynamics. The average learning curves were highly correlated without any significant lag between saccade and pursuit. However, even when the monkey consistently made a saccade to the target that was associated with a larger reward, the degree of pursuit bias towards the larger reward target did not reach the bias towards the familiar larger reward targets.

We conclude that a shared process controls learning of pursuit and saccade eye movements. Additional slower process is expressed in the pursuit but not in the saccade learning.

Changes in Apparent Preferred Directions Induced by Brain-Computer Interfaces

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Brain Machine Interfaces (BMIs) rely on the correlation between neural activity and the direction and speed of movement. The dependence of the firing rate on the direction of movement can be described well by a cosine function of the angle between the movement direction and a fixed direction, dubbed the preferred direction (PD) of the neuron. Since the PD is evaluated from the recorded neural activity, we refer to it as the apparent PD. BMI experiments reveal that the apparent PDs of some neurons change after the transition to brain control. However, the mechanisms behind those changes, and whether they reflect just the effect of the BMI filter or internal adaptation to brain control, are poorly understood.

Here we investigate changes in the apparent PD of simulated neurons within the framework of optimal feedback control (OFC). Within this framework, simulated neurons encode the estimated state of the cursor and the control signal. Simulated BMI experiments based on the OFC framework demonstrate that changes in the apparent PD may occur even with no adaptation, i.e., no change in the OFC or tuning parameters. Theoretical analysis specifies the special conditions under which the PDs would remain the same after switching to brain control. Those conditions are usually not met, and thus the PDs may change even with no adaptation.

Thus we conclude that apparent changes in PDs may be introduced by the BMI filter, even if there is no internal adaptation. BMI filter design should take this effect into account. Rather than just minimizing the reconstruction error, BMI filters can be designed to endow the neurons with desired PDs in brain control.

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Combining Artificial Skin Stretch and Kinesthetic Force in Tool-mediated Interaction with Elastic Objects: the Effect on Perception of Stiffness and Grip Force Control

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There are two major kinds of force sensing modalities in our body – kinesthetic and tactile. During interactions with objects like a pen or a scalpel, kinesthetic force information is sensed by muscle spindles and Golgi tendon organs, while tactile information is sensed by cutaneous mechanoreceptors that respond to skin deformation. In such interactions, we use both types of information to estimate mechanic properties of the object and of the environment, such as stiffness and friction, and other external forces acting on our limbs. From these, we create internal models, which allow us to predict the consequence of the interaction. We use these internal models to modulate our applied grip force to prevent objects from slipping or being damaged by excessive force. Moreover, when cutaneous receptors indicate that slippage is occurring, our grip force increases through closed-loop feedback control. This suggests that not only perception, but also our grip force control is affected by both kinesthetic and tactile information.

Recently, tactile stimulation devices were developed. These devices can augment tactile sensation without affecting the kinesthetic force. In a previous study, artificial tactor displacement-induced skin stretch was added to a kinesthetic force and caused a linear additive effect on participants' stiffness perception. However, the effect of such skin deformation on grip force adjustment was not investigated to date.

In this study, we set out to investigate how different conditions of tactile information gains and kinesthetic force affect the perception of stiffness and grip force adjustment. We hypothesized that due to direct stimulation of cutaneous mechanoreceptors by the skin stretch, a greater grip force would be observed when the skin is stretched. We used a skin-stretch device and a standard robotic device to manipulate the tactile and kinesthetic information that the users experienced in a stiffness perception task. Our preliminary results suggest that inducing artificial skin stretch together with a kinesthetic force leads to an increase in perceived stiffness. Surprisingly, the grip force trajectories have a double peaked pattern that appears predominantly in the trials in which skin stretch was applied. We will discuss the additive skin stretch-induced augmentation of stiffness perception, the anticipatory modulation of grip force with load force, and the possible explanations of the double peaked grip force pattern.

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In interaction with elastic objects, the variability of action, unlike perception, decreases with increasing stiffness

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In the sensorimotor system, and especially in the touch system, perception and action are tightly coupled. However, there are numerous examples for disassociation between perception and action. For example, in grasping, where perception of object size obeys Weber's law, the accuracy of grasping action does not depend on the size of the object. It is well documented that perception of stiffness obeys Weber's law – the sensitivity to small changes decreases when the stimulus intensity increases. Signal detection theory suggests that this is due to increased variability in estimation of stiffness with the increase of stiffness. However, the effect of stiffness on the variability of probing movements and of the grip force that users apply on the tool is not clear. We hypothesized that a similar disassociation exists in interaction with virtual elastic objects, and the accuracy of movement and grip force adjustment would not depend on the stiffness of the object.

To test this hypothesis, we designed a series of adapation and perception experiments. In the adaptation experiments, participants made out-and-back movements to invisible targets inside elastic objects, and received feedback after each trial to achieve a desired movement magnitude. In Experiment 1, the target position was consistent across different stiffness levels. In Experiment 2, the target position varied such that the endpoint force was consistent across different stiffness levels. In Experiment 3, to validate that in our setup and stiffness range the perception of stiffness obeys Weber's law, we used a forced-choice paradigm to test the perception of stiffness.

We found that as stiffness increased, the variability of the movement and the variability of the adjustment of the grip force to the anticipated load force decreased. This observation suggests that the estimation of stiffness that was used for action planning violated Weber's law.

Understanding the effect of stiffness on the accuracy of action and perception is important for understanding the distinct processes of perception and action in the motor system, and for designing bilateral teleoperation control laws that will optimize the presentation of force information to users.

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Understanding the Perception of Dramatic Action from Visual Stimuli

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Accurate and quantitative descriptions are central for studying social interactions, but the quantitative tools currently available are limited. Theatre has a reservoir of practical concepts to recreate authentic human behavior and social interactions. Basing on this knowledge, we establish the theatre concept of dramatic action (DA), the effort that one makes to change the psychological state of another, as a quantitative means to describe human behavior. We defined a set of basic dramatic action verbs that fall into 3 categories: change of emotion, change of arousal and change of status. Additionally, we compiled a set of visual cartoon stimuli for these basic DA groups. Our findings show that people can reliably and reproducibly assign DA verbs to these stimuli. The relation between DAs and emotions was tested, and showed that the same dramatic action can be carried out with different emotions, implying that the two constructs are distinct. We are interested in studying the perception of DAs from visual stimuli. To this end, we intend to use stick figure dyads as stimuli to reduce dimensionality and variability while simplifying the representation of humans in the images. By systematically sampling the stick figure space, we will map this space to the DA perception space and explore the mapping's properties. We are interested in identifying the features in the body position that elicit the most prominent effect on DA perception. We also plan to study how small alterations of angles of the stick figure's joints induce different DAs and the nature of transitions between two different DAs. This opens the way to explore how people physically perform and perceive dramatic actions, and to enrich the psychological understanding of short social interactions. This knowledge can be employed to interpret DAs from videos and to elicit DAs using avatars in virtual reality applications.

Postures analysis of complex motor tasks

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Humans are capable of an enormous variety of movements that can be adapted to a huge number of specialized tasks. Models of sensory-motor planning using a cost function and optimizing parameters, can predict trajectories for simple movements such as reaching, but with unconstrained full body motions, the multiple degrees of freedom and complexity of natural task means that the solution may not be as straightforward. Indeed neural and behavioral results suggest that with complex natural movements, several alternative actions are generated, each probably governed by lawful principles such as energetic cost or kinematic constrains and with potential competing sensory motor control policies (Gallivant 2016).

The current study explores the choice of postures generated for complex motor tasks. First we look at the repertoire of postures being generated, then we examined whether they are repeated and are stable over repetitions. Subjects performed a tracing task in a virtual environment while their posture was recorded with a 50 marker PhaseSpace motion capture device. The virtual environment was displayed using an Oculus HMD. Subjects saw a 3D curve with small white sphere attached to it. Their right index finger was represented by another small sphere. On each trial subjects approached the curve from common starting point and could choose an initial posture with which to start the tracing. Each curve was composed of four different sections and repeated five times by each subject. Each section appeared in three curves. When the subject contacted the white sphere on the virtual curve, it started to move along the curve. Subjects were required to keep the index finger on the white sphere as it moved along the virtual curve.

Subject's recorded postures revealed that for each curve, one to three posture were used. Posture classification over all subjects, shows that subjects, in general, favored one posture over the other. Comparing posture from the same section that was embedded in different curves reveals an effect of context on posture selection, such that over all subjects, posture is more similar for sections embedded in the same curve (posture SEM 2.5m +-0.06m) than posture from single subject embedded in all curve (posture SEM 23.35m +-0.28m).

These results suggest that for natural complex movements, the common constraints of human kinematics tend to generate similar solutions, each generated with consideration of the global property of the required task. Our future work will explore whether these common postures reflect an energetic minimum.

An intermittent control based model predicts the nature of EMG activity during hand reaching

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Hand reaching movements between two points are an elementary motor activity. While there are various ways to reach from one point to another, these movements are typically made using a straight-line path with a stereotypic bell-shaped velocity trajectory. These motion features suggest that a simple control mechanism is responsible for the activation of the muscles needed to generate such movement. Many optimal control models were proposed to explain this mechanism, such as minimum jerk or minimum joints torque. Usually, these models are based on continuous control. Although we observe continues signals of position and velocity during reaching movements, the EMG activity exhibit bursts and silent periods occurring in a synchronized way between different muscles. These transitions raise the question whether the brain employs a continuous or discrete control strategy for muscle activation during reaching movements.

Here, we suggest a motor system hierarchy that is based on intermittence control. We propose that the brain uses a piecewise constant control signal to activate muscles. We suggest a model that explains this control signal as an output of an optimization problem in which the brain minimizes the hand acceleration during movement. To support this hypothesis, we derived transitions that are predicted from the transitions in the jerk signal of the Minimum Acceleration with Constraints (MAC) model. We also used a change-point analysis using a Monte Carlo Markov Chain (MCMC) method to extract transitions from the EMG signals that were recorded during reach movements. We show that the timing of transitions in the piecewise-constant control signal used to describe the hand trajectory are synchronized with the transitions times observed in EMG signals.

This result suggests that the nature of the control signal transferred from the high-level controller in the brain to the muscles may be based on intermittence control.

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Frequency of oscillations produced by central pattern generators composed of Matsuoka oscillators

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Central pattern generators (CPG) are neuronal circuits that can produce rhythmic motor patterns such as walking, breathing, flying, and swimming in the absence of sensory or descending inputs that carry specific timing information. CPGs can be modeled as a network of coupled oscillators. Matsuoka neuron is a simple mathematical model, which includes non-linearity and adaptation, and can produce sustained oscillations when coupled with other Matsuoka neurons. Thus, a CPG can be modeled as a network of coupled Matsuoka neurons. By varying the parameters, and especially the coupling weights between different Matsuoka neurons, a wide variety of oscillations can be produced. However, the challenge is to design a network of Matsuoka oscillators that would produce the desired oscillations, and in particular, oscillations with a desired frequency. This is especially important when designing CPGs or walking, since the desired frequency of oscillations should correspond to the natural frequency of the leg.

In a recent work Matsuoka estimated the frequency of oscillations for the simple case of symmetric 2neuron CPGs. For this simple case, the CPG becomes a second order system, and the frequency can be estimated by considering the first Fourier component of the output. However, even in this simple case, accuracy is limited, and the estimation does not capture well the non-linear change in the frequency with the coupling weight.

Here we develop neural networks for estimating the frequency of oscillations produced by networks of coupled Matsuoka neurons. Performance of multi-layer neural networks, with different number of hidden neurons will be compared with that of Mixture of Experts, with different number and types of experts. This work provides the basis for designing CPGs for stable walking using Genetic Algorithms.

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Re-Embodied, Re-Imagined, Cognition: Using Illusory Virtual Embodiment for Real-Time Recording and Adjustment of Sensorimotor Mental Imagery, and Its Implications for Cognitive Enhancement

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The coupling of spatiotemporal cognitive processes with mentally-simulated motor mechanisms has already been well established, and various bi-directional dynamics have been experimentally demonstrated. It is not yet clear, however, how one's mental imagery may change following re-coupling with altered bodily motor dynamics, and to what extent may novel spatiotemporal cognitive patterns be thus re-learned and applied. The current study aims to shed light on this question by inducing illusory feelings of ownership towards virtually simulated hands, precisely tracking one's physical hands while rotating a virtual 2D projections of Shepard and Metzler's (1971) classic mental-rotation shapes. The experiment groups differ by the virtual hands' effective rotation speed, simulated based on a physical-virtual motion-mapping factor, which is either 1:1 or 1:2. In order to experimentally establish both physical and mental spatio-temporal training, and get direct access to tracking the mentally rotated shapes, we use a novel physical-mental coupling technique, where subjects have to rotate an invisible shape towards a target angle, seeing only the simulated virtual hands, and getting a snapshot of the rotated shape's state only before and after the rotation. Mixed-effect comparison of pretest and posttest mental-rotation assessments shows a significantly higher increase in the following mental rotation speeds of the 1:2 motor remapping subjects over the 1:1 ones. In addition, all the physical and virtual hand motions were constantly tracked and recorded, to allow detailed post-analysis of the subject's physical and mental motor profiles, and their dynamics along the experiment. We report here also the results of this analysis, along with its assumed theoretical and practical implications. We suggest this virtual re-embodiment experimental design as a general motor and cognitive research platform, presumably enabling a more direct examination of internal motor control models, mental imagery, and a variety of embodied-cognition phenomena. We also plan to use it for future studies of the overall relation between mental and motor dynamics, concurrent cognitive and motor degradation, and the development of novel cognitive enhancement techniques.

Stochastic modeling of grasp CONFIGURATIONs

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Grasping is a critical component in activities of daily living and thus, a critical target for motion rehabilitation. Grasp analysis is complex, partly since most objects afford multiple grasp configurations. In the current work, we propose an innovative stochastic modeling method, which differentiates between grasp configurations according to their multi-dimensional spatial distribution, and quantifies the variability within each configuration. The proposed grasp configuration model is based on a six dimensional mixture probability distribution function. Each mixture component represents a grasp configuration type, where three dimensions represent grasp location using Gaussian functions and three dimensions represent grasp orientation using Von Misses Fisher cyclic functions. A non-parametric Bayesian estimation was applied for estimating the distribution parameters and the number of mixture components i.e., of grasp types. Non-parametric Bayesian estimation infers distribution parameters thus providing improved model generalization inference with respect to commonly used optimization based estimation methods, e.g., Expectation Maximization. Four subjects aged 50-75 years performed 20 reach-to-grasp movements each towards two cones placed at arm length distance and at 2/3 arm length distance. Arm movement was recorded using electromagnetic sensors (G4™ Polhemus). Movement trajectories were filtered using a Butterworth filter with 6 Hz cutoff frequency and start and end points were determined using a semi-autonomous procedure. Grasp configuration models were estimated for the wrist configuration at movement end for each subject and cone using 30,000 iterations where initial conditions were estimated based on user data. As expected, all subjects had a single grasp type with a low position variability (SD 1.4-6.8) and medium orientation variability (kappa 2.45-8.33).

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Motor acuity acquisition is rapid and does not generalize within and across effectors

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A central component in motor skill learning is improvement in motor acuity, which is thought to be the outcome of prolonged training. Using the Arc Pointing Task (APT), we investigate the effect of training duration on the performance and generalization of finely controlled wrist movements.

In the first day, after a short familiarization, 36 subjects performed 4 variants of the APT: clockwise (CW) and counter-clockwise (CCW) with their left, non-dominant, wrist and with their right wrist. Performance was estimated at 4 different speed ranges. Then, two groups of subjects trained in one speed on the CCW task with their left wrist for 2 and 3 days, and two control groups did not train at all. The performance in all groups, in all task's variants, was tested again after training.

Subjects from all groups showed a marked improvement in accuracy in the four task variants in the second test session, suggesting that the performance estimation session, that lasted approximately one hour, was enough to improve the skill levels in the task. Furthermore, all groups also showed a reduction in trial-by-trial positional variability at the end of the trajectory, suggesting that the improvement may be driven by an improvement in motor acuity. Two additional control groups, tested only on one variant of the APT and retested within 2 days and 2.5 hours, also showed a significant improvement in task performance.

Subjects that trained for 2 and 3 days gained additional improvement in performance and in variability compared to the control groups. The length of training (2 or 3 days) did not show an effect on performance, but did show an effect on variability, suggesting that the variability measure is more sensitive than the performance measure. We did not find any generalization of training gains to the other APT variants.

Our results suggest that motor acuity improves substantially following a single exposure to a task. Further training-induced gains in performance are specific to the trained task. Thus, while motor acuity acquisition was shown to generalize across speeds, it does not generalize across tasks performed with the same effector or across effectors.

Smooth Leader or Sharp Follower? Playing the Mirror Game with a Robot: Who Takes the Lead, and What Movements Are Most Liked?

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Rehabilitation has always been an arduous process, and thus the invention of rehabilitation robots seems to be not only essential but inevitable. Since Rehabilitation robotics has the potential to reduce the reliance on the daily care of one-on-one therapy time, we set out to test people's preferences when playing an interactive game with a robotic arm. Most research on Socially Assistive Robotics (SAR) so far has focused on designing robotic systems that serve as coaches in an exercise program. However, it has been shown that a partnership approach is preferable to a coaching approach in order to achieve collaboration. Therefore, we present a rehabilitation robot that serves as a partner in a game setting. We employed "the mirror game", a theatre exercise in which actors put their hands against each other, and move together in space – one leading and the other following. This is the first time that the mirror game is played with a robot. Twenty two young participants aged 20-30 played the mirror game with the robotic arm (22 trials, each lasting fifteen to twenty seconds), where each player (person or robot) follows the movements of the other in 3D space. We used a Kinect camera to capture the real-time location of the participants' hand. When the person was instructed to lead, the robotic arm followed the participant's hand. When the robotic arm lead, it performed a set of movements that were either sharp (a vertical zigzag, a horizontal zigzag and a rectangle) or smooth (a circle, an infinity sign and a cloud), which the participants were later asked to rate in terms of preference. We hypothesized that the participants would prefer the smooth movements because those movements are reminiscent of humanlike movements. We indeed found a preference for the smooth movements. Half of the participants preferred to lead, and half to follow. This experiment demonstrates the importance of the robotic motion paths in the human-robot interaction. It also sheds light on interpersonal differences (e.g., preference to lead or to follow), which highlight the importance of personalize human-robot interactions.

Where One Hand Meets the Other: Effector-Invariant Movement Encoding in the Human Motor System

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Cortical motor control exhibits clear lateralization: each hemisphere controls the motor output of the contralateral side of the body. Nevertheless, neural populations in ipsilateral areas across the visuomotor hierarchy are active during unilateral movements and even exhibit reliable directional selectivity during reaching movements to peripheral targets. It is unclear whether this directional selectivity is similar for ipsilateral and contralateral movements. If it is similar, in what coordinate frame is it similar: extrinsic/world-centered or intrinsic/joint-coordinates?

To address these questions, we measured fMRI responses in multiple visuomotor system areas of the human brain while subjects performed 'out and back' reaching movements to peripheral targets with either the right arm or the left arm. We used a multivariate classification analysis and a pattern-component correlation analysis (Diedrichsen et al., 2011) to determine if the voxel-by-voxel response patterns of specific cortical areas during movements of the ipsilateral hand were similar to the response patterns during movements of the contralateral hand. Our complementary analyses revealed that fMRI response patterns in visual cortex were invariant to the acting arm in extrinsic/world-centered coordinates, demonstrating that voxel-by-voxel fMRI patterns in visual cortex were selective to the location/target of the movement. In contrast, response patterns in motor cortices showed effector-invariant representation after flipping/mirroring the movement direction across the midline (e.g., activity patterns during left hand movements to left targets were similar to activity patterns during right hand movements to right targets). This suggests that in motor cortices, ipsilateral and contralateral neural populations encode movements in an effector-invariant manner in intrinsic/joint coordinates.

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Does the archerfish use motor adaptation to correct for light refraction?

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The archerfish is unique in its ability to hunt by shooting a jet of water from its mouth that hits insects above the water surface. To aim accurately, it needs to overcome the problem of light refraction at the air-water interface as there is a considerable difference between the actual and visible location of the insects as seen from below the water surface. Nevertheless, archerfish can still hit the target with high success rate from various angles and positions. Is the ability to compensate for the refraction a built-in mechanism or is it achieved by trial and error through motor adaptation?

As a first step towards this question, we determined if the fish can adapt to perturbations in the environment and make appropriate adjustments to its shooting method. We trained archerfish to shoot at a target situated above the water surface. If the hit was successful, it was rewarded with a food pellet. After several shots, an air flow applied horizontally to the water surface perturbed the fish's shot. The shots were recorded using a high speed camera and measured the fish's ability to deal with the perturbation.

We found that fish have the ability to adapt to our perturbation. Immediately after the introduction of the air flow perturbation, there was an increase in aiming error. Then, over the course of several trials, the error got smaller and, eventually, plateaued. On the first trials after the air flow perturbation was removed, the error was in the opposite direction, and this was washed out after several trials. This indicates that the fish was generating motor command that anticipated the perturbing air flow. Archerfish is capable of motor adaptation, which is a possible explanation for the light refraction correction

Our next step is to characterize in greater detail the fish behavior during adaptation and to record brain activity in the cerebellum and the optic tectum to reveal the mechanism of archerfish aiming.

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Novel Methodology for the Assessment of Balance Recovery During Gait in a Virtual Reality environment set up – preliminary report

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Introduction: Effective stepping reactions are essential for avoiding falls while standing and walking. Most studies addressed stepping reactions strategies while using treadmills (TMs) with fixed walking speed. To provide more ecological context, the aim of this study was to characterize stepping reactions during balance recovery, on a self-paced TM within a virtual reality (VR) environment.

Methods: Ten young healthy participants (age: 27.1±3.7, 2 females) walked in an immersive VR system (CAREN High End, Motek Medical, The Netherlands) which projected a virtual environment simulating a road on a full-room dome-shaped screen. Unexpected Medio-lateral (ML) and anterior-posterior (AP) perturbations were randomly introduced during the trials. Kinematic data were used to characterize balance recovery prompted by loss of balance during perturbed walking. This work reports step width and step length values obtained from one subject.

Results: Since the data were not normally distributed a-parametric statistics were performed. Median recovery time for all conditions combined was 3.17 seconds for step length (range 0.2-14) and 3.06 seconds (range 1.8-16.32) for step width. Median recovery time from ML perturbations was 3 seconds (range 0.2-14) for step length and 2.7 seconds (range 1.8-16.32) for step width. Corresponding results from AP perturbation were 3.9 seconds (range1.1-7.29) for step length and 3.3 seconds (range 2.5-6.4) for step width.

Conclusions: This preliminary report suggests that studying balance recovery responses to an unexpected perturbation using a self-paced treadmill, within VR environment is feasible for young heathy adults. Future analysis will attempt to differentiate between step length and width recovery times, compared across the type of perturbation (i.e., ML vs. AP) and during different gait phases. The results presented here indicate the potential merit of this approach. Methodologies for replacing the 'visual inspection' should be developed and introduced.

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Stroop effect in motion errors of remotely controlled agents

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Can cross modality Stroop effect raise as a result of incongruent visual and proprioceptive feedback in case of error in motion of manually controlled remote agent? In this case, visual feedback will alarm on error, while proprioceptive feedback from controlling limb will indicate correct operator action.

Recent results suggest that incongruence between visual and proprioceptive feedback is expected to be accompanied by reduced accuracy and slower processing speed. Hecht and Reiner, 2010, asked participants to judge applied forces in terms of direction, object weight, deformability of shape and vibration of object, while congruent, neutral and incongruent label cues, were presented visually. Judgments were done by pressing a button or moving an object in a 3D virtual reality environment which included real motion with haptic feedback. As found in the Stroop effect, response time was longer for incongruent, intermediate for neutral and least for congruent events.

In our study, we examine EEG correlates of interface errors with congruent and incongruent proprioceptive feedback. In our experiment, participants played a tennis game in an immersive 3D virtual world, against a computer player, by controlling a virtual tennis racket with a force feedback robotic arm. Errors with congruent visual-proprioceptive feedback were generated by unintended induced shifts of the end-effector-handle. Shifts were matched with the user's hand while controlling the virtual racket on the screen. Controlling interface errors with incongruent proprioceptive feedback were introduced by execution errors elicited by shifts of the user's virtual tennis racket on the screen without matched shift of the controller end effector handle, resulting in incongruent visual and proprioceptive feedbacks.

To evaluate a possible Stroop effect, we tested significance of the delay between the highest peaks of "Incongruent interface error" (grand average and mean individual ERP third positive peak latencies are 312.5 and 347.01±60.15 millisec (mean ± standard deviation) over all participants) and "Congruent interface error" (grand average and mean individual ERP fourth positive peak latencies are 314.5 and 316.88±56.53 millisec over all participants). Paired right one tailed t-test had shown that "Incongruent interface error" was marginally significantly delayed ($t(20) = 1.6258$, $p=0.0598$), with significance level of 5%, relative to "Congruent interface error", suggesting a visual-proprioceptive Stroop effect.

Inconsistent semantics, across visual-proprioceptive cues, is associated with longer response time, as in the classical Stroop effect. Therefore, effect of incongruence of sensory feedbacks should be taken into account during design of remote controllers.

The Effect of Robotic Embodiment on Repetitive Task Motivation in Young and Old Populations

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In recent years, rehabilitation practitioners have made increasing use of rehabilitative robotics to improve patient compliance, which is consistently low in medical interventions. To date, these tools have demonstrated limited efficacy in improving clinical outcomes. Recent research in the field of Socially Assistive Robotics (SAR) has shown promise in increasing patient motivation through hands-off interaction strategies. However, previous research has not incorporated the robotic entity as an active partner in the interaction. Here, we studied the effects of an embodied non-anthropomorphic robotic partner versus a non-embodied computerized partner on two age populations while participants played a game of Tic-Tac-Toe placing cups on a 3-dimensional grid.

The dependent variables included subjective evaluation questionnaires and motion analysis measurements. The independent variables were the environment (robot vs. computer-controlled lighting system) and the population (young vs. old).

Sixty-two participants (40 young (17 male, 23 female) aged 18-26 (mean 25.6±1.7 yrs) and 22 senior (10 male, 12 female) aged 65-80 (mean 73.1±6.5 yrs) played a series of 10 Tic-Tac-Toe games, five against each partner (embodied and non-embodied). In their turn, the participants placed a green cup in one of 9 locations on a physical 3x3 grid. To make a move, the robotic arm placed blue cups on the grid, and the computer-controlled lighting system turned on blue LEDs in the desired cell on the grid. Participants' motion was tracked via a Microsoft Kinect 2 camera.

We found significant differences between the embodied and the non-embodied systems in both game completion times (p=.006) and average arm velocity during reaching movements (p=0.001). A statistical difference was found between the age groups in average velocity of movement (p=.001), where the young participants were 15% faster than the senior participants. Younger participants demonstrated a clear preference for the robotic system (60%), especially when correcting for the robot's slower response time (85%), as opposed to the senior group, where 41% preferred the robot, and 59% of them did not have a clear preference.

This preference for the robotic opponent is interesting, given that it had minimal features to encourage user engagement. It is likely that this appeal can be increased in order to increase user compliance, e.g., by including more anthropomorphic features. An important factor in determining preference in the younger cohort was the time each system took to carry out a 'move'. These results highlight the importance of tailoring engagement strategies to individual users when designing SAR systems.