The 11th Karniel

Computational Motor Control

Workshop

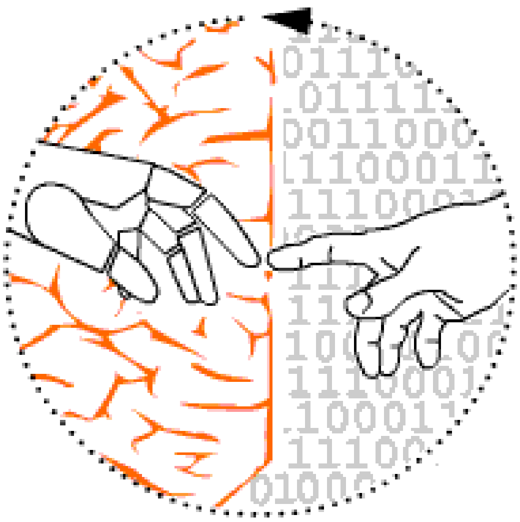
and

Agricultural, Biological and Cognitive

Robotics Initiative

Ben-Gurion University of the Negev

June 16-18, 2015, W.A. Minkoff Senate Hall,
BGU Marcus Family Campus, Beer-Sheva, Israel



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ABC Robotics Annual Workshop

June 16, 2015

Joyce Goldman Auditorium, Faculty of Health Sciences,
Ben-Gurion University of the Negev (BGU)
Beer-Sheva, Israel

מרכז זלוטובסקי למדעי העצב
Zlotowski Center for Neuroscience

Agricultural, Biological and Cognitive Robotics Initiative
Zlotowski Center for Neuroscience
Ben-Gurion University of the Negev

Tuesday, June 16

- 8:30-9:00 Registration, Poster placement and Refreshment
- 9:00-9:15 Opening remarks, Yael Edan, BGU, Israel

Human-in-the-loop Robotics

Chair: **Ilana Nisky**, BGU, Israel

- 09:15-9:45 **David Abbink**, TU Delft, Netherlands
"Haptic Shared Control for physical human-robot interaction"
- 09:45-10:15 **Anthony Jarc**, Intuitive Surgical, USA
"Robotic surgery and sensorimotor control – current research and opportunities"
- 10:15-10:45 **Jose Carmena**, UC Berkeley, USA
"Closed-loop design strategies for neuroprosthetic control"
- 10:45-11:15 Coffee Break

Autonomous Robotics

Chair: **Ronen Brafman**, BGU, Israel

- 11:15-11:45 **Amir Ayali**, TAU, Israel
"Insect-inspired robotics"
- 11:45-12:15 **Avital Bechar**, Volcani Institute, Israel
"Agricultural robots for field operations"
- 12:15-12:45 **Reid Simmons**, CMU, USA
"Robust Autonomy"
- 12:45-13:30 Lunch
- 13:30-14:15 Posters

Dedication of the Karniel Memorial at the Schwartz Movement Analysis & Rehabilitation Laboratory

- 14:30-15:00 Greetings, Joyce Goldman Auditorium
Prof. Rivka Carmi, President of BGU
Prof. Joseph Kost, Dean of BGU's Faculty of Engineering Sciences
Prof. Amos Katz, Dean of BGU's Faculty of Health Sciences

Faculty of Health Sciences, Ruth and Heinz-Horst Deichmann Building for Health Professionals (M8), room 050

- 15:10-15:30 Lab Dedication
Prof. Dan Blumberg, VP & Dean of Research and Development
Rinat Karniel, Family representative
Prof. Itzhak Melzer, Director, Recanati School for Community Health Professions

Lab Tours & Posters

- 15:45-17:15 Lab tours and posters in two rounds
    - Schwartz Movement Analysis & Rehabilitation Laboratory – Itshak Melzer
    - The Laboratory for Rehabilitation and Motor Control of Walking – Simona Bar-Haim
    - The Cognition, Aging & Rehabilitation – Shelly Levy Tzedek

Festive Dinner

Lawn of Beit HIAS Campus (BGU campus across from the Leonardo Hotel)

- 19:00-20:00 Festive Dinner
- 20:00 **Netta Pulvermacher**, Dean of the Faculty of Dance, Rubin Academy of Dance and Music, Israel
"To Fold the Big Bang"

agricultural biological & cognitive robotics

The Agricultural, Biological, and Cognitive Robotics Center of
Ben-Gurion University of the Negev
(Established based on generous support from the Helmsley Charitable Trust)

The 11th Karniel Computational Motor Control Workshop
June 17-18, 2015

W.A. Minkoff Senate Hall, BGU Marcus Family Campus
Beer-Sheva, Israel

מרכז זלוטובסקי למדעי העצב
Zlotowski Center for Neuroscience

Department of Biomedical Engineering
Zlotowski Center for Neuroscience
Agricultural, Biological and Cognitive Robotics Initiative

Wednesday, June 17

- 08:30-08:50 Registration, poster placement and refreshments
- 08:50-09:00 Opening Remarks

Motor physiology

Chair: **Roni Azouz**, BGU, Israel

- 09:00-09:30 **Opher Donchin**, BGU, Israel

"Hierarchies in cerebellar models"

- 09:30-10:00 **Jose Carmena**, UC Berkeley, USA

Keynote Lecture - "Large-Scale Neural Circuit Dynamics during Neuroprosthetic Skill Learning"

- 10:00-10:30 **Benny Hochner**, HUJI, Israel

"The embodied organization of the octopus motor control"

- 10:30-10:40 Discussion
- 10:40-11:20 Coffee

Motor memory

Chair: **Shelly Levy-Tzedek**, BGU, Israel

- 11:20-11:50 **Pablo Celnik**, JHU, USA

"Neurophysiological markers of motor learning"

- 11:50-12:20 **Miriam Reiner**, Technion, Israel

"Memory consolidation of motor sequences"

- 12:20-12:50 **Jean-Jacques Orban De Xivry**, KU Leuven, Belgium

"Reading and manipulating motor memories in the motor cortex"

- 12:50-13:00 Discussion
- 13:00-14:30 Lunch and Posters

Structure of movement

Chair: **Naftali Tishby**, HUJI, Israel

- 14:30-15:00 **Aldo Faisal**, ICL, United Kingdom

"The structure of natural human motor behavior"

- 15:00-15:30 **Sandro Mussa-Ivaldi**, Northwestern University, USA

“On the formation of inverse kinematic models through the operation of a human-machine interface"

- 15:30-16:00 Prof. Amir Karniel Memorial Young Investigator Lecture **Firas Mawase**, JHU, USA

"The hidden connectivity of the cerebellar-thalamic-cortical network predicts learning and retention of motor memory"

- 16:00-16:10 Discussion
- 16:10-16:20 Poster awards

Sponsors: Intuitive Surgical, AlphaOmega, NBT

- 16:20-17:00 Coffee break and walk to Building 51 Room 15

Motor control

Chair: **Miriam Zacksenhouse**, Technion, Israel

- 17:00-17:30 **Oron Levin**, KU Leuven, Belgium

"Aging and Motor Control: Does inhibition Matter?"

- 17:30-18:00 **Frederic Danion**, CNRS Timone Institute of Neuroscience, France

"Challenging grip force control during object manipulation tasks"

- 18:00-18:30 **Claude Ghez**, Columbia University, USA

"Auditory kinesthetic feedback enhances both accuracy and adaptive control of hand trajectory in reaching"

- 18:30-18:40 Discussion
- 19:00 Dinner

Thursday, June 18

Desert Hike

Makhtesh Ramon (Ramon’s crater), Ramon's Visitors center and a hike in the heart of the crater in the trail of mount "Saharonim" and Wadi "Nikarot".

We are grateful for the generous support of our sponsors: the President of BGU, the Dean of Engineering Sciences, the Dean of Health Sciences, Zlotowski center for Neuroscience, ABC Initiative supported by Helmsley Charitable Trust, Intuitive Surgical, Alpha Omega, and NBT.

Talks

ABC Robotics

June 16

Haptic Shared Control for physical human-robot interaction

David Abbink

TU Delft, Netherlands

Manual control tasks - like driving or flying - are prone to human errors. A popular engineering solution is to increasingly automate the task, which tends to physically decouple human operators from control interfaces and push them towards a more supervisory role. In the real world, persistent issues regarding human-automation interaction occur in case of unexpected situations: lack of situation awareness, overreliance, difficulty in handing back control etc.

In this talk, Dr. Abbink shows that the main cause of these problems lies in a lack of intuitive communication: the human doesn't fully understand the intelligent system, and vice versa. He will argue that a powerful solution is haptic shared control, where human and intelligent system can physically and dynamically share control over the task.

In his work, Dr. Abbink has used human motor control as a central theme for both the design and the evaluation of haptic shared control systems. This talk will illustrate his lab's main findings on how humans adapt to (and benefit from) haptic shared control; including a haptic gas pedal to support drivers with car-following (marketed by Nissan), and haptic shared control of telerobotic arms operating in complex remote environments (maintenance of nuclear reactors, deep-sea mining, space).

Robotic surgery and sensorimotor control – current research and opportunities

Anthony Jarc

Intuitive Surgical, USA

Effective surgeon-robot interaction is vital to enhancing the capabilities of surgeons during robot-assisted minimally invasive surgery (RAMIS). Critical to these interactions is a thorough understanding of how a surgeon plans and executes her movements. Conveniently, many aspects of surgeon behavior, such as hand movements and tool trajectories, can be measured unobtrusively during RAMIS. This offers the potential to improve surgeon training, user interfaces, and robot design while at the same time developing and testing theories of human sensorimotor control. In fact, similar to wearable technologies, RAMIS offers an unparalleled opportunity to record these movements for every surgery completed with a robotic system which could lend itself to extremely large datasets for a challenging and highly coordinated motor task.

In this talk, I will present an introduction to the da Vinci surgical systems and augmenting technologies, such as tele-mentoring tools and fluorescence imaging. Next, I will highlight several examples of interesting surgeon behaviors that correlate with expertise and that might be influenced or driven by foundational aspects of human sensorimotor control. These behaviors include frequent camera adjustments across both surgical and training tasks, efficient workspace range with their hand controllers, choices of motion scaling, and eye gaze. Finally, I will provide an overview of academic outreach opportunities supported by Intuitive Surgical, Inc., including technical and clinical research grants and the da Vinci Research Kit (a master-slave robotic system that uses recycled components from old da Vinci systems).

Closed-loop design strategies for neuroprosthetic control

Jose Carmena

University of California, Berkley, USA

Brain-machine interfaces (BMIs) hold great potential to aid large numbers of people with sensory, motor and cognitive disabilities. BMIs provide also a framework for examining basic neuroscience questions, especially those related to the understanding of how neural plasticity relates to the acquisition and consolidation of neuroprosthetic skills, i.e. accurate, readily-recalled control of disembodied actuators irrespective of natural physical movement. In this talk I will postulate that achieving skillful, natural control of a multi-degree-of-freedom prosthetic device will entail synergizing two different types of adaptation processes: natural (brain plasticity) and artificial (decoder adaptation), as well as providing realistic sensory feedback from the prosthetic device. I will present recent work from our laboratory showing that 1) neuroplasticity facilitates consolidation of neuroprosthetic motor skill in a way that resembles that of natural motor learning; and 2) closed-loop decoder adaptation (CLDA) techniques can expedite the learning process by adapting the decoder parameters during closed-loop BMI operation (i.e., while the subject is using the BMI). We believe that BMI systems capable of exploiting both neuroplasticity and CLDA will be able to boost learning, generalize well to novel movements and environments, and ultimately achieve a level of control and dexterity comparable to that of natural arm movements.

Insect inspired robotics

Amir Ayali

Tel-Aviv University, Israel

Insects are an inexhaustible source for scientists who desire to inspire ideas, processes, structures, functions, and behaviors from biology and implement them into engineering, specifically those interested in locomotion and in the improvement of robot mobility. Prof. Amir Ayali and his group at the Tel Aviv Department of Zoology are utilizing an interdisciplinary approach in the study of Insect inspired robotics. Several projects in the lab focus on different insect models and on different means of locomotion.

While insects' six-legged locomotion is acknowledged as extremely stable, suited for any kind of terrain, and allowing both high speed and extreme maneuverability, understanding its complex neural control is very challenging. The common cockroach is a leading model of six-legged locomotion and a great inspiration for robotics. High-speed video monitoring of behavior, electrophysiological recordings of nerves and muscles activity, mathematical modeling and computer simulations are combined to offer novel insights into the details of six-legged walking and its control.

Recent years have seen an increasing demand for miniature mobile robots in order to perform tasks in fields such as medicine and defense. The locust has been an attractive candidate to mimic because of its size and jump performance. We develop a locust-inspired 25 gr robot that jumps to a height of 2.5 meters. Locust jumping includes two phases: a slow charging of elastic elements in the leg joints, and quick energy release from the elastic elements to the legs structure, which converts to kinetic energy generating the jump. The robot converts electrical energy to mechanical energy by way of a small battery and a motor, and utilizes the energy for the leap in a similar, two phase process. We further explore the behavior of locusts in order to reveal the mechanics of their azimuth control, and implement these results in the design of the miniature jumping robot. A first successful prototype is currently being tested.

In recent years there has been much interest in understanding how the noisy and chaotic behavior of individuals congruent to novel group-level dynamics and capabilities. This applies to animal swarms such as locusts, birds or fish, as well as to optimization methods in computer science and robot swarms. Locust swarming is a quintessential example of collective motion. In the lab we obtain natural-like locust collective marching behavior in a closed circular arena. Our recently initiated project is first aimed at developing an autonomous robot that mimics the behavior of a locust in the marching swarm. The robot will simulate a locust in size but not in details of its shape and motion mechanism (i.e. wheeled rather than legged). In the first phase, the robot will be controlled by a fuzzy control system (expert system FIS) and later it will be upgraded to ANFIS controller, with an option to adjust the algorithm to the changing needs.

Agricultural robots for field operations

Avital Bechar

Volcani Institute, Israel

Robots are perceptive machines that can be programmed to perform a variety of agricultural tasks, such as cultivating, transplanting, spraying, selective harvesting and etc. Agricultural robots have the potential to enhance the quality of fresh produce, lower production costs and reduce the drudgery of manual labor. However, in agriculture, the environment is highly unstructured. The terrain, vegetation, landscape, visibility, illumination and other atmospheric conditions are not well defined; they continuously vary, have inherent uncertainty and generate unpredictable and dynamic situations. Extensive research has been focused on development of agricultural robots to a variety of field operations and technical feasibility has been widely demonstrated. Autonomous robots in real-world unstructured environments still yield inadequate results, and the promise of automatic and efficient autonomous operations has fallen short of expectations in such environments. Despite the tremendous effort, very few are operational in agriculture production systems.

In order for robots to satisfactory perform in agricultural environments and execute agriculture tasks, the research must focus on fusion of several complementary sensors to reach adequate localization and sensing abilities; develop simple manipulators performing the agricultural task description; develop path planning, navigation and guidance algorithms suited to greenhouse environments besides; and, integrate human operators in this complex and highly dynamic situation.

Four case studies for development of autonomous and human-robot collaborative systems developed at the agricultural robotics lab (ARL) are presented: 1) an autonomous robot for disease monitoring – the system is developed based on a holistic approach integrating the design of both motion and perception; 2) a spraying robot for greenhouse specialty crops - an adaptive algorithm for navigation of a robotic sprayer in pepper greenhouses was developed, implemented and tested on an experimental robot and on a prototype of a robotic sprayer based and retrained from a commercial sprayer.; 3) a human-robot melon collector; and, 4) an advanced human-robot collaborative system for selective tree pruning.

Robust Autonomy

Reid Simmons

Carnegie Mellon University, USA

The world is an uncertain and unpredictable place, and autonomous robots need to deal robustly with whatever situation they encounter.

Unfortunately, most current robots are not very good at handling situations that were not previously anticipated. To deal with this, we are investigating several model-based techniques that use probabilistic reasoning and planning to detect, and recover from, unexpected situations. We describe techniques for learning task models, reasoning about the probability of failure, taking risk into account, and using a hierarchy of models to recover from failure. The hope is that combinations of such techniques, which combine planning and execution, will lead to much more robust autonomous robots.

Talks

CMCW

June 17

Hierarchies in Cerebellar Models

Opher Donchin

Ben-Gurion University of the Negev, Israel

The idea that the cerebral cortex in hierarchically organized is well accepted. However, the same notion, when applied to the cerebellum, is rarely discussed. I will discuss existing models of the cerebellum and its role in the larger motor architecture. However, I will take a particular interest in the hierarchical nature of the surrounding motor architecture and how this affects our understanding of the cerebellar model. I will explore specifically the cortical hierarchy associated with reaching movements and the brainstem neural structures associated with the compensatory eye movement system. In both cases, I will use feedback control models as a starting point for my understanding of the system. In the case of reaching movements, I will argue, on the basis of results from Voxel Based Morphometry, that only a hierarchical approach can explain the way our motor system is structured. In the case of the compensatory eye movement system, I will use a detailed model of the system to explain a wide variety of behavioral data. In this case, as well, only a hierarchial approach can explain the existing data.

Large-Scale Neural Circuit Dynamics during Neuroprosthetic Skill Learning

Jose Carmena

University of California Berkley, USA

We are interested in how sensorimotor skills are learned and consolidated in the brain. We approach this problem using a neuroprosthetic skill learning paradigm. This is a very powerful framework for studying the neural correlates of learning behavior as it offers researchers the unique opportunity to directly control the causal relationship between neuronal activity and behavioral output. In particular, we focus on the question of how neuroplasticity relates to the acquisition and consolidation of neuroprosthetic skills, i.e. accurate, readily-recalled control of disembodied actuators irrespective of natural physical movement. The importance of this question is paramount as it impacts both brain function and dysfunction. In this talk I will present recent work from our laboratory using electrophysiology and imaging techniques in awake behaving primates and rodents, showing that 1) neuroplasticity facilitates consolidation of neuroprosthetic motor skill in a way that resembles that of natural motor learning; 2) corticostriatal plasticity is necessary for neuroprosthetic skill learning, and 3) operant learning occurs through the selection of specific neural patterns via feedback and reinforcement. A greater understanding of the neural substrates of neuroprosthetic skill learning can provide insight into the mechanisms of natural sensorimotor learning as well as help guide the development of neurobiologically-informed neuroprosthetic systems designed to aid people suffering from devastating neurological conditions.

The embodied organization of the octopus motor control

Benny Hochner

Hebrew University, Israsel

In my talk I will review previous and recent findings on the unique motor control system of the octopus. A comprehensive assessment of our findings have led us to conceptualized the idea that the octopus, because of its soft body with eight long and flexible arms and unusual morphology, is an exceptionally good instructive system to show that 'embodied-organization' is not only an important concept for designing autonomous robots (Pfeiffer, R et al 2007), but it is likely also an important constraint in the evolution of highly adaptive and efficient motor control mechanisms. This is especially apparent in animals like the octopus that have evolved from a soft bodied, shell protected, hardly moving mollusks into highly active maneuverable predators. Indeed, I will show that the research of octopus motor behavior is a vivid biological demonstration of concepts like: embodied organization; embodied intelligence; emergence; self-organization; morphological computation; reshaping; and even "Intelligence without representation" (Brooks 1991).

Neurophysiological markers of motor learning

Pablo Celnik

Johns Hopkins University, USA

Non-invasive brain stimulation has allowed the investigation of physiological processes underlying motor learning. In recent years we have shown that acquisition and retention phases of motor learning are associated to changes in cerebellar-M1 connectivity and LTP-like processes in M1 respectively. Interestingly these studies addressed different motor behaviors which likely weight differently the many mechanisms of motor learning (i.e. error-based learning, use-dependent learning, reinforcement). In this presentation I will discuss this research as well as the advantages and limitations of non-invasive brain stimulation in motor learning investigations.

Memory consolidation of motor sequences

Miriam Reiner

Technion, Israel

The literature suggests that theta oscillations of the hippocampus and remote distinct brain regions, is involved in motor memory consolidation, and happens during night sleep. My question was whether the same process of memory consolidation could be replicated during the day. I used a neurofeedback protocol to train users to increase their relative power of theta and compared performance after neurofeedback in the experimental and two control groups. Results show significant enhanced performance, after theta training, in the experiment group, but not in the control group. This improvement was further enhanced over the following nights.

This work is based on a published paper in biological psychology. In a continuing study we found that speed was enhanced and the speed-accuracy tradeoff is broken following theta neurofeedback.

Reading and manipulating motor memories in the motor cortex

Jean-Jacques Orban de Xivry

Katholic University Leuven, Belgium

The motor cortex (M1) has been associated with motor memories for decades. However, the conditions to obtain the formation of motor memories in M1 are still unclear. In this talk, I will show that the experience of a reward prediction error is necessary to observe the formation of a motor memory during motor adaptation and that it is likely that this memory is hosted in M1. Indeed, the experience of a reward prediction error after the abrupt introduction of a perturbation gives rise to saving (i.e. faster relearning) compared to when the perturbation is introduced gradually (which does not induce a reward prediction error). In addition, abrupt introduction of a force-field perturbation but not its gradual introduction induces a change in motor-evoked potentials elicited by TMS on M1 before movements, which suggest that abrupt but not gradual introduction of a perturbation induces the formation of a motor memory in M1, which can be read with TMS. Finally, I will provide some evidence suggesting that the state of M1 is critical to the encoding and retrieval of motor memories. Here, I will demonstrate that tDCS of M1 can act as a context for the encoding of motor memories in M1 and that this context can be used later to induce the artificial retrieval of the motor memory. Together, these studies suggest that motor memories are very sensitive to the environment at the time of memory formation (reward prediction error or state of M1).

The structure of natural human motor behavior

Aldo Faisal

Imperial College of London, United Kingdom

Our research questions are centered on a basic characteristic of biological systems: noise and structured variability in behaviour and its meaning. Variability can be observed across many levels of biological behaviour: from the movements of our limbs, the responses of neurons in our brain, to the interaction of biomolecules. Such variability is emerging as a key ingredient in understanding biological principles (Faisal, Selen & Wolpert, 2008, Nature Rev Neurosci) and yet lacks adequate quantitative and computational methods for description and analysis. Crucially, we find that biological and behavioural variability contains important information that our brain and our technology can make us of (instead of just averaging it away): The brain knows about variability and uncertainty and it is linked to its own computations. Therefore, we use and develop statistical machine learning techniques, to predict behaviour and analyse data. Using advanced body sensor networks, we measured eye-movements, full-body and hand kinematics of 40+ humans living in a studio flat and are going to present some insightful results on motor control and visual attention that suggest that the control of behaviour "in-the-wild" is predictably different ways than what we measure "in-the-lab".

On the formation of inverse kinematic models through the operation of a human-machine interface

Sandro Mussa-Ivaldi

Northwestern University, USA

Human machine interfaces, based either on neural signals or on body motions, map a high-dimensional signal vector onto some lower-dimensional control vector, such as the position of a cursor on a two-dimensional monitor, the configuration of a robotic arm or the speed/direction command to an electrically powered wheelchair. In this sense, controlling a device via an interface presents a computational problem analogous to controlling a limb by the activity of multiple muscles: many "equivalent" solutions can be derived for a particular kinematic goal. The human-machine interface offers therefore an unparalleled opportunity to investigate how this computational problem is solved by human subjects through a learning process that effectively starts from "tabula rasa", that is from the absence of a well-established prior. I will present some recent investigations based on an interface system (the body-machine interface, BMI) that maps linearly a vector of "body signals", h, onto a two-dimensional cursor point x. The body signals are generated by inertial measurement units placed on the shoulders of participants with tetraplegia following cervical spinal cord injury. The mapping established by the BMI has the form

$x=\mathbf{A}\ h$

where $\mathbf{A}$ is a rectangular Nx2 matrix (N>2). To be successful, the participants must learn an inverse mapping from target cursor location, to body vectors. Assuming that this is a linear mapping

$h=\mathbf{B}\ x_T$

this mapping must be a right-inverse of $\mathbf{A}$. That is, it must satisfy the condition

$\mathbf{A}\ \mathbf{B}=\ \mathbf{I}_2$ where $\mathbf{I}_2$ is the 2-dimensional identity matrix. Since, there are infinite such candidate mappings, we consider if subjects practicing the control of a cursor via the interface learn a particular inverse. We address this question experimentally by a least squares procedure over the body-signal and target data. We also consider a state based-computational model where the evolution of the inverse mapping depends upon its initial value and upon the experienced pattern of reaching errors.

The hidden connectivity of the cerebellar-thalamic-cortical network predicts learning and retention of motor memory

Firas Mawase[1], Simona Bar-Haim[2] and Lior Shmuelof[2]

[1]*Johns Hopkins University, USA*
[2]*Ben-Gurion University of the Negev, Israel*

Individuals show different levels in learning and retention of motor memories, yet little is known about the neural basis behind this variability. Why do some people show faster learning of a given task than others and why do others retain better the learned pattern? In an attempt to answer these basic questions, we investigate the neural basis of motor learning and retention, by examining the relationship between functional connectivity in resting state fMRI and the ability to learn and retain novel locomotor patterns. In light of previous results in human patients and nonhuman primates, we focus on the connectivity between the primary sites of the cerebellar-thalamic-cortical pathway, which have shown to be involved in forming and learning motor memories.

We were specifically interested in asking whether baseline connectivity levels are indicative of the ability of subjects to learn and retain novel locomotor patterns and how functional connectivity between regions of interest changes following learning.

Thirteen subjects participated in a protocol of three consecutive days. In the first day, subjects did a baseline session in which they were instructed to walk on a split-belt treadmill with no speed perturbations. Subjects then moved to the MRI scanner and underwent anatomical, functional and structural MRI. In the second day, subjects adapted to the split-belt treadmill with the belts of the treadmill moving at different speeds, and then moved to the scanner and underwent comparable MRI session. On the third day, and in order to evaluate the level of task's retention, subjects performed behavioral session of adaptation-washout-readaptation protocol.

Interestingly, we found that the connectivity between cerebellum and thalamus predicted savings (i.e. rate of relearning) across individuals while baseline connectivity between thalamus and motor cortex predicted the retention (i.e. initial bias of relearning) of the motor task across individuals. Moreover, we detected significant change in functional connectivity both between the cerebellum and thalamus and between the cerebellum and motor cortex following motor learning.

Our results provide two main findings: First, the best of our knowledge, we are first showing that connectivity in the cerebellar-thalamic and the thalamic-cortical networks can serve as a predictor for consolidation upcoming motor memories. Second, we extended previous results and showed that cerebellar-cortical network play a major role in locomotor adaptation and subject to change following locomotor training. Taken together, these results provide experimental support for a potential component of the core underlying variability across people, by showing that variability across individuals to learn and recall motor memories can be predicted based on the default mode of the cerebellar-thalamic-cortical system.

Aging and Motor Control: Does inhibition Matter?

Oron Levin

Katholic University Leuven, Belgium

Many motor related declines that healthy older adults experience in daily life (such as longer reaction times, impaired coordination skills, and deterioration of fine motor control) could be explained by structural and biochemical alterations associated with gray matter (GM) loss, white matter (WM) microstructural changes, and reduction in the concentration of chief neurotransmitters. Neurochemical studies using animals suggest that in the aging brain the efficacy of gamma-aminobutyric acid (GABA)-ergic, primary inhibitory neurotransmitter in the mammalian central nervous system (CNS), mediated cortical inhibition is compromised. In the human aging brain, it is suggested that decline of inhibitory (as well as excitatory) functions within the primary motor cortex (M1) may be a consequence of diminished neurotransmitter release, degradation of neurotransmitter receptors, shifts in neurotransmitter concentrations. In addition, age-related changes in the structural and neurochemical properties of CNS may affect functional communication between substructures of the brain's (inhibitory) network which ultimately give rise to age-related declines in (motor) behavior.

Over the past two decades the architecture and functional characteristics of the inhibitory brain network have been studied extensively by non-invasive neuroimaging and brain stimulation techniques. Evidence for linking poor inhibitory control with declined performance of voluntary movements has become available with the combined use of neuroimaging techniques (in particular functional magnetic resonance imaging-fMRI and diffusion tensor imaging-DTI) and noninvasive brain stimulation techniques (specifically, transcranial magnetic stimulation-TMS). Specifically, observations suggest that successful performance of a motor task in older adults is related to the capacity to modulate inhibition through the GABAA and GABAB receptor-mediated neurotransmission systems. As a decline in the integrity of the GABA-ergic inhibitory processes may emerge due to age-related loss of white and gray matter, a promising direction for future research would be underscoring relationships between declines in the inhibitory control of movements and other biomarkers of aging which reflect changes in structural, biochemical and functional brain metrics.

The working hypothesis that is currently examined by our research group (and others) put forward the idea that changes in brain structural and neurochemical properties may provide the key for changes in the functional reorganization of the aging brain as well changes in functional communication between substructures of the brain's (inhibitory) network which ultimately give rise to age-related changes in (motor) behavior. Nonetheless, the boundaries and structure of the brain network that regulate inhibition are not fully acknowledged and some substructures of this network (e.g., the prefrontal network) are more prone to the aging process than others. Specifically, there is still a lack of clarity about the factors contributing to age-related declines in the ability to inhibit actions. In the present talk I aim, specifically, to point at the missing part of the puzzle and open a discussion about possible theoretical and empirical frameworks that could shed light on the neurological mechanisms underlying impaired inhibitory control of movements in healthy aging.

Challenging grip force control during object manipulation tasks

Frederic Danion

Aix-Marseille University & CNRS, France

During my talk I will provide an overview of our studies investigating the control of grip force when humans need to transport and manipulate objects. Many studies have demonstrated that when we move an object, our grip force is scaled as a function of object properties but also as a function of the load that results from the object motion. The fact that grip force is adjusted in synchrony (or slightly ahead) of the resulting load force is taken as an evidence that the brain can predict the consequences of self-initiated movement. My plan will be to present a series of studies that were performed to investigate the sensory-motor processes underlying these anticipatory grip force adjustments. I will first review two experiments in which grip force control during object manipulation was examined in the context of biased visual feedback. In the first experiment subjects were exposed to delayed visual feedback, a situation frequently encountered in teleoperation, while in the second one subjects were exposed to a visual flow giving rise to the illusion of whole body movement. Then I will present an experiment in which subjects had to transport an object toward a target that could jump unexpectedly at movement initiation. These three experiments were performed in Marseille in collaboration with Fabrice Sarlegna, Gabriel Baud-Bovy and Lionel Bringoux. Finally I will present two experiments in which subjects had to manipulate object with unusual dynamics. In the first one we investigated the contribution of visual and haptic feedback when learning to control non-rigid objects. In the latter one we tried to identify whether hand and arm use separate representation of objects dynamics. These two studies were conducted jointly with Randy Flanagan, and Jonathan Diamond using state of the art robotic devices at Queens University.

Auditory feedback enhances accuracy and adaptive control of hand trajectory in reaching

Claude P. Ghez[1], Aaron T. Faith[2]

[1] *Columbia University, USA,*
[2] *Arizona State University, USA*

These experiments investigate subject's ability to use auditory feedback of kinematic and/or kinetic variables improve the accuracy of aimed point-to-point movements and to adapt trajectories to changes in visuomotor gain or dynamic perturbations. Different variables were sonified in different in each experiment. Movement extent was mapped discretely as notes of a C-Major scale. Following movement, a white noise sound whose middle frequency was modulated with the distance from the target center allowed subjects to complete target acquisition after each trial. Finally, in studies of dynamic adaptation we sonified the forces that subjects applied to the handle of the manipulandum as a continuously varying pitch somewhat like the sound of a cello. In these experiments we compared endpoint distributions and hand trajectories of horizontal reach-and-hold movements made with visual knowledge of results (KR) of final hand positions but without visual feedback with those of movements made with auditory feedback.

(1) Terminal accuracy and precision was substantially and consistentoly greater when subjects were allowed to calibrate their estimates of the required final position in proprioceptive coordinates by bringing their hand to the center of the target after movements. Improvements were similar when subjects used visual or auditory feedback for this purpose.

(2) In adapting to gain changes, subjects increased or decreased the movement extents and rescaled movement speed appropriately whether the change was experienced with auditory feedback of movement extent or as visual KR after movement termination. With auditory feedback. However, subjects adjusted trajectories already during the first movement itself when auditory feedback provided real time information of movement extent than with visual KR alone. Adaptive changes in also peak speed developed more rapidly and terminal accuracy was greater.

(3) In our study of adaptation to altered dynamics subjects moved the handle of a two-joint robotic manipulator. We used a novel acceleration curl field, which selectively perturbed and deviated initial trajectories rather than movement termination. Successful target acquisition was signaled by an explosion sound and a change in target color. Target size was titrated such that all subjects achieved the same number of successes in all comparison groups. Our results thus far indicate that movements made with proprioception feedback alone tend to progressively decrease initial deviations and recover the rectilinearity of control paths. However, when subjects are provided with auditory feedback of their lateral force on the handle, they showed systematic curvatures directed into the perturbations. We hypothesize that auditory augmentation of haptic feedback improves subjects' ability to identify the applied perturbations and to develop a functionally useful control policy for target acquisition that does not require rectilinearity.

Posters

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A Difference of Convex Stochastic Optimal Control Formulation for Describing Reaching Movements in Presence of Obstacles

Arun Kumar Singh, Sigal Berman and Ilana Nisky

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Robotics applications featuring physical interaction between humans and robots may benefit substantially from frameworks that model the cognitive and dynamical aspects of human motion. For example, assisted teleoperation heavily relies on predicting the trajectory that a human intends to employ to perform a particular task. However, the current trajectory prediction mechanisms employed in robotic applications do not exploit well known characteristics of human motion stemming from the experimental and computational motor control studies.

In this study we attempt towards bridging this gap. We propose a stochastic optimal control framework for modelling human reaching movements in the presence of obstacles. The objective function of the proposed optimization consists of terms minimizing the control effort, the end point variance, and maximizing the probability of collision avoidance. The computational challenge of the problem stems from the multiplicative nature of the noise as well as presence of probabilistic terms in the objective function. We present simulation results which demonstrate the interplay between various uncertainty components in various non-trivial configurations of multiple obstacles.

In future studies, we intend to employ this framework to develop a trajectory prediction mechanism for applications such as robot assisted surgeries. Various anatomical structures can be viewed as obstacles to be avoided by the surgeon while navigating between a given start and goal locations. Since the proposed formulation has a difference of convex form, it can be efficiently solved, thus making it suitable for real time applications. In addition, the theoretical exposition provided here has important implications for understanding human motor control. As opposed to robotic motion planning research, there have been only a few attempts towards modeling human obstacle avoidance motion. Finally, we strive to bring the formulation closer towards optimal feedback control, which does not incorporate probabilistic collision avoidance constraints.

Research supported by the Helmsley Charitable Trust through the Agricultural, Biological and Cognitive Robotics Center of Ben-Gurion University of the Negev.

Action Perception Model for Navigational Learning

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We present a model of spatial learning based on the reference memory task in the Morris watermaze. The model applies basic principles of Newtonian mechanics, optimal control and information theory to analyze the value-complexity tradeoff of the empirical trajectories exhibited by mice over several days of training in the watermaze. Our analysis suggests that mice initially try to optimize the value of the trajectories, by finding relatively short and energy efficient paths to the target, and only afterwards they turn to optimizing the complexity of the trajectories, by finding simpler paths to the target with only marginally lower values.

This model could provide new ways of analyzing experimental data obtained from the Morris watermaze or similar paradigms.

Data provided by the lab of Dr. Sagiv Shifman

Activity in superior parietal lobule during training by observation predicts subsequent performance gains

Ori Ossmy, Roy Mukamel

Tel-Aviv University, Israel

A dominant idea in motor cognition links motor control with action observation. Previous behavioral and imaging studies in humans have shown that training by passive observation of actions can result in motor skill learning and performance gains. Nevertheless, the role of observed hand identity (left/right) during such training is unclear. Through the use of 3D Virtual Reality devices we generated visual input simulating the subject's real hands. 18 subjects trained on a novel motor skill (sequence of finger movements) while passively observing their virtual right or left hand performing the action. Gains in each hand (difference in performance level before/after training) were obtained. We found no difference in performance gains across hands following training by observation of left or right virtual hand. However, across subjects the correlation between left and right hand performance gains depended on the identity of the observed hand. Training by observation of the left hand yielded positive correlation between performance gains of both hands, while right hand observation resulted in a negative correlation. Next, we investigated the underlying neural mechanism of this phenomenon. We recorded functional magnetic resonance imaging (fMRI) data from an additional set of 18 subjects and found that activity in bilateral Superior Parietal Lobule (SPL) during training by observation correlated with subsequent performance gains. This was true for both tested hands and observational training condition. These results imply that in the absence of overt physical practice the bilateral SPL plays an important role in the process of learning by observation irrespective of the identity of the observed hand.

Affine differential geometry and smoothness maximization as tools for identifying geometric movement primitives

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Neuroscientific studies of the drawing-like movements usually analyze neural representation of either geometric (eg. direction, shape) or temporal (eg. speed) features of trajectories rather than trajectory's representation as a whole. This work is about empirically supported mathematical ideas behind splitting and merging geometric and temporal features which characterize biological movements. Movement primitives supposedly facilitate the efficiency of movements' representation in the brain and comply with different criteria for biological movements, among them kinematic smoothness and geometric constraint. Criterion for trajectories' maximal smoothness of arbitrary order n ($n = 3$ is the case of the minimum-jerk model) leads to a class of differential equations obeyed by movement paths for which n^{th} order maximally smooth trajectories have constant rate of accumulating geometric measurement along the drawn path: $\frac{d\mathbf{r}}{d\sigma} \cdot \frac{d^{2n}\mathbf{r}}{d\sigma^{2n}} = 0$. The geometric measurement σ is invariant under a class of geometric transformations. Equations' solutions presumably serve as candidates for geometric movement primitives. The geometric measurement may be chosen to be an arc in certain geometry. For example the two-thirds power-law model corresponds to piece-wise constant speed of accumulating equi-affine arc. The equation means that the 1$^{\text{st}}$ and the 2n$^{\text{th}}$ order derivatives of the position vector with respect to the geometric measurement are orthogonal. Equations in different geometries in plane and in space and their known solutions are presented. A method for constructing trajectories based on coarticulating straight segments (primitives in Euclidian geometry) into parabolic elements (primitives in equi-affine geometry) is discussed. The derived class of differential equation is a novel tool for discovering candidates for geometric movement primitives.

Ageing shows a pattern of cerebellar degeneration analogous, but not equal, to that in patients suffering from cerebellar degenerative disease

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Ageing generally leads to impairments in cognitive function and the ability to execute and learn new movements. While the causes of these impairments are often multi-factorial, integrity of the cerebellum in an elderly population is an important predictive factor of both motor function and cognitive function. A similar association between cerebellar integrity and function is true for cerebellar patients. We set out to investigate the analogies between the pattern of cerebellar degeneration of a healthy ageing population and cerebellar patients. We quantified cerebellar regional volumes by applying voxel-based morphometry (VBM) to a publicly available dataset of MR images obtained in 313 healthy subjects aged between 18 and 96 years and a dataset of MR images of 21 cerebellar patients. We observed considerable overlap in regions with the strongest loss of cerebellar volume in the two datasets. In both datasets, the anterior lobe of the cerebellum (lobules I-V) and parts of the superior cerebellum (primarily lobule VI) showed strongest degeneration of cerebellar volume. However, the most significant voxels in cerebellar patients were shifted posteriorly (lobule VII) compared to the voxels that degenerate most with age in the healthy population. The results showed a pattern of significant degeneration of the posterior motor region (lobule VIIIb) in both groups, and significant degeneration of lobule IX and X in the healthy population, but not in cerebellar patients. Furthermore, we saw strong volumetric degeneration of functionally defined cerebellar regions associated with cerebral somatomotor function in both groups.

Predominance of degeneration in the anterior lobe and lobule VI suggests impairment of motor function in both groups, while we suggest that the posterior shift of degeneration in cerebellar patients would be associated with relatively stronger impairment of higher motor function and cognitive function. Thus, these results may explain the specific symptomology associated with cerebellar degeneration in ageing and in cerebellar patients.

Keywords: Ageing, voxel-based morphometry, cerebellum, cerebellar degeneration, motor control, cognition

An investigation of the first harmonic of mutual inductace

Yotam Frechter

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An autonomous induction generator (IG), while both the stator and the rotor are single-phase, could be used as power/voltage source. This arrangement would be cumbersome to analyze even without the inductances magnetic saturation nonlinearity as it contains three coupled differential equations. This circuit was proposed and analyzed both by numerical simulations of its differential equations and experiments before about 15 years. This talk is about exact mathematical solution of the circuit operation frequency and its oscillation parameters, the suitable values of the circuit components. These solutions were validated versus the numerical simulation and experimental results show in the previous paper 15 years ago.

The exact mathematical solutions were obtained by the Wolfram Mathematica program.

Autonomous robot-assisted rehabilitation based impedance control

Fares Marjieh, Reuven Katz, Miriam Zacksenhouse

Technion, Israel

The goal of the research is to build an autonomous robot for forearm rehabilitation that demonstrates the concept of brain-in-the-loop (BITL) robot-assistive rehabilitation.

A controlled robotic system was designed to facilitate the rehabilitation of stroke patients, and in particular the rehabilitation of pronation/supination movements (Fig. 1). The system was designed to provide force feedback to either help or resist these movements.

Fig. 2 depicts the model of the robotic system, its interaction with the patient, and the impedance controller. The impedance controller is designed to work on three modes:

1. Normal operation mode: this mode is designed for allowing the patient to perform pronation/supination in a natural way while the hand is attached to the robotic device. Hence, the robot should be completely compliant to the subject movement. In order to minimize the loading of the robot on the patient, it is critical to minimize gravitational and frictional effects.

2. Rehabilitation mode: this mode is designed to help the movement of the patient. To assure that the robot does not apply large torques, the impedance controller will implement position control with low impedance and limited torque.

3. Experimentation mode: this mode is designed to provide haptic feedback for healthy subject to generate motor errors. In this mode, the robotics system will resist the movement of the subject at a predetermined phase of his movements in order to generate error between the planned and actual movement.

Results: the first mode is achieved both by proper mechanical design, balancing the handle, and by proper design of feed-forward controller to compensate for friction. For the others two modes, I am working now to implement the computer simulation that I have built.

Brain potentials evoked by outcome errors during continuous 3D motion

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We investigated brain potentials recorded by non-invasive electroencephalography (EEG) in response to participant outcome errors during continuous 3D motion. Outcome errors occur when the goal of the intended movement is not achieved. Invasive research based on electrocorticography (ECoG) recordings have shown that it is possible to detect a clear Error-related neural responses (ERNR) signals in response to outcome errors while controlling the motion of an agent in 2D. EEG based studies have shown brain potentials evoked by outcome errors in 2D continuous aiming tasks.

During our experiment participants played a 3D virtual Tennis game, in multimodal immersive virtual reality environment, designed with high ecological validity. The control of the experimental task involved a "Phantom" haptic feedback device, for manual manipulation and highly valid sense of force in the game. The task of the participant was to play tennis against a computer player. When the participant missed the ball, it was counted as an outcome error event "Miss". When the participant repelled the ball, it was counted as a "Repel" event and used as a reference. The experiment was conducted on 10 male and 11 female participants.

The experimental results show well-defined event related potentials (ERPs) with different waveform profiles and distributions depending on the conditions. The grand-average of ERPs at Cz electrode of the "Repel" and "Miss" events measured are characterized, respectively, by the following: (1) "Repel" – negative peak of 87.9 msec latency, amplitude of -2 μV, centro-frontal distribution and positive peak of 306.6 msec latency, amplitude of 8.2 μV, centro-frontal distribution; (2) "Miss" – positive peak of 478.5 msec latency, amplitude of 3.3 μV, centro-parietal distribution.

These results provide a basis for EEG based recognition of outcome errors and application as a feedback signal in EEG based Brain-Computer Interfaces.

Co-adaptive Learning in EEG-based Brain Computer Interfaces

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A Brain Computer Interface (BCI) enables direct control of brain activity over external devices, such as robots. Motor imagery (MI) based BCI detects changes in brain activity associated with imaginary limbs movements, such as tapping with the right or left hand. MI based BCIs require training, during which the user gradually learns how to control the relevant patterns of brain activity with the help of feedback. Additionally, it is common to use machine learning techniques to improve BCI performance and adapt the decoding algorithm to the user's brain. Therefore, the brain and the BCI need to "collaborate" in order to constantly improve performance. To study the role of co-adaptive learning in a BCI paradigm and the time scales involved, we investigated the performance of subjects in a cued MI task over 6 consecutive days. One group performs the BCI task using a fixed readout algorithm based on MI data from day 1. For the other group, the readout algorithm was adapted every 40-trial block, in a closed-loop manner, based on brain activity patterns during that block.

Preliminary results from the first group showed that, in general, the performance with the fixed readout algorithm decreases, probably due to variations in brain activity from day to day. Reanalysis of the same data by artificially adapting the readout algorithm suggested that continuous update of the readout algorithm would improve the BCI performance. Results from the second group supported the idea that machine adaptation would positively affect the BCI performance.

In the next phase of the experiment, we will investigate several factors that may improve the performance of the co-adaptive system, such as: adapting the classifier to subject specific features (e.g. individualized frequency bands), modifying the rate of classifier adaptation, and increasing the duration of the training.

Distributed Coordination of Teams of Mobile sensing Robots

Harel Yedidsion, Roie Zivan

Ben Gurion University, Israel

As robots are becoming increasingly cheaper and more autonomous, distributed coordination of teams of mobile robots is generating great interest. Multi-agent applications that include teams of mobile sensing agents are challenging since they are inherently dynamic and a single movement of a mobile sensor can change the problem that the whole team is facing. A new model based on Distributed Constraint Optimization Problems (DCOP), for representing problems of Mobile Sensor Teams, DCOP_MST, is proposed along with algorithms that were enhanced with exploration methods. In contrast to conventional, static DCOPs, DCOP_MST not only permits dynamism but exploits it by restricting variable domains to nearby locations; consequently, variable domains and constraints change as the agents move through the environment. DCOP_MST confers three major advantages. It directly represents the multiple forms of dynamism inherent in MSTs. It also provides a compact representation that can be solved efficiently with local search algorithms, with information and communication locality based on physical locality as typically occurs in MST applications. Finally, DCOP_MST facilitates organization of the team into multiple sub-teams that can specialize in different roles and coordinate their activity through dynamic events. The DCOP_MST model has been extensively tested using a software simulator but was not tested on a team of real mobile sensing robots which introduce properties/difficulties, which were not addressed in the DCOP_MST model, e.g., sensors with a directional field of vision, collisions between robots etc. This work describes the challenges faced when applying the DCOP_MST model to a team of real mobile sensing robots with directional sensing abilities (e.g., cameras). We describe the adjustments required in order for it to represent the realistic properties of the problem. Following these modifications, we present the DCOP_MST^R which is a specific implementation of the DCOP_MST model for a real world robot application with directed field sensors (cameras). We further test the problem of target coverage by teams of mobile sensing robots in two settings. In the first setting, there is one team of robots which are homogeneous in their abilities and tasks. In this setting we compare the performance of selected algorithms that performed well in the software simulation, specifically DSA_MST, Max-sum_MST and their explorative versions. In the second setting we consider two teams of robots: a search-and-detection team responsible for finding new targets and a surveillance team tasked with coverage of known targets. The two teams work together using the DCOP_MST framework to coordinate. We develop and test several cooperation methods. The various experiments were performed with a real robot team and compared to the results obtained by the software simulator.

Electroencephalographic responses to disturbances and distractors during continuous reaching movements

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It has been demonstrated that target jumps during reaching movements evoke error-related negativity (ERN) only if they are uncorrectable, while correctable target jumps induce mainly a P300 like component. Uncorrectable jumps prevent target reaching, and hence considered high level errors that are hypothesized to be processed by a frontal-central system and in particular the anterior cingulate cortex. However, low level disturbances to the movement – especially when externally induced, are hypothesized to be processed by a posterior system and in particular the posterior parietal cortex .

Here we extend the investigation on disturbance induced event-related potentials (ERPs), and include also cursor jumps, dual cursor and target jumps, and distractors, i.e., environmental changes that are not related to the movement. These allow us to investigate which sub-components of P300 are evoked and how they are related to the movement task (disturbances versus distractors) and movement correction (cursor or target jumps versus dual jump).

In line with previous results, we also show that ERN is evoked only when jumps cannot be corrected. More importantly, we show that P3a is similarly evoked both by disturbances and distractors, while P3b is significantly stronger in response to disturbances than distractors. Furthermore, P3b appears also in response to dual jump, which does not require any movement correction. Hence, we conclude that while P3b is task related it is not associated with movement correction. This supports previous results, based on the temporal relationship between P300 and onset of movement correction, which also suggested that P300 is not related to movement correction.

Equivalence of plane wave and spherical harmonics rendering of binaural room impulse response

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Binaural technology has various applications in virtual acoustics, architectural acoustics, tele-communications and auditory science. One key element in binaural technology is the Binaural Room Impulse Response (BRIR), which represents a continuum of plane waves spatially filtered by Head Related Transfer Functions (HRTFs). Such BRIRs can be rendered from spherical microphone array recordings and free-field HRTFs, either in the space domain using plane-wave composition or in the spherical-harmonics domain using order- limited spherical harmonics representation of the sound field. While these approaches have been individually employed in a number of recent studies, it appears that the literature does not offer a comprehensive analysis or a theoretical framework relating the two representations with respect to binaural reproduction and perception. In this paper, we provide a mathematical analysis showing that when certain sampling conditions are maintained, the plane-wave and spherical-harmonics representations are equivalent. Further, we show that under these conditions, resulting binaural signals are independent of the employed spatial sampling schemes. The analysis is complemented by a listening experiment, in which both plane-wave and spherical-harmonics representations are perceptually evaluated for different spatial sampling schemes and spherical harmonic orders.

Experimental framework for the analysis of central threshold elements in neural feedback mechanisms

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In human perception and sensorimotor control, recent studies have proposed central threshold elements to explain non-linear effects in experimental data. However, little is known about threshold properties and their functional effects. Strong evidence for the importance of thresholds in sensorimotor control stems from human reactive balancing. During support surface tilts, humans show a non-linear increase in sway responses when increasing the stimulus amplitude. This non-linear increase has been successfully mimicked by a model, which uses central thresholds in the sensory reconstruction of external disturbances [1]. In a recent study, the model was applied to explain human sway responses to support surface tilts during different visual conditions in a stationary visual scene [2]. The results of the study showed that visual cues reduce the thresholds, resulting in smaller tilt evoked body sway. Furthermore, visual cues reduced the sway component which was not evoked by the tilt stimulus (remnant sway), which is mainly evoked by sensory noise. Based on these findings, it was hypothesized that visual cues reduce sensory noise, indicated by the reduction in remnant sway. This reduction, in turn, was argued to allow for a reduction of the thresholds, thereby improving the disturbance compensation during tilts.

In the model simulations of the previous study, thresholds were estimated using averaged human sway responses, implicitly assuming noise free sensory signals. In order to investigate the hypothesized relation of noise and thresholds, additional model simulations including sensory noise are needed. However, the interaction of noise and thresholds is highly complex and requires a detailed analysis of the threshold properties in general. Here we propose a framework consisting of experimental data and a model of the human balance control, which allows the analysis of central threshold elements.

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Exploring characterization of movement in robot-assisted and open needle driving

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In the recent years, the use of robotics is surgery has gained popularity due to the numerous benefits such as dexterity, accuracy, and minimal invasiveness. However, using robots to teleoperate remote instruments may lead surgeons to adopt different movement characteristics compared to using conventional surgical tools. Characterizing these movement patterns in experienced and novice users will eventually lead to developing new training methods, improving robot design, and advance our understanding of motor control in fine manipulation tasks.

In this study, we set out to analyze and characterize movements during a structured needle driving that was performed using a robot-assisted surgery research platform, and with needle drivers. The task consisted of a sequence of 5 movements: reach to target, drive the needle through tissue, catch the needle, pool the needle out of the tissue, and reach to a target. We aimed to characterize robot-assisted performance, and to examine whether the movement characteristics of a participant are related to their surgical expertise. Sixteen participants (ten novice users and six experienced surgeons) performed the experiment. Here we present a preliminary analysis that focused on: (1) the geometry of movement paths, emphasizing segments that have a large amount of between-subject variability;. (2) the speed of movement, including improvement over time, average root mean square speed; and .(3) the execution time. Our preliminary analysis suggests that there is a high within-subject correlation between the geometry of open tools movement and movement using the robot, but each user exhibited a characteristic geometry of movement. In addition, we found three predominant movement patterns in the first reach movement, each corresponding to a different quality of the performance in the entire needle driving task.

Future work will focus on developing a quantitative model of the characteristic movements that may also allow for estimation of parameters that can be used for assessment of performance quality and expertise. In addition, we will examine the relation between geometric and temporal characteristics of movement.

Genetic determinants of visuomotor adaptation in humans

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Visuomotor adaptation has been a topic of wide scientific interest for decades as many interesting claims about the way humans move can be made from this relatively simple paradigm. Specifically, three learning concepts have recently been defined that became highly influential in human movement research. First, movement exploration was shown to increase learning. Second, adaptation was found to be composed of a fast and forgetful and a slow and retentive learning system. Third, movement speed or "vigour" was shown to be correlated with reward appreciation.

However, relatively little is known about the consistency of these motor learning qualities for individuals across different visuomotor adaptation paradigms. In this study, we explored this question by training 75 individuals on both a saccade and reaching adaptation paradigm and sequencing two genes involved in "slow" learning and long term potentiation and reward prediction and dopamine breakdown (BDNF and COMT) known to contain common functional polymorphisms. We hypothesized that higher dopamine concentrations would increase movement vigour and variability, whereas stronger BDNF release would improve slow rate learning.

Our results indicate that higher dopamine levels are correlated with more vigorous movement and an increase in variability. This confirms the concept of vigour as an individual quality and indicates a possible relation between movement variability and vigour. Second, no effect of BDNF on learning retention was found, possibly because the effect of the polymorphism is relatively small. Animal research might be necessary to address this question in future research.

We conclude that small genetic variations determine some of the differences in the way humans move. This finding might be interesting for both fundamental and clinical movement research.

Global movement properties arising from conservation laws of optimization criteria

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While some characteristics of human motion are dictated by task requirements, others do not influence the outcome of the task, and the motor system has freedom in selecting them. This is the case for **global timing** (motion durations) of trajectories of drawing and locomotion, whose relation to **geometry** (path shapes) we hereby examine.

While geometric speed profiles of motion trajectories are well modelled by movement optimization models (e.g. minimization of acceleration or jerk) and by assuming geometric invariance (the two-thirds power law), global human motion properties are less well understood. The phenomenon of isochrony, characteristic of human motion, may arise from affine invariance (the mixed geometry model). However, current models are yet unable to predict well the temporal duration of a trajectory given its geometric shape and extent, even if one knows the durations of other trajectories executed by the same person in a similar context.

We examine motion durations by applying an optimization based approach. Previous optimization methods either used duration as a parameter of the system, or optimized with respect to it. Huh (2012) presented an interesting viewpoint. He asserted that movement durations may arise from control of an intensive quantity of optimal motion, termed drive $D = \partial A/\partial t$, which is conserved within each optimal motion. For the minimum jerk model the drive $D = \dddot{r}^2 - 2\,\ddot{r}\,\ddddot{r} + 2\,\dot{r}\,\overset{\cdot\cdot\cdot}{\ddot{r}}$ is previously known to be theoretically conserved (Polyakov 2009, Meirovitch 2014). The extent to which the drive is conserved within and across actual human movements is not well studied.

We generalize the ideas of examining and utilizing conserved quantities of optimization models to infer global properties of motion. We apply Noether's theorem to extract conserved quantities for each optimization model. Each symmetry of an optimization criterion predicts a conserved quantity. For instance, drive arises from time-shift invariance and Euclidean invariant optimization criteria (minimum acceleration, jerk or snap etc.) have rotational symmetries which result in additional conservation laws. We present new theoretic formulations of conservation laws for well-studied Euclidean models as well as formulations of drive for non-Euclidean optimization criteria. We present new numeric methods for calculation of conservation laws for both Euclidean and non-Euclidean models, overcoming the need for extracting high numerical derivatives. Finally, we examine human motion data and examine the extent to which it satisfies the different conservation laws predicted by each model.

Implementation of minimal feedback CPG controller for dynamic walking using Series Elastic Actuation

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Dynamic walking refers to gaits that exploit the natural dynamics of the body and limbs, thus being more energy efficient as shown in [7]. In a dynamic gait the body actually 'falls' forward at every step and static equilibrium does not have to be monitored.

A minimal feedback CPG based controller has been previously developed in our lab to control dynamic walking for legged robots [1] [2]. The design is inspired by the study of the role of GPGs in animal locomotion [3][4][5]. In biological CPGs, a network of neurons act as coupled oscillators that produce a periodic electric signal sent to the muscles and generate dynamic locomotion [6]. These signals were shaped by years of evolution for the needs of the specific animal. In our control algorithm, we use a CPG to produce a periodic set of torque pulses applied to the hip and ankle motors. The optimized control values were obtained by a genetic algorithm that was tuned to determine the torque pulses for either the fastest, the most energy efficient, or the fastest converging gait.

A prototype was designed and built to demonstrate the CPG controller on a compass biped robot. The implementation includes series elastic actuation (SEA) as introduced in [8], which facilitates the control of the applied torque, while exploiting the natural dynamics of the system and providing inherent compliance. Parametric system identification was implemented using sine-sweep input, and low-level motor control was implemented using LQR control and a state observer based on Kalman filter.

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Is the perception of Hand Location Affected by Adaptation to Sensorimotor Delay?

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While we interact with the environment by performing a motor activity, our sensory system receives various inputs of different modalities (visual, auditory, proprioceptive etc.). These inputs may originate from a single event, but due to the differences in their transmission velocities, they arrive at different times to the relevant areas in the brain that process the information. The fact that we perceive these sensory inputs as a single simultaneous event is likely related to active processes in the brain that account for the time differences. Here, we examine the way a disruption of the simultaneity between the proprioception and other sensory modalities affects the explicit perception of participants' hand location.

Recent studies used an experimental paradigm in which participants played a virtual game of pong in which the movement of the controlled paddle was delayed with respect to the movement of the participant's hand. It was shown that adaptation to the delayed feedback was associated with target overshoots in subsequent reaching task when no visual feedback of the hand location was provided (blind reaching). To explain these results, it was suggested that participants adopted a state-based representation to cope with the external delay.

The goal of this study is to explore whether the change in the representation of the state of the hand involves also a change in the explicit perception of hand location. To test this, we designed an experimental protocol which combined the virtual pong experiment with perceptual assessments. After each session of pong (non-delayed or delayed) participants performed a blind reaching task, in which they were also requested to provide verbal assessments of their hand location. We hypothesized that if the perceived location of the arm is also affected by the delayed environment, participants will provide biased assessments of their reaching performance, and that this bias might be partially responsible for the overshoot in movement. We present preliminary results and discuss the implications of the effect of delay on implicit and explicit processes in movement control.

Understanding the way delay is represented in the motor system and the way it influences state representation may help in understanding pathological conditions that are characterized by delayed information transmission, such as Multiple Sclerosis, and conditions characterized by deficiencies in the perceived space such as Hemispatial Neglect.

Mechanisms of Left-Right Coordination in Mammalian Locomotor Pattern Generation Circuits: A Mathematical Modeling View

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The locomotor gait in limbed animals is defined by the left-right leg coordination and locomotor speed. Coordination between left and right neural activities in the spinal cord controlling left and right legs is provided by commissural interneurons (CINs). Several CIN types have been genetically identified, including the excitatory V3 and excitatory and inhibitory V0 types. Recent studies demonstrated that genetic elimination of all V0 CINs caused switching from a normal left-right alternating activity to a left-right synchronized "hopping" pattern. Furthermore, ablation of only the inhibitory V0 CINs ($V0_D$ subtype) resulted in a lack of left-right alternation at low locomotor frequencies and retaining this alternation at high frequencies, whereas selective ablation of the excitatory V0 neurons ($V0_V$ subtype) maintained the left–right alternation at low frequencies and switched to a hopping pattern at high frequencies. To analyze these findings, we developed a simplified mathematical model of neural circuits consisting of four pacemaker neurons representing left and right, flexor and extensor rhythm-generating centers interacting via commissural pathways representing V3, $V0_D$, and $V0_V$ CINs. The locomotor frequency was controlled by a parameter defining the excitation of neurons and commissural pathways mimicking the effects of N-methyl-D-aspartate on locomotor frequency in isolated rodent spinal cord preparations. The model demonstrated a typical left-right alternating pattern under control conditions, switching to a hopping activity at any frequency after removing both V0 connections, a synchronized pattern at low frequencies with alternation at high frequencies after removing only $V0_D$ connections, and an alternating pattern at low frequencies with hopping at high frequencies after removing only $V0_V$ connections. We used bifurcation theory and fast-slow decomposition methods to analyze network behavior in the above regimes and transitions between them. The model reproduced, and suggested explanation for, a series of experimental phenomena and generated predictions available for experimental testing.

Modulation of reach adaptation using transcranial direct current stimulation (tDCS) in patients with cerebellar degeneration

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Treatment of ataxia in patients with cerebellar degeneration remains a major challenge. Because of the general lack of medication, the mainstays of therapy remain physiotherapy, occupational therapy and speech therapy. Recent findings showed that motor learning was facilitated by cerebellar tDCS in young and healthy subjects in a visuomotor reach adaptation task (Galea et al. Cerebral Cortex 2011). It has therefore been proposed that cerebellar tDCS may be beneficial in patients with cerebellar degeneration by improving their known motor learning deficits. In the present study reach adaptation in a force field was tested in 20 patients with pure cerebellar degeneration (mean age 54.1 ± 10.7 years; range 30–74 years) and 20 age and gender matched controls (mean age 55.3 ± 11.3 years; range 28–74 years). Three sessions were performed which were one week apart. During each session subjects received either anodal tDCS of the cerebellum, anodal tDCS of the primary motor cortex (M1) or sham tDCS in a randomized order. As expected, reach adaptation was significantly reduced in cerebellar patients compared to controls. However, there was no significant effect of stimulation neither in controls nor in cerebellar patients. A control experiment was performed in three groups of ten young controls who received either cathodal, anodal or sham tDCS of the cerebellum. Again, there were no significant effects of tDCS on force field adaptation. In conclusion, neither tDCS of the cerebellum nor tDCS of M1 were able to improve reach adaptation deficits in patients with cerebellar degeneration. tDCS effects, however, may be task-depended given that anodal tDCS did not facilitate learning in controls.

Motor Neuro-Kinemes: neural representation schemes of primitive motor movements

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Previous studies have been successful in extracting muscle synergies and decomposing point-to-point movements into sub-movements. However, further computational and electrophysiological tools are required in order to unravel the neural representations as well as the mechanisms underlying successful combination of movement primitives into complex movements. The aim of the current study is to identify optimal neural representation schemes of the EEG signal during primitive motor movements. To this end, we collected EEG data from 12 subjects while they performed 40 repetitions of 8 simple motor movements (right, left, up, down, and diagonal lines) on a tablet. We then constructed several Support Vector Machine (SVM) models which differed by their complexity and underlying input features, and compared between the performances of the models on the task of classifying primitive motor movements. The different representation schemes were constructed according to different frequency bands (1-8Hz, 10-20Hz, 20-45Hz), averaging time windows, filters (rectangular, triangular and point filters), and decorrelation methods (Principal Component Analysis -PCA, Discrete Cosine Transform - DCT) of the features. Results show that representing the EEG signal in the high frequency band of 25-45Hz, with an averaging window of ~100ms, using triangular filtering and DCT for decorrelation, achieves best performance (accuracy = 65%, $p<0.005$) We suggest this scheme for future research, aiming to examine the relationship between the combined EEG data of primitive movements and the EEG signal of complex motor movements.

Motor-sensory Closed-Loop Perception (CLP) models and robotic implementation

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Perception, the acquisition of information of ones surrounding, is an active process. We hypothesize, based on biological data, that perception is a closed-loop process where sensor's motion affects the incoming sensory signal which in return modifies sensor's motion. In such a process both sensory and motor components are essential. We use mathematical tools to formulate these notions and model specific feature perception (e.g. object localization) using specific modality (e.g. rat's whisking system) as simple dynamical closed-loop systems. Perception is achieved in such systems through convergence of the dynamic variables. In addition we use our motor-sensory closed-loop approach to come up with algorithms and implement them in artificial agents composed of at least one sensor and one motor. The single-feature perception algorithms we come up with require very little processing power and almost no memory, which makes them suitable for small independent agents with limited resources.

Multi finger force production: Role of vision

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During the control of an ongoing movement, performance specific feedback is provided by the vision. Role of vision, through thoroughly studied in a variety of motor tasks, remains unclear in individual finger force production and control in a multi-finger system. In this study, the subjects were asked to match the finger force (index, middle, ring and little) on screen in presence of visual feedback (vision on condition). Midway in the trial, the force profile was turned off (vision off condition). The subject was instructed to continue generating the same individual finger forces when vision was turned off.

The data was acquired for 20 sec at 200 Hz with 10 sec each of vision on and vision off. The data was filtered and divided into bins of 2 seconds each (bins 1-5 represent vision on and 6-10 represent vision off condition). All the further analysis was performed on these bins. Results show that the force generated by middle, ring and little finger significantly decreases when vision is turned off. The fingers continued to lose significant amount of force in the subsequent bins (bins 7-10). However, only ring finger showed a significant decrease in regression coefficient. Bin 6 shows significantly higher variations in mean forces compared to bin 5 (vision on) and bins 7-10 (vision off). The decrease in finger force was found out to be linear in bin 6 (Pearson's coefficient >0.70). The rate of loss of finger force in ring finger and little finger is higher than that of index and middle.

In summary, sudden removal of visual feedback causes a reduction of the finger forces. This shows that a continuous visual feedback is required for force sustenance.

Neural Substrates of Enhanced Intermanual Skill Transfer during Online Manipulation of Visual Feedback

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In the realm of motor skill learning it has long been known that physical practice with one effector results also in performance gains of another (un-practiced) effector. Here, we examined the role of sensory feedback (visual and tactile), and its neural correlate, on the transfer of motor skills across hands in humans. To this end, we manipulated visual feedback of right-hand finger movement through the use of 3D Virtual Reality devices. 18 subjects learned a novel motor skill (sequence of finger movements) through physical training with their right hand, while real-time movement-based visual feedback of their left hand fingers was provided. We found that this manipulation facilitates inter-manual transfer and enhances performance gains with the untrained (left) hand. Additionally, we examined whether adding passive left-hand movement to the manipulated visual input can further enhance the transfer effect. Using a custom-built device, 18 additional subjects trained on a similar task by physical training with their right hand while their left-hand was passively moved in a yoked manner to these voluntary right-hand movements. We found that adding this passive training led to further increases in left hand performance gains. Finally, we collected functional magnetic resonance imaging (fMRI) data from an additional set of 18 subjects during physical training with the right hand, coupled with visual feedback of left-hand movement. We found that activity in the right Superior Parietal Lobule (rSPL) during training correlated with subsequent gains in left-hand performance. Optimizing the transfer of motor skills across limbs has key consequences on real-world learning (such as sports and music) and for the development of new approaches for rehabilitation of patients with unilateral motor deficits such as ALS or stroke. Our results point to the right SPL as an important node in this process.

Perception and action in teleoperated interaction with an elastic environment

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In bilateral teleoperation, the user interacts with a master manipulator to move a remote robot and sense environment forces.Teleoperation has the potential to improve many minimally-invasive medical procedures, including gastrointestinal endoscopy. During this procedure, the physician has to move accurately to avoid tissue damage, but also perceive delicate differences between the tissues to make appropriate decisions. The forces that are presented to the user may greatly influence perception and action.

It is well documented that perception of stiffness obays Weber's law – the sensitivity to small changes decreases when the stimulus intensity increases. However, the effect of stiffness on the accuracy of probing movements and the grip force that users apply on the tool remains unclear. In this study, we explore these effects by combining an adapation and a forced-choice paradigms. Participants made out-and-back movements to unvisible targets inside elastic objects, and received feedback after each trial to achieve a desired performance. We measured the displacement of their hand and the grip force that they applied, and presented to them questions to extract psychometric curves.

A change in the stiffness of the environment may lead to a change in either the applied force, the extent of the movement, or both. To distinguish between these strategies, we plan to perform two experiments. In the first experiment, the subjects are instructed to reach to a certain position, while the stiffness and the force vary. In the second experiment, the subjects are instructed to apply a certain force, while the stiffness and the distance of the target vary. The preliminary results of the first experiment will be presented.

Understanding the effect of stiffness on action and perception is important for modeling interaction with elastic objects and for determining the parameters of teleoperation control laws that will optimize the presentation of force information to users.

This study is supported by the Helmsley Charitable Trust through the ABC Robotics Initiative of Ben-Gurion University of the Negev.

Representations of Different Magnitudes of Sensory Delay in the Motor System

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When we interact with the external world, our brain integrates various sensory inputs that are processed at variable delays with respect to their external source. Thus, our perception of multisensory events as simultaneous must be the outcome of active processes that account for these delays. Here, we examine how the magnitude of the delay affects the representation of state and time in the motor system.

To study the effects of delayed feedback on motor performance, we used a virtual game of pong in which the movement of the controlled paddle is delayed with respect to the movement of the participant's hand. Previous results indicated that for delays smaller than 150 ms, adaptation to the delayed environment also causes an overshoot in subsequent reaching to targets without vision of the hand (blind reaching). We suggested that these results can be explained by a state-based model in which a representation is based on a perceived change in the impedance parameters of the arm, rather than by a time-based representation model.

Here, we explore whether a state-based representation of the delayed pong environment is bounded to small delays. We hypothesize that for large delays, the representation of the perturbation is more likely to be time-based. To test this, we exposed participants to delays of up to 300 ms. During the experiment, participants also performed blind reaches, enabling us to examine the way they generalize their adaptation to the delay to a task that requires an accurate proprioceptive spatial representation. If large delays are explicitly compensated by a temporal representation, we expect this representation to be reflected in a different strategy of movement during the pong game from the one employed during small delays, consequently affecting target overshoot during the blind reaching movements.

Understanding the way delay is represented is important for understanding how forward models are formed, and also pathological conditions that are characterized by delayed information transmission, such as Multiple Sclerosis.

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Seeing by the Fingers: Active Sensory Substitution speeds up perception and training

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Sensory substitution systems deliver environmental information we normally receive through one sense through another sense. We developed an active visual-to-touch substitution system in which the visual information is substituted by touch based on active sensing principles. Blindfolded participants were asked to recognize in each trial one object, from a collection of 5 possible objects that were presented at a distance of ~1 meter. In the first stage (5 days, 30 minutes session) the stimuli were 2D black shapes and in the second stage (3 days, 30 minutes session) 3D colored objects. We measured their accuracy, recognition time and hand motion. Results showed a steep learning curve. Participants reached success rates of 86.6% in the 2D task and 95% in the 3D task in less than 30 s per trial. Fast and accurate perception lasted for ~2 years. During training participants attained externalization of the sensed data, and developed an ability to identify local features (e.g., curvatures, vertex and corners). The participants' scanning trajectories exhibited a salient common pattern - a focal scanning of an object-specific informative region. The distance between the focal area and the point of maximal entropy computed from the image was inversely correlated with performance. Over all our results suggest that allowing the participants to employ natural-like active sensing strategies using motion-dependent tactile sensation and having motion and sensation on the same organ can improve significantly perception via sensory substitution, and that this improvement depends critically on the participant's strategy.

Signatures of motor skill learning in the temporal dynamics of muscle groups

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The mastering of a novel motor skill increases speed, accuracy and fluency in performing task relevant movement sequences. However, while brain activity and behavioral-kinematic changes related to motor learning processes are attracting many research groups in the neuroscience, the study of motor learning processes as expressed by neuromuscular network level is given relatively little attention. Here, we show that a unique pattern characterizes the dynamic interactions of the muscles involved in the execution of a well-trained motor task – a 5 element sequence of finger-to-thumb opposition movements; a pattern that was not observed during the execution of unfamiliar sequences composed of the same opposition movements.

In the current study, sEMG signals were recorded from the thenar, hypothenar, finger flexors and finger extensors of the performing hand in 13 young healthy participants, while performing an intensively practiced a predefined finger opposition movement sequence and a corresponding novel sequence wherein the opposition movements were arranged in a different (mirror-reversed) order. The trained sequence was practiced in multiple sessions over a three weeks interval. Participants were asked to perform the sequences as fast and accurately as possible, and repeatedly, as many time as they could within a 30 seconds of the test interval.

Evaluating the interactions between muscles recruited during the motor tasks, we found that a unique pattern characterizes the temporal dynamics of sEMG during the execution of the well trained motor sequence compared to unfamiliar ones. Practice resulted in the generation of new muscle synergies, reflected in robust increases in within and between muscles synchronizations, and in decreases in the dominant frequencies of the temporal interactions, from approximately 15 for the untrained movement sequence, to three in the well trained sequence. The specific signature of the new synergies was undetectable by conventional analysis methods (such as RMS, MDF and RQA).

This pattern of results suggests that intensive practice of specific movement sequences results in increases in synergy between multiple muscle groups in a manner that reflects the task relevant movement syntax. We propose that this is consistent with the notion of complex co-articulation and the generation of complex movement units which embody the specific order of component movements.

Stopping performance is dependent on the internal representation of the movement

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Stopping performance is known to depend on low-level motion features, such as movement velocity. It is not known, however, whether it is also subject to high-level motion constraints. Here, we report results of fifteen subjects instructed to connect four target points depicted on a digitizing tablet and stop 'as rapidly as possible' upon hearing a 'stop' cue (tone). Five subjects connected target points with straight paths while eleven subjects generated movements corresponding to coarticulation between adjacent movement components. For both subject groups, stopping performance was very weakly correlated with motion velocity. The generation of a straight point-to-point movement or a smooth, curved trajectory was not disturbed by the occurrence of a 'stop' cue. Overall, the results indicate that stopping performance is subject to high-level motion constraints, such as the completion of a geometrical plan and that globally planned movements, once started, must run to completion providing evidence for the definition of a motion primitive as an unstoppable motion element.

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Störung/הפרעה: A German-Israeli Interdisciplinary Project on Movement and Movement Disorder

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Störung/ הפרעה is a unique collaborative interdisciplinary project that brings together scientists, professional dancers, physicians, as well as people with Parkinson's disease, from Israel and Germany. Together, we explore different aspects of human movement and movement disorder. The project involves Theater Freiburg and Exzellenzcluster BrainLinks-BrainTools of the University of Freiburg from the German side, and Yasmeen Godder Dance Company, Ben-Gurion University, Israel Institute of Technology (Technion), University of Haifa, Weizmann Institute of Science, Bar-Illan University, and the Hebrew University of Jerusalem from the Israeli side.

Throughout 2015, weekly dance lessons are offered for a total of 25 people with Parkinson's disease in Freiburg and in Tel Aviv, while graduate-level students participate in the dance lessons and conduct related studies. In this poster, we would like to present the studies conducted within the scope of the project, report preliminary results, and discuss insights from the collaborative work of scientists and professional dancers interested in movement.

The research projects include studies of different nature, among them:

Contemporary Dance as an Intervention for People with Parkinson's Disease. Assessing the effects of a weekly dance class on people with Parkinson's disease, with respect to a wide range of human functioning, over an 8-month time period.

The Move-Inter-Action Project. A focus on qualitative aspects of the participants' movement assessed using Laban Movement Analysis and their associations with self-reported psychological well-being.

The Underlying Mechanism of Synchrony. Examining how moving in synchronization during dance is related to interpersonal emotion regulation, patients' social interactions and feelings of contact with others.

Emotions and the Moving Body. Collaboration between a scientist and a choreographer to explore how scientific research paradigms utilized in the study of emotions can be used in professional dancers' artistic work.

Störung/הפרעה is funded by the German Federal Cultural Foundation, קרן פורום העתיד גרמניה-ישראל, and the Deutsche Forschungsgemeinschaft within the German Excellence Initiative (EXC 1086).

Studying perception and action in telegrasping of small objects for improving transparency in robot-assisted minimally-invasive surgery

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*Ben-Gurion University of the Negev*In robot-assisted minimally-invasive surgery (RAMIS), a surgeon teleoperates surgical instruments using robotic manipulators. Often these surgical instruments have a grasper end-effector and the surgeons perform surgical procedures by telemanipulating objects and tissue via this grasper. To increase accuracy and due to the small surgical workspace the movements of the instruments are often down-scaled compared to the actual actions performed by the surgeon. One of the main design goals in RAMIS is to create a transparent experience to the surgeon, i.e. that the surgeon's actions are as natural and similar as possible to what the movements would be in open surgery, and the perception of the surgeon is of directly interacting with the tissue.

Toward these goals, we aim to understand how RAMIS affects human sensorimotor control, and develop quantitative metrics that can be optimized to improve perceptual and motor transparency. Our experimental setup consists of the RAVEN II surgical research platform (Applied Dexterity) teleoperated by two 7 degrees-of-freedom Sigma.7 haptic devices (Force Dimension). The RAVEN II platform allows for a manipulation of RAMIS control, and the haptic devices enable us to study the contribution of haptic feedback.

In the first study, we focused on the disassociation between perception and action in object grasping (Ganel, Chajut and Algom, 2008) as a measure of natural interaction with the environment in scaled unilateral teleoperation. Participants performed actual and perceptual telegrasping tasks in which they are to actually grasp very small objects or show the intent of grasping them, respectively, while receiving direct visual feedback of the surgical scene.

Preliminary results suggest that the aperture trajectories during actual and perceptual telegrasping are similar to real grasping: the peak aperture during the reach to grasp is proportional to the size of the object, and so does the perceptual aperture. However, we see preliminary evidence that the disassociation between perception and action, which characterizes neutral human control does not hold during grasping in a RAMIS environment. We will discuss potential explanations for these observations, and their future use for quantifying transparency of RAMIS systems.

This study is supported by the Helmsley Charitable Trust through the ABC Robotics Initiative of Ben-Gurion University of the Negev.

The effects of multimodal feedback on the acquisition of rowing skills

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This study focused on the selection and evaluation of different modes of information feedback in virtual environment to facilitate acquisition and transfer of a complex motor-cognitive skill of rowing. Rowing skill is based on a periodic movement, where stroke is a unit cycle, and requires coordination of several body limbs to make the oars cover the right cyclic trajectory in the right direction as smooth as possible. Skill acquisition necessitates multi-session practice and thus can benefit from simulator environment empowered by virtual reality technologies that allow enrichment of indoor training. High cost efforts are invested in developments of virtual reality simulators to mimic ecological tasks with high fidelity. However, there is no evidence that information available in the real world is integrated in the same way in the virtual environment and the necessity in keeping high fidelity between ecological to virtual task should be questioned. We established a simplified platform of indoor rowing with similar feedback modalities as the ecological task (Visual & Haptic), that were designed to provide feedback on the accuracy of performed arm movement per stroke: a. haptic sense was engaged by creating air flow at three critical points along the trajectory of arm movement or/ and b. visual representation of going through or missing the three critical points along the hand path. Changes in hand trajectory during stroke across were analyzed in reference to the”ideal” performance signatures extracted from expert rowers' performance data. We compared the training performance of 4 experimental groups: Visual, Haptic, Visual + Haptic augmentation, Standard condition (no augmentation). Results showed that all experimental groups improved performance with training and converged to similar levels of error rates and variance of performance in the standard transfer session at the end of training. Surprisingly, the standard training group, with no augmented feedback provided, showed the best learning results, as reflected in highest rates of drop proportions at the final retest. To conclude, the benefits of enriched augmented feedback in similar modalities as the ecological task environment are questionable.

The neural basis of Cerebral Palsy related movement disorders – a combined DWI and behavioral pilot study

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Cerebral Palsy (CP) refers to a heterogeneous group of permanent but non-progressive movement disorders caused by an injury to the developing fetal or infant brain. Studying the correlation between the neuronal damage, the clinical outcomes and the walking patterns in CP subjects is important both for gaining a better understanding of the neural causes of CP-associated disorders and for designing patient-based rehabilitative treatments.

The aim of this project is to develop the methodology for identifying anatomical connectivity abnormalities in subjects with CP and to study the correlates of these abnormalities with various clinical scores and with specific deficits in locomotor execution and adaptation.

We will present a preliminary diffusion weighted imaging (DWI) dataset from two diplegic CP and 12 control subjects, focusing on fiber tracking results of the major motor control pathways (CorticoSpinal Tract, Anterior Thalamic Radiations, Superior Thalamic Radiation and Cerebellar peduncles). These results will be accompanied by results from locomotor adaptation experiments that were carried out both on CP and on control subjects. Additionally, clinical functional tests of the CP subjects (Gross Motor Functional Measurement (GMFM), Time UP & Go (TUG) test and 10 Meter Walk Test (10MWT)) will be presented.

Comparison of the DWI results point to abnormalities in the CP subjects in the CorticoSpinal tract of the affected side and in the Superior Thalamic Radiation, bilaterally. Further assessment of the points of deviation along the tracts point to areas which are close to the lateral ventricles associated with periventricular leukomalacia, a common casual factor in diplegic CP. Clinical functional tests point to an impaired ability in functions which require standing, walking, running, jumping and ascending and descending stairs. In addition, the clinical functional tests indicate a reduction in the ability to perform a complex interaction between balance and movement, including planning, initiating, executing, and completing a series of linked movements that are common in daily activities.

We conclude that the rich description of the connectivity deficits of CP subjects, together with the careful assessment of the behavioral deficits of the CP subjects, using both clinical and adaptation measurements, are potentially suitable for a large scale study for assessing the neural basis of CP-related movement disorders.

The robot-assisted surgeon: quantifying sensorimotor behavior

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Basic studies of human sensorimotor control typically use simple tasks to uncover fundamental control strategies employed by the nervous system in healthy and impaired populations. However, it remains unclear how these theories translate to more complex sensorimotor tasks, and to highly skilled movement practitioners (such as professional athletes or experienced surgeons). Part of the difficulty in performing such experiments has been a lack of appropriate tools for measuring and quantifying complex motor skills in real-life tasks. Robot-assisted minimally invasive surgery (RAMIS) provides this opportunity by enabling unobtrusive measurements of many behavioral features during surgical tasks. Here, we highlight several behaviors exhibited by RAMIS surgeons during surgical tasks that relate to human sensorimotor control. These behaviors include the frequency of camera (or viewpoint) adjustments and the workspace of hand movements. During simulation exercises, dry-lab exercises, and wet-lab tasks, experienced surgeons develop a common strategy to frequently adjust their camera. Similarly, experienced surgeons maintain a compact workspace of their hands across many different types of tasks. Several of these behaviors have been used to define surgeon performance metrics that are routinely included in surgical simulators to provide feedback throughout training. However, future research is needed to fully understand the driving factors behind these distinct sensorimotor strategies. In the end, RAMIS is an emerging research area that integrates neuroscience and robotics while having a great clinical impact (over 500,000 patients per year). It has many features from unobtrusive measures of behavior to a common platform for a range of experimental conditions that are useful for studies of human motor control.

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The scientific talk: quantifying and modeling the nonverbal interaction

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Understanding the inner state of speakers or listeners and assessing the quality of a conversation is at the core of social intelligence. How does one disclose one's inner state and reflect qualities of the conversation? Here we set out to study social signals on a *microanalytic* level, recording dyads of scientists while being engaged in a scientific conversation. By using Kinect camera as primary source of data acquisition we adopt a novel view of the dyadic scientific interaction which enables pinpointing formerly invisible rules of the motoric interaction. In addition, we evaluate empathy and attachment style via questionnaires. We aim to model and interpret nonverbal dyad interaction and study the correlation between the overt motion and the psychological state of the subjects. We hypothesize that aspects of quality of dyad interaction can be understood from a few degrees of freedom per interlocutor such as the absolute value of center of mass velocity. By this study we hope to tap into the mechanisms of social meaning making of humans during discourse. Among various applications, such models may benefit human-computer interaction, as well as the study of underlying neural correlates capable of manifesting our models.

Unique control strategies underlie octopus crawling

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The soft and flexible octopus body is highly complicated to control. Control is simplified in goal directed arm movements by using stereotypical motor programs that reduce the complexity. Here we present a novel analysis of the crawling behavior of the octopus, focusing on how the octopus copes with the complexity involve in arm coordination.

Octopuses were adapted to crawling in shallow water and then video recorded from below. Points of interest were labeled on consecutive video images. Distances were measured and then velocities and angles were calculated. These parameters were used for characterizing the behavior of the arms and their coordination in crawling. The results were surprising in several aspects.

Octopuses have a preferred crawling direction of ~45° to either left or right relative to the body direction but surprisingly, the deviation of crawling direction is very large because the octopus normally crawls in any direction relative to its body direction. During crawling the octopus can rotate about its body or change the crawling direction, but there is no linear correlation between these two types of maneuvers. To create the thrust to move, each active arm uses only simple stereotypical shortening-then-elongating movements that push the body in the opposite direction of its position around the body; arms that push together produce virtually equal forces. Rotating the body in crawling is achieved by a different stereotypical behavior of the arm that is based on the creation of a bend and then, after attaching to the substrate, changing the bend angle. Our attempts to detect rhythmical patterns in arm coordination have failed, indicating either a complete lack of such patterns, or of the existence of very complicated ones that we could not find. We believe that a central coordinator uses *ad hoc* decisions to evoke intrinsic motor programs in the arms, contrasting locomotion coordination in other animals that depends on CPGs.

Our findings thus reveal that the evolution of the highly maneuverable behavior of the octopus, which is based on a soft molluscan body, is achieved through special embodied organization of the morphology, biomechanics, and motor control mechanisms.

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Variability of pre-training motor performance predicts amount of learning in a finger opposition sequence task

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Improvement in motor performance speed is an accepted measure of both short term motor learning and long-term memory consolidation. However, the changes on a kinematic level underlying this improvement, and the connection between different kinematic quantities and the observed improvement in speed are poorly understood. In this study, subjects performed a sequence of finger opposition movements (touching the thumb and another finger of the hand in a specified order), with the goal to perform the task repetitively as fast and accurately as possible. The trajectories of the fingertips were recorded during testing and training with a magnetic motion capture system. The subjects were retested the following day (after sleep) to assess memory consolidation as reflected in delayed, off-line, gains in sequence performance. The movements were segmented into the time of the finger movements (a continuous closing of the finger until the thumb is touched), and the gaps between the movements.

We found that the coefficient of variation of pre-training finger movement times (CVpreTMT) fingers predicts both within and between session improvements in performance (i.e., number of sequences performed), where higher variability is correlated with lower initial performance, but greater immediate and delayed improvements. This is despite the fact that finger movement time actually makes up only a small proportion of the sequence time (which is mostly taken up by gaps between the movements). Surprisingly, within and between session improvements in relative timings of finger movements (gaps) are also predicted by CVpreTMT and not by the coefficient of variation of pre-training gap times. Our results provide experimental evidence for the importance of an early action exploration strategy in acquisition of complex motor tasks, in line with reinforcement learning theory predictions. Engaging with training protocols inducing initial movement time variability may therefor facilitate motor learning experience-driven motor plasticity in sequential motor tasks.

Voluntary saccadic eye movements contribute to timed trajectory prediction in baseball and non-baseball players

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A baseball hitter must decide first, to swing or not to swing, and next, to make accurate contact of the bat to the ball. Therefore it has been characterized as a go no-go task during the ball's initial flight trajectory and an online motor control task in the latter trajectory, which requires elite baseball players to simultaneously tune physiological feedback gains depending on the state of the body and environment. We aimed to find out if elite baseball players exhibit superior (1) psychophysical tuning properties and (2) corresponding decision making compared to non-baseball players in a timed, trajectory prediction, go no-go task. We hypothesized that elite baseball players would show superior performance on the most challenging of trial variables; fast flight speed and short preparatory periods and that these performance differences would be related to optimal eye and hand movements. We instructed seated subjects to observe a simulation of a ball moving 30-45 vertical visual angle degrees across a touch screen toward a visible square target and decide within the trial time whether the ball will end in the target by touching the screen. We measured eye/hand movements, and touch screen responses. We found that: (1) when stimulus speed was fast and pre-stimulus fixation presentation times were short, baseball players improved performance more over sessions, indicative of faster learning and (2) baseball players performed better than controls overall on these stimulus parameters; (3) eye and hand movement measures such as saccadic reaction time, amplitude and number as well as hand movement initiation and screen touch timings were related to stimulus speed and preparatory signals. We conclude that implicit, interacting, endogenous and exogenous temporal cues play a role in timed trjactory-prediction and that elite baseball players optimally utilize these cues.

Weber's law during remote grasping

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According to Weber's law, the sensitivity of human perception at virtually all sensory modalities to a change along a physical dimension is linearly related to the intensity of the stimulus, i.e., the just noticeable difference (JND) is larger for stronger stimuli. In grasping JND is measured as the variability of finger aperture during reach-to-grasp movements and remains invariant with object size, in violation of Weber's law. This difference in behavior is in-line with the proposal of a functional separation between the visual systems underling action and perception, which has been supported by converging evidence from neuropsychological patient data and behavioral psychophysics.

Remote manipulation scenarios introduce multiple challenges such as communication delays, information loss, and discrepancies between agents. There are many open questions regarding human motor control, sensory integration, and the interrelation between perception and action in such conditions. In the current research we are examining whether the dissociation between perception and action transforms to remote manipulation scenarios. In the future this phenomenon may be used for quantifying transparency in telerobotic systems guiding improvement of system usability and fidelity.

A bi-lateral telerobotic system was constructed based on a robotic manipulator (Motoman, Japan), a controlled jaw gripper (Schunk, Germany), and two Phantom Premium haptic devices with finger thimbles (Geomagic, USA). The robotic gripper aperture is controlled by the human finger aperture and the tool center point is controlled by the center of the human aperture. The force conveyed to the operator is based on the difference between the apertures. The environment is designed such that the control directions of the human subjects are aligned with the robotic motion directions, yet the human is outside the robotic work-volume. Subjects reach and grasp cylindrical objects of different sizes, arranged in pseudo-random sets. Preliminary tests have highlighted the importance of perception of object position with respect to gripper aperture.

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