מרכז זלוטובסקי למדעי העצב
Zlotowski Center for Neuroscience

The Tenth

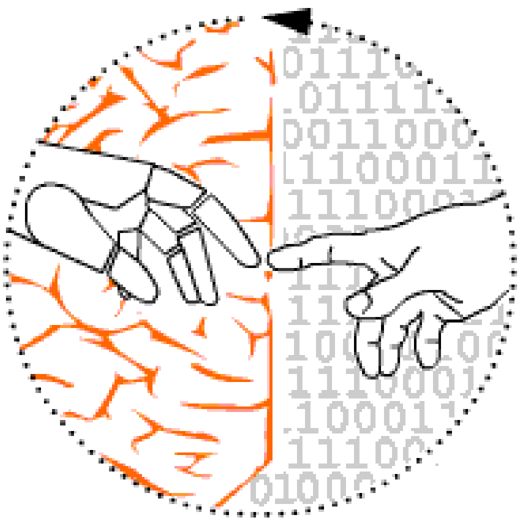
Computational Motor Control Workshop

and

Agricultural, Biological and Cognitive Robotics Initiative

Ben-Gurion University of the Negev

June 17-19, 2014, W.A. Minkoff Senate Hall,
BGU Marcus Family Campus, Beer-Sheva, Israel



http://www.bgu.ac.il/cmcw

In memoriam
Professor Amir Karniel

Prof. Amir Karniel, one of the founders of the Computational Motor Control Workshop, passed away on 2 June 2014, after a two-year battle with cancer, just two weeks short of the Workshop's 10^{th} anniversary. Amir collaborated with many of us, taught some of us, was a friend to many of us, and was an inspiration to all.

Amir was an excellent scientist and an avid science philosopher. Amir's career was short, yet remarkable. He graduated with a PhD in Electrical Engineering from the Technion–Israel Institute of Technology, Haifa in 2000, where he worked with Prof. Gideon Inbar and Prof. Ron Meir. He spent two years as a postdoc in the Department of Physiology at Northwestern University Medical School and the Rehabilitation Institute of Chicago, working with Prof. Sandro Mussa-Ivaldi. He returned to the Technion as a research associate, and then transferred to Ben-Gurion University of the Negev (BGU) in 2003. At BGU, he was one of founding members of the Department of Biomedical Engineering and in the past two years served as its head. There, he established the Computational Motor Control Laboratory and later organized the first annual international Computational Motor Control Workshop. His lab flourished and he received national and international recognition and funding from competitive funding agencies. He contributed to several international efforts, such as the EU COST Action on Rehabilitation Robotics, the Israeli group competing in the DARPA Robotics challenge, and the EU USA Topical Team dealing with motor control in space. He also led the US-AID MERC funded project to promote an active lifestyle in teenagers with cerebral palsy in the Middle East (Israel, Palestine, Jordan, and Morocco).

Amir's approach to the study of the motor system was notable for its combination of traditional engineering principles – modelling, control theory, and robotics – with a firm emphasis on placing the human being at the center. Amir made significant contributions using this principled approach to many aspects of our understanding of motor control. He developed a theoretical approach to the motor system – unifying reaching and object manipulation – based on the hypothesis that the motor system is an intermittent controller that minimizes transitions. In the context of far-reaching studies on adaptation at different levels of the motor system, he proposed that the system has no internal clock and uses state dynamics to stand in for time representation. The research on the representation of time also led to a systematic exploration of the way humans adapt to delayed force feedback. These studies led to the development of a novel framework for human-centered teleoperation transparency, work for which Amir was awarded the prestigious Juludan Award. This award is granted for outstanding research in the application of modern scientific or engineering techniques to medicine. The studies on teleoperation were the basis for the development of a Turing-like handshake test for motor control. Amir's goal was to develop a machine handshake that is undistinguishable from that of a human. He organized an international competition for developing such a handshake, the first of its kind. In recent years, Amir grew increasingly interested in the clinical applications of his research. One example that demonstrates how his theoretically based approach can have real clinical relevance is his work on predictive control. He showed that the role of our motor memories is to predict the future rather than to store the past. He further showed that individuals with cerebral palsy lack this ability to prepare for future events.

In his research synopsis, Amir wrote:

> *I am trying to think of the best way to convey my legacy to my children, my students and my community, a legacy of contributing to my society as a Jewish agnostic, believing in science and the ability of humans to discover and understand everything around us and in us. As an Engineer, I follow the words of Lord Kelvin: "I am never content until I have constructed a mechanical model of the subject I am studying. If I succeed in making one, I understand; otherwise I do not." Following this philosophy, in order to evaluate my understanding of the motor control system I would have to build a robotic device indistinguishable from human in its motor behavior.*
> *My long term goal is to understand how the brain controls movement. I am passionate about brain science, and about the vision of RoboSapiens as the next step in our evolution; I believe that humans can build and understand everything. I also believe that we need to explore space and master the universe. We have to work on these technological challenges along with being ethically sensitive to the capabilities of humans for evil and constructing the social breaks and balances without eliminating or slowing the natural desire of humans to explore and improve the world around us.*

Last but not least, Amir was a great teacher. He passed on his passion for engineering and research and his belief in our power to transform the world for the better, both to his students and to his colleagues.

We will miss you, Amir.

The Tenth BGU-CMCW June 17-19, 2014
The first BGU ABC Robotics Workshop

Dear Colleagues,

In what has now become a tradition, we welcome you to the tenth annual Ben-Gurion University Workshop on Computational Motor Control on **June 18th 2014**, in the W. A. Minkoff Senate Hall at Ben-Gurion University of the Negev, Beer-Sheva, Israel. In addition to the traditional workshop, this year we will have a special robotics workshop prior to the meeting, on **June 17th**. The following information is also available on our website: http://www.bgu.ac.il/cmcw

Thank you for your attention,
Opher Donchin, Lior Shmuelof and Yael Edan
donchin@bgu.ac.il ; Shmuelof@bgu.ac.il; Yael@bgu.ac.il

Overview:

The nervous system analyses sensory information and orchestrates motor commands. In so doing, it faces challenges that it shares with many artificially engineered systems. In the spirit of the classic field of cybernetics, the field of computational motor control makes scientific and technological progress simultaneously by exploring the differences between artificial control theory and biological motor control.Computational motor control is a multidisciplinary research program in which mathematics, engineering, biology, medicine and the cognitive neurosciences all play important roles. This workshop will bring together world leaders in the field of computational motor control including Israeli researchers and distinguished guests. The goal will be to learn about the current state of the field and to identify the directions that will provide the medical and scientific breakthroughs of the next decades.

Posters:

The posters will be available throughout the day near the lecture hall to facilitate fruitful discussions.

The Best Poster Award Sponsors:

- Alpha Omega
- SenseGraphics / Geomagic
- NanInsturments

Tour:

On Thursday, **June 19th** , we plan a hike to the Negev. This is part of the CMCW tradition and offers the opportunity to see the beauty of the desert, to become exposed to the different cultures of people living in it, and to continue scientific discussions from the conference. If you intrested

Desert in motion

in joining the tour, please let us know that at registration. A small additional fee may be required.

Dinners:

We planned a festive welcome dinner on the evening of **June 17 th**. This will be used as way to commemorate our dear colleague, Prof. Amir Karniel who passed away. Speakers and chairmen will be guests of the workshop at the dinner. For others wishing to join us, the dinner will be subsidized and will cost no more than 100 NIS per person. We will also have a more modest dinner and discussion in the evening following the workshop that will be payed by the participants.

CMCW Sponsors:

- The President, Ben-Gurion University
- The Zlotowski Center for Neuroscience, BGU
- The Dean of the Faculty of Health Sciences
- The Dean of the Faculty of Engineering

ABC Robotics Initiative supported by:

- Leona M. and Harry B. Helmsley Charitable Trust

ABC Robotics Annual Workshop

June 17, 2014
W. A. Minkoff Senate Hall, BGU Marcus Family Campus,
Beer-Sheva, Israel

מרכז זלוטובסקי למדעי העצב
Zlotowski Center for Neuroscience

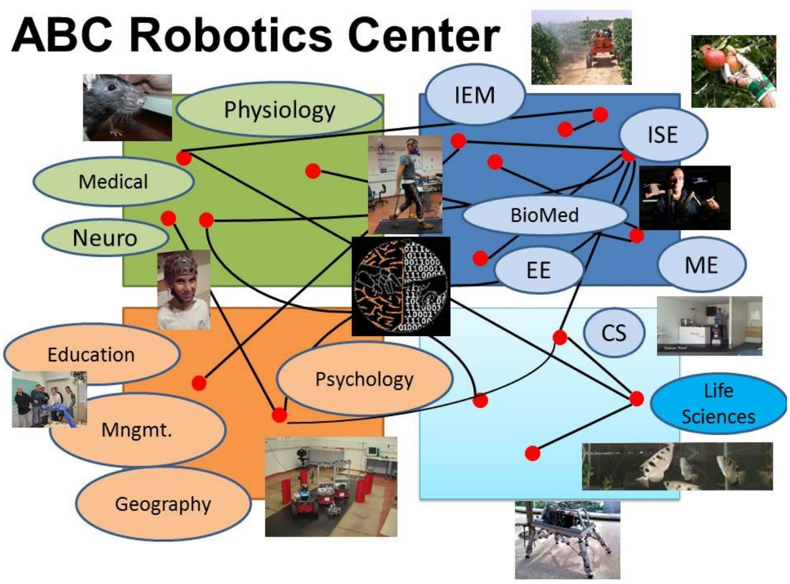
Zlotowski Center for Neuroscience at Ben-Gurion, and
Agricultural, Biological and Cognitive Robotics Initiative
Supported by the Helmsley Charitable Trust

Tuesday, June 17

ABC Robotics Annual Workshop
See Robotics Link for links and details

Chair: Tamar Flash, Weizmann Institute

- 8:30-9:00 gathering coffee
- 9:00-9:15 Opening remarks, **Prof. Yael Edan**
- 9:15-9:45 **Neville Hogan**, MIT
  "Biological and robotic control of physical interaction"
- 9:45-10:15 **Miriam Zacksenhouse**, Technion
  "Bio-inspired and Bio-controlled robots"
- 10:15-10:45 ABC Robotics Research Projects Presentations (2 min Teaser for Poster Session)
- 10:45-11:30 Poster Session and Coffee
- 11:30-12:00 **Frans van der Helm**, Delft
  "Robots for the diagnostics and therapy of patients with neurological disorders"
- 12:00-12:35 **Guy Hoffman**, IDC
  "Fluency in Human-Robot Joint Activities"
- 12:30-12:45 Discussion/Concluding remarks
- 12:45-13:30 Lunch
- 13:30-16:30 ABC Robotics Lab Tours
- 18:00 Dinner and memorial



The Tenth Computational Motor Control Workshop
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מרכז זלוטובסקי למדעי העצב
Zlotowski Center for Neuroscience

Department of Biomedical Engineering,
Zlotowski Center for Neuroscience at Ben-Gurion

Wednesday, June 18

- 8:15-8:45 Registration, Poster placement and coffee

In memoria of Prof. Amir Karniel

- 8:45-8:50 In memoria of Prof. Amir Karniel, **Opher Donchin**, BGU, Head of the organizing committee
- 8:50-9:00 Remarks, **Prof. Rivka Carmi**, the President of BGU
- 9:00-9:01 A moment of silence
- 9:01-9:30 Opher Donchin, "Open questions in Computational Motor Control: The scientific legacy of Prof. Amir Karniel"

Motor variables

Chair: Sigal Berman, BGU, Israel

- 9:30-10:00 **Tamar Flash**, Weizmann, Israel
  "Timing, segmentation and variability in human movement: models and brain networks"
- 10:00-10:30 **Claude Ghez**, Columbia, USA
  "Untangling the neural control of trajectory dynamics, position and impedance through auditory feedback of kinematic and positional variables"
- 10:30-10:40 Discussion
- 10:40-11:20 Coffee break and Posters

Motor physiology

Chair: Lior Shmuelof, BGU, Israel

- 11:20-11:50 **Steve Chase**, Carnegie-Mellon, USA
  "Internal model mismatch is responsible for the majority of errors in neuroprosthetic control"
- 11:50-12:20 **Ilan Dinstein**, BGU, Israel
  "Selective and invariant movement encoding in the human motor system"
- 12:20-12:50 **Sandro Mussa-Ivaldi**, Northwestern, USA
  "Understanding the environment as compatible forces and motions"
- 12:50-13:00 Discussion
- 13:00-14:30 Lunch and Posters

Motor control

Chair: Armin Biess, BGU, Israel

- 14:30-15:00 **Frans van der Helm**, Delft Technical University, Netherlands
  "Continuous modulation of sensorimotor reflexes during motor control"
- 15:00-15:30 **Shelly Levy-Tzedek,** Hebrew University, Israel
  "Sensorimotor integration using sensory substitution for the blind"

- 15:30-16:00 **Jordan Taylor,** Princeton, USA
  "The identification of multiple processes underlying learning in a sensorimotor adaptation task"
- 16:00-16:10 Discussion
- 16:10-16:20 Poster awards
  Sponsors: Sensegraphics/Geomagic, NanInsturments, AlphaOmega
- 16:20-16:50 Coffee break

Motor dynamics

Chair: Jason Friedman, TAU, Israel

- 16:50-17:20 **Mark Latash**, Pennsylvania State, USA
  "Equifinality and Its Violations in a Redundant System"
- 17:20-17:50 **Anatol Feldman**, University of Montreal, Canada
  "Harmonizing action and perception with physical laws: parametric control"
- 17:50-18:20 **Mindy Levin**, McGill, Canada
  "Redundancy, compensation and recovery after stroke"
- 18:20-18:30 Discussion
- 19:00 Dinner

Thursday, June 19

Desert Hike

- 08:30 - we will leave the hotel, be sure a had a good breakfast.
- 09:30 - **Ein Avdat**. This National Park located in a beautiful canyon in the Negev desert. The Ein Avdat Spring flows down in a waterfall towards an 8-meter deep pool of water. The oasis created by the springs attracts ibex and other animals. After sitting near the spring we will walk on a beautiful up hill road, climbing ladders which pass through ancient caves, Ein Avdat was inhabited by catholic monks who lived in those caves.
- 12:00 - **Ben-Gurion's Tomb National Park**- the final resting place of Israel's first prime minister and his wife, in a desert garden
- 12:30 - We will have a lunch at **Midreshet Sde- Boker**, a beautiful settlement which host the desert research institute of the University. The place that served as the residence of David Ben Gurion and his wife Pola, today is used as a museum showing his heritage through the way he chose to live his private life.
- 15:30 - **Nahal Havarim** till 18:30.
- Bring with you: a wide hat, long comfortable clothes (for a hot warm and sunny day) and good hiking shoes, sun's cream.

* On this day we plan to hike for the most of the day.

* There is no need for flashlights or bathing suits

Talks

ABC Robotics
June 17

Biological and robotic control of physical interaction

Neville Hogan

Massachusetts Institute of Technology, USA

Human dexterity and agility vastly exceed even the best of contemporary robots, despite noisy sensors, slower actuators and profoundly slower communication and computation. How is that possible? I will argue that studying the control of physical interaction—critical for that quintessentially human ability, the use of tools—provides insight. Controlling physical interaction presents unique challenges not encountered in controlling movement: conventional control and information processing theory is based on unilateral operations (inputs yield outputs but not vice-versa) but physical interactions are bilateral. Computers and brains essentially process information; physical systems process energy. Conventional information processing theory does not work well but concepts grounded in physical system theory have proven effective. Actuators such as muscle occupy the interface between information processing and energy processing. I will discuss how the venerable concept of an equivalent network may be re-purposed to integrate both processes [1]. One key property of muscle is its modifiable mechanical impedance. I will review examples showing how this fundamentally nonlinear property can dramatically simplify the control of physical interaction and argue that modifiable mechanical impedance is a key dynamic primitive that may contribute to the spectacular performance of humans [2, 3].

[1] N. Hogan, "A General Actuator Model Based on Nonlinear Equivalent Networks," IEEE/ASME Transactions on Mechatronics, vol. 99, pp. 1-11, 2013.

[2] N. Hogan and D. Sternad, "Dynamic Primitives of Motor Behavior," Biological Cybernetics, vol. 106, pp. 727-739, 2012.

[3] N. Hogan and D. Sternad, "Dynamic Primitives in the Control of Locomotion," Frontiers in Computational Neuroscience, vol. 7, pp. 1-16, June 21 2013.

Bio-Inspired and Bio-Controlled Robots

Miriam Zacksenhouse

Faculty of mechanical Engineering, Technion –IIT, Israel
mermz@tx.technion.ac.il

I will cover two promising directions in bio-inspired legged robots and bio-control of rehabilitation robots.

The interaction of central processes and external feedback in the generation and control of biological movements is a basic concept, related both to internal models and their role in reaching movements and to central-pattern generators (CPGs) and their role in locomotion (and rhythmic movement in general). While the concept of internal models has a close parallel in classical control, the use of CPGs in robotic control is clearly bio-inspired. One of the main advantages of CPGs is their open loop stability – however, sensory feedback is critical for enhancing robustness and adaptation to environmental changes. I will describe a unique paradigm for integrating minimal, once per cycle, feedback with CPGs and demonstrate its application for dynamic legged locomotion. Legged locomotion is modeled as a hybrid dynamical system, and the stability is quantified numerically using Poincare map and theoretically using the Saltation Matrix. Control parameters are tuned using multi-objective optimization, taking into account stability, robustness and energy efficiency. The resulting control strategy greatly improves robustness and adaptability to slope variations for a simple compass-gait biped model.

Recent advances in brain-computer interfaces (BCIs) provide the foundation for integrating brain signals in robot control and rehabilitation. I will describe our initial work on decoding arm movements from EEG data using convolutional neural networks (CNN), and on characterizing error-related potentials (ErrPs). CNN provide superior performance to standard linear decoder, however, the issue of generalization is still a major challenge. Error-related potentials provide valuable feedback for correcting and adapting BCIs and for timing the operation of rehabilitation robots, and our initial results suggest that they may also convey information about the magnitude of the error.

Robots for the diagnostics and therapy of patients with neurological disorders

Frans C.T. van der Helm

Biomechatronics & Biorobotics group
Dept. of Biomechanical Engineering
Faculty of Mechanical, Materials and Maritime Engineering
Delft University of Technology, Netherlands

In rehabilitation, robots are more and more used for therapy. Proper therapy is based on adequate diagnostics and continuous monitoring of the results.

The neuromuscular control system is a closed-loop system, with sensors (muscle spindles, Golgi tendon organs), actuators (muscles) and a control system (spinal cord, brain). In the system identification of the closed-loop neuromuscular system, one has to impose an external signal to quantify the properties of the elements inside. Usually position perturbations are being used. In contrast, we are using a variety of robot manipulators to impose force perturbations on the limbs, e.g. for the shoulder, wrist, ankle, head-neck and low-back systems. The advantage of the force perturbations is that the system is still a closed-loop system, and that the efforts of the subjects to increase the impedance helps to resist the perturbation. A continuous perturbation signal is being used, based on a multisine with a limited number of frequencies. The response to the perturbations is being recorded, i.e. the exerted force, the position and the EMG signals. Recently, we have also started to record the EEG signals in order to monitor the changes in the sensoricortical areas. Using the input-output signals, the transfer function of the system in between can be estimated, which we usually do in the frequency domain. We calculate the admittance (inverse impedance = deviation / force) and the reflexive impedance (EMG / deviation) to characterize the reflex settings. In the applied frequencies there is a very high SNR, enabling the identification of muscle visco-elastiticity, muscle spindle and Golgi tendon reflexes.

The multisine signal is perceived as a small additional noise signal. It allows recording during functional tasks as positioning the limb or maintaining a certain force level, but also car driving and airplane control. For examination the position task and force task are mostly being used. In the force task the reflexes are being used to actively give way, i.e. the arm becomes more compliant than in the passive condition. In these tasks the position and force feedback gains switch between positive and negative.

The system identification techniques have been applied to patients with neurological disorders, like stroke patients and patients with dystonia. Dystonic patients are hardly able to modulate the force reflex gain. It is hypothesized that this is due to a malfunctioning inhibitory interneuron at the spinal cord level. In a computer simulation it has been shown that the inability to modulate the force reflex gains could explain all symptoms of dystonia. Stroke patients tend to be not very capable to modulate their reflex gains at all. Interesting enough, they have the strategy to maintain a larger stability margin than healthy subject, presumably anticipating undesired perturbations which they have difficulties to cope with.

Fluency in Human-Robot Joint Activity

Guy Hoffman

Interdisciplinary Center, Israel

Within decades, robots are expected to enter homes, offices, schools, and nursing facilities, and we should expect them even sooner in operating rooms, battlefields, construction sites, and repair shops. Successful human-robot interaction design is key to enable these robots to work smoothly and intuitively with untrained human partners. This challenge has led to the emerging field of Human-Robot Interaction (HRI) research, investigating computational, cognitive, and design approaches to human-adaptive robots, and evaluating people's responses to such robots.

This talk gives an overview of seminal and current HRI research, as well as my own research in human-robot collaboration. I discuss the design of non-verbal behaviors such as turn-taking, gaze, and gestures for shared attention, which we have implemented on an expressive humanoid robot, and how it impacts joint task performance between a human and a robot. In another project, we evaluate the role of anticipation of the human's actions, showing effects on team performance, as well as on the human partner's sense of the robot's trustworthiness and commitment. I then describe an embodied cognitive framework for robots, based on a model of perceptual simulation and cross-modal reinforcement, demonstrating how this model supports physical practice in an ensemble, and its effects on human subjects. For example, we see effects on the perception of the robot's intelligence, credit, and even gender, but also the induction of stress and self-deprecation.

In the field of entertainment robotics, I present a robotic theater control system using insights from acting theory, which enables robotic nonverbal behavior that is both reactive and expressive. I then discuss an interactive robotic Jazz improvisation system that uses embodied gestures for musical expression, enabling simultaneous, yet responsive, joint improvisation.

Finally, I present the design of a smartphone-based media companion robot. Human-subject studies show effects on music enjoyment and social presence when the robot responds to music that participants listen to, but no apparent sensitivity to the beat-alignment of the robot's motion.

Talks

CMCW

June 18

Open Questions in Computational Motor Control
or – The First Last Talk of Prof. Karniel

Prepared by
Amir Karniel
who passed away on June 2, 2014
The Computational Motor Control Laboratory, Department of Biomedical Engineering, Ben-Gurion University of the Negev, Israel.

I have metastases Osteosarcoma, and therefore the audience knows that this is one of my last talks, putting me in a position to try and provide a legacy for my students and for the computational motor control community. In this talk I will review some of my studies trying to understand how the brain controls movement using computational models and psychophysics human studies. I will try to highlight wide questions left unsolved, discussing open questions such as: (i) Does the motor system use intermittence control strategies? (ii) Does the brain use time keepers or clocks during motor adaptation; And (iii) Can we build a robot indistinguishable from human in its motor control capabilities?

The first question is very simple and technical, while the second and third opens various sub questions such as the issue of internal models and actually each and every question on computational motor control eventually burns out to the third imminent open question and the tools provided in my lab to address it, such as The Turing-like handshake test, which has been designed to measure our progress in understanding the motor control system in units of human likeness, under the assumption that being able to simulate the motor control system is a prerequisite for understanding it.

I will conclude this talk by discussing the scientific and technological implications and future applications of studying motor control of human movements during locomotion of teenagers with Cerebral Palsy in the Middle East, in natural environment as well as over a split belt treadmill, and of course, using arm movements in augmented reality of the PONG game as well as simple reaching, probing, tracking, and grasping movements.

The studies in the computational motor control laboratory have been supported by the United States-Israel Binational Science Foundation (BSF); by the National Institute for Psychobiology in Israel (NIPB); by the ministry of science (MOS); by the US-AID Middle East research collaboration program (MERC); and by the Israel Science Foundation (ISF).

Timing, segmentation and variability in human movement: models and brain networks

Tamar Flash

Department of CS and Applied Mathematics, Weizmann Institute of Science, *Israel*

In my talk I will provide an overview of our studies of different aspects of trajectory formation.
In particular I will present recent advancements of our studies that focus on the notion that motion planning involves mixture of several geometries including Equi-affine, Full Affine and Euclidean geometries as well as the hypothesis that motor timing and durations arise from the combination of such geometries. Recently this theory was further generalized to address the issue of motor compositionality—the idea that complex movements are constructed from elementary building blocks. In particular in a recent study conducted jointly with Meirovitch and Bennequin we examined the possibility that elementary strokes correspond to full affine orbits that minimize jerk. We also examined what combinations of the different geometries correspond to different drawing paths. The full affine orbits were then extracted from measured drawing movements and investigations were conducted how geometrical singularities affect the speed profiles of the movements. In another study jointly conducted with Titon and Bennequin we analyzed the variability of drawing movements and used auto-correlation analysis performed on the velocity profiles. By examining the statistical independence between variability values at adjacent sampling points, the drawing movements were segmented into strokes. Given the similarity between the kinematic laws of motion underlying motion perception and production, I will also review EEG and fMRI studies aimed at identifying spatiotemporal patterns of brain activities that respond more strongly to motions that comply with the two-third power law, i.e. motions having constant equi-affine speeds, than to other laws of motion. This latter study was conducted jointly with Meirovitch, Harris, Dayan and Arieli.

Untangling the neural control of trajectory dynamics, position and impedance through auditory feedback of kinematic and positional variables

Claude Ghez

Columbia University, USA

TBA

Internal model mismatch is responsible for the majority of errors in neuroprosthetic control

Steven Chase

Carnegie-Mellon University, USA

Sensory feedback delays make it impossible for us to have real-time knowledge of the positions of our limbs. We can compensate for these delays by using an internal model of how our limbs respond to motor commands to predict the sensory consequences of those commands. This in turn allows us to generate appropriate motor commands before resulting sensory feedback becomes available, allowing for the fast, fluid production of a series of movements. Here we present evidence that subjects perform feedback delay compensation when operating neuroprosthetic devices. Using a novel inference technique, we are able to extract the subject's internal model of the prosthetic system, and infer his moment-by-moment estimate of the real-time position of the device. Surprisingly, we find that a mismatch between the subject's internal model and the actual dynamics of the prosthesis explains the majority of the subject's control errors. Our ability to extract internal models from neural population activity enables inspection into the real-time decision making processes that unfold throughout motor control. The neuroprosthetic control system thus provides a paradigm through which we may probe the neural underpinnings of feedback motor control and motor learning.

Selective and invariant movement encoding in the human motor system

Ilan Dinstein

Ben-Gurion University of the Negev, Israel

In the lab we are using fMRI to reveal new insights regarding movement encoding in humans. I will describe a set of recent studies where we have used pattern classification techniques to learn about the encoding of hand writing movements and changes in directional encoding associated with learning a visuo-motor rotation.

Understanding the environment as compatible forces and motions

Ferdinando A. Mussa-Ivaldi

Northwestern University, USA

The goal of recovering the desired behavior against external perturbations can be achieved by feedback mechanisms. When the environment is unpredictable, the maintenance of a desired motion or a desired contact force by feedback mechanisms can be accomplished by shifting the interface impedance toward two opposing limits. In motion control, random forces are counteracted by high position feedback gains, resulting in high contact impedance. In force control, random motions are compensated by high force feedback gains, resulting in low contact impedance.

The possibility to shift impedance toward high or low values is constrained by the passive mechanics of muscles and bones and by the long transmission delays of neural feedback. However, when the environment acts upon us in a predictable way, our brain may form internal representations of the external mechanics and modify the feedforward commands accordingly. This leads to an adaptive response that has been extensively investigated in the generation of movements against predictable force fields.

I will consider this issue in a theoretical framework that extends the concept of internal models and unifies the approach to the motor learning of forces and motions. In this framework, the brain generates a vast spectrum of interactive behaviors by combining two independent processes. One is competent to control movements in free space and the other is competent to control contact forces against rigid constraints. Free space and rigid constraints are singularities at the boundaries of a continuum of mechanical impedance. Within this continuum, forces and motions occur in "compatible pairs" connected by the equations of Newtonian dynamics. The force applied to an object determines its motion. Conversely, inverse dynamics determine a unique force trajectory from a movement trajectory. In this perspective, motor learning is a process that leads to representing the environment dynamics through the discovery of compatible force/motion pairs.

Continuous modulation of sensorimotor reflexes during motor control

Frans C.T. van der Helm

Biomechatronics & Biorobotics group
Dept. of Biomechanical Engineering
Faculty of Mechanical, Materials and Maritime Engineering
Delft University of Technology, Netherlands

The motor cortex is involved in initiating the volitional motions of the muscular system. Through the direct connection between primary motor neurons and α-motor neurons, the muscles are being activated. In addition, it is hypothesized that the motor cortex is involved in the modulation of the reflex gains at the spinal cord level, thereby adapting the impedance of the limbs.

The impedance of the limbs is the result of the segment inertia, the muscle stiffness and viscosity and the proprioceptive reflexes, i.e. the position and velocity feedback through the muscle spindles, and the force feedback through the Golgi tendon organ. It has been frequently shown that the impedance is being modulated, e.g. by muscle co-contraction increasing the visco-elasticity, and by the reflex modulation.

However, since the neuromuscular control system is a closed-loop system, one has to impose an external signal to identify the properties of the elements inside. We are using robot manipulators with force perturbations to perturb the neuromuscular system. It requires some recording time to observe the system reacting to the force. The challenge is to observe changes in the neuromuscular system resulting from the continuous reflex modulation despite the observation time necessary. This can be achieved using a Linear Time Varying (LPV) system identification paradigm in the time domain.

In the experiment the subjects were requested to move their hand back- and forward. During the movement continuous force perturbations were applied. In the LPV algorithm, position was used as scheduling function, and a time-varying state space model was estimated on the data set. After fitting a neuromuscular model to the state space model, with mono-articular shoulder and elbow muscles and also bi-articular muscles, it showed that the intrinsic muscle viscosity and reflex gains varied regularly with the change of position. The VAF in lateral-medial direction was 92% and in forward/backward direction 73%, affected by the volitional motion.

Feedforward (volitional) muscle control for a complex system as the shoulder and elbow might be relatively easy compared to the reflex gain control in order to provide the desired impedance. Such a highly multivariable and coupled system is unequalled in robotic control. It is likely that larger parts of the cortex, and presumably the motor cortex, is occupied with this task. The total reflex gain is a combination of tonic drive to the α-motor neuron, the presynaptic inhibition and the γ-motor neuron activating the intrafusal muscle fibers. Previous studies showed that in each experimental condition a wide variety of co-contraction and reflex gains settings were present. The current study showed that the gain settings are continuously modulated, presumably in a feedforward manner simultaneously with the muscle activation.

Closing the action-perception loop, using sensory substitution

Shelly Levy-Tzedek

Hebrew University, Israel

A key property of a sensory substitution device (SSD) – where one sense is used to convey information usually conveyed using another sense – is that it would enable users to successfully move within their environment. I will review the (few) studies in the field that have explored the inseparable link between action and perception with sensory substitution, and will present the results of our studies examining movement guided by SSDs. I will discuss how information flowing through the action-perception loop transfers across senses, and will argue that sensory-motor learning is not sensory-modality-specific, but rather novel sensorimotor information can be transferred between sensory modalities. I will conclude by outlining the important implications of these findings for visual rehabilitation, and for the visually impaired.

Keywords: Audition; Cognitive Control; Judgment / Decision Making; Learning; Memory; Motor Processing / Control; Multisensory Integration; Spatial Cognition; Vision

The identification of multiple processes underlying learning in a sensorimotor adaptation task

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Traditionally, visuomotor adaptation has been regarded as reflecting a unitary function involving implicit "procedural learning". More recently, however, it is becoming clear that multiple learning processes can be involved. In the case of a visuomotor rotation, which is a visual mismatch between movement and feedback, the motor system needs to counter the rotation by moving in a direction opposite to the rotation.

This solution can potentially arise through a number of different learning processes, such as internal model adaptation, reinforcement learning, and strategy utilization. The relative contribution of each process may be influenced by various factors including the type of feedback used to indicate action outcomes, the form of the instructions that shape how the task is conceptualized, and manipulations of visual cues in the environment. The aim of the current set of studies is to unravel how these factors influence learning a visuomotor rotation.

To elucidate these different learning processes we manipulated information in error feedback, verbal instructions, and visual landmarks in the task workspace while participants learned to counter a visuomotor rotation. These manipulations had a profound effect on how the rotation was countered. With reduced error feedback, the learning curves exhibited a high degree of variability until the correct aiming location was discovered, and then stabilized. This form of learning is reminiscent of reinforcement learning tasks where learning occurs through exploratory trial-and-error until an action is reinforced. In contrast, with more informative error feedback, performances curve were monotonic with a smooth reduction in target error during training. Aftereffects, a measure of the degree of sensorimotor remapping, scaled as a function of the information in error feedback suggesting that detailed cursor information is necessary for training an internal model. Increasing information in instruction also increased trial-and-error learning through exploration of the action-outcome space. The visual landmarks provided an anchor for developing explicit strategies to counter the rotation and also provided a means to directly assay the contribution of explicit learning during training. We find that participants utilized various strategies throughout training and that the degree of their engagement appears to be the result in a push-pull interaction, with reward-based learning potentially suppressing error-based adaptation.

Taken together, these results suggest that a rotation can be solved by multiple, different learning systems and differences in information in feedback, instruction, and visual cues may bias the relative contribution of different processes.

Equifinality and Its Violations in a Redundant System

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To understand physics and physiology that bring about natural human movements, we accept as an axiom that neural structures do not perform computations but behave according to laws of nature. The only current hypothesis that is compatible with both physics and physiology is the referent configuration (RC) hypothesis, a generalization of the equilibrium-point hypothesis for multi-effector actions. The RC hypothesis assumes that voluntary actions start with neural signals that lead to shifts of body RC, given the external force field. RC at the task level is defined as a relatively low-dimensional set of referent values for salient, task-related variables. Further a sequence of few-to-many (redundant) mappings result in RCs at lower levels such as those related to individual limb, digit, joint, and muscle states. The problems of motor redundancy that seem to emerge at all levels of analysis of this system have recently been re-cast as the bliss of abundance. According to this approach, few-to-many mappings are associated not with finding single (e.g., optimal) solutions but with facilitation of families of solutions that ensure movement stability in the poorly predictable environment. Such mappings have been addressed as synergies leading to task-specific stability properties within the redundant spaces of elemental variables. Studies of task-specific stability used both perturbations of ongoing movements and analysis of variance across repetitive trials. Recently, we explored the phenomenon of equifinality within this theoretical scheme. Equifinality refers to a property of a motor system to come to about the same state following a transient perturbation. In recent series of experiments, we quantified the effects of smooth, transient perturbations in spaces of task-related variables (low-dimensional) and elemental variables (high-dimensional). The subjects were always required to perform a steady-state task and not to react to the perturbations. We used force perturbations in positional multi-joint tasks (analysis was performed in both kinematic and muscle activation spaces) and positional perturbations in multi-digit force production tasks. In both cases, the task-specific variables showed equifinality after the perturbations while elemental variables showed large variance in directions that did not affect the task-specific variables (violations of equifinality). If the perturbation lasted for a longer time, violations of equifinality were also seen at the level of task-related variables. We interpret these effects as consequences of back-coupling between the actual body configuration and RC with the RC being attracted to the actual body configuration.

Harmonizing action and perception with physical laws: parametric control

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One of the important criteria for accepting or rejecting a theory of action and perception is that it should be consistent with the fact that biological systems obey natural laws (also called physical laws). Therefore, theories that are inconsistent with this fact should be disregarded, like the theory that the earth is flat and is the center of universe created less than six thousand years ago. The problem is that researchers may also make errors in judgement and be unaware of inconsistencies of their theories with physical laws. In other words, the inconsistencies can be inadvertently hidden and only recognized after careful analysis of the properties of physical laws, which I am going to undertake. I will start from recognition that physical laws dictate certain relationships and causality between variables for which I coin the term law-constrained variables. In particular, laws of mechanics constrain relationships between variables that are used to describe the outcome of motor actions – motor commands to muscles (EMG patterns), kinematic and kinetic variables typically used in biomechanical studies. The nervous system cannot directly specify law-constrained variables without breaking the causality principle inherent in physical laws. Therefore, based on this criterion, theories of action and perception that assume that the nervous system pre-programs the motor outcome with or without help of internal models should be rejected. Given this criterion, how are action and perception harmonized with physical laws? Such laws include parameters. Parameters are constants or variables that determine particular forms of physical laws without influencing their general structure and causality. In other words, parameters do not influence the essence of physical laws but play a fundamental role in defining how these laws are manifested. For example, the mass of a stone is a parameter in Newton's second law that governs free motion of the stone. Pushed by the same force, different stones will be accelerated differently depending on their masses, manifesting different outcomes of the same physical law. Parameters can be subdivided into two subsets. One subset consists of invariants inherent in physical laws. For example, the speed of light (c), the gravitational constant (G) and the acceleration of free fall near the surface of Earth (g) are examples of such invariant parameters. The other subset of parameters is especially important if we include in our analysis the inhabitants of the environment – biological systems that deal with physical laws. This subset of parameters consists of constants and variables that are not constrained by physical laws and therefore can be changed by biological systems independently of law-constrained variables. Parametric control is thus the only way of harmonizing action and perception with physical laws. The physiological essence of parametric control will be illustrated in several experimental examples of action and perception in humans.

Redundancy, compensation and recovery after stroke

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In the healthy nervous system, the capacity for kinematic redundancy allows the system to find many different solutions or combinations of joint rotations to perform any given task, leading to a desirable amount of motor adaptability. After damage to the central nervous system such as brain injury or stroke, sensorimotor activity is disrupted and individuals are less able to accomplish functional tasks using pre-morbid muscle activation and/or kinematic patterns. One reason for this is a decrease in redundancy, limiting the number of ways a movement can be performed. Because of this limitation, the system seeks to find alternative solutions to movement through motor compensations. Changes in motor patterns used to accomplish the same task may be considered to be adaptive if they lead to positive functional outcomes but they are considered compensatory when they represent deviations from motor patterns observed in healthy individuals. Compensations are undesirable because they may interfere with recovery of typical movement patterns and may lead to 'learned non-use' or 'bad-use'. Compensations used for motor actions of the upper limb in patients with stroke will be described such as excessive trunk displacement for reaching towards targets placed within arm's reach, trunk and scapular displacement during arm swinging, excessive shoulder abduction during attempts to reach sagittally and use of the trunk to orient the hand for grasping. Compensations will be explained in terms of limitations in the regulation of motoneuronal thresholds at the single and double-joint level. The threshold control theory of motor control describes how central regulation of reflexes, including the stretch reflex, results in different motor actions, in particular, muscle relaxation, motion, and isometric torque production in single- or multi-joint systems. Research in animals and in healthy subjects suggests that tonic stretch reflex thresholds (TSRT) are regulated by descending systems mediating both direct and indirect influences on motoneurons. Deficits in agonist-antagonist muscle activation in patients with spastic hemiparesis are related to limitations in the range of regulation of TSRTs. This results in motor compensations and has implications for sensorimotor recovery.

Posters

Towards a theory of inspiring tutorship –
On being mentored by Amir Karniel

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Days before his parting, in one of his last emails to us, Amir writes:

> Indeed, I am full of pride and derive tremendous pleasure from my students. Recently I read "Jews and Words" by Amos Oz and his historian daughter. I immensely enjoyed their observation that the teacher-student relationship is central to Judaism. The Sages even had the courage to portray God, in the famous Talmudic fable of the debate he held with the Sages, as exclaiming in admiration "my sons have defeated me" when they bested him in the debate! So, to put it simple, it's not about genetics or about biological parenthood – It's the transmission of the knowledge from Moses to Akiva, from teacher to student. And in Israeli secular Judaism, from the Professor/Lecturer/Researcher, to her students.

As students who had the privilege to be mentored by Amir, we wish to share with his family, colleagues and scientific community, a few personal insights and memoirs that portray Amir's special tutorship by inspiration.

Inertial Properties of Human Arm Motion

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In this study we analyze the inertial properties of the human arm motions in the context of the inverse kinematics problem. We show how the kinetic energy can be decomposed into end-effector kinetic energy and null space kinetic energy. This decomposition is related to a possible solution to the inverse kinematics problem using the generalized pseudo-inverse control where the arm inertia matrix is used as the configuration space Riemannian metric (Khatib 1995). It also allows us to identify the inverse of the end-effector mobility matrix (Hogan 1985) as a Riemannian metric on the task space.

We applied this decomposition on experimental data of drawing motions, and found that the subject's end-effector kinetic energy was very close to the total arm kinetic energy, and that the null energy was close to zero for most of the movement's duration. This phenomenon was observed for many different drawing movements and under different conditions. In order to characterize the behavior of the null energy, we computed a simple statistics for the portion of the null energy, averaged over movement time, out of the total arm kinetic energy. This analysis revealed that for motions which require more resistance to gravity, the null energy portion was slightly larger.

From these results we conclude that the arm inertial characteristics when expressed at the end-effector have a significant effect on the subject's trajectories in the configuration space. In fact the optimization principle of moving in the locally minimum kinetic energy direction explains 80-95% of the total arm kinetic energy. We hypothesize that the remaining null kinetic energy reflects the discrepancy between the produced versus predicted joint velocities that result from the effects of gravity and arm impedance.

Olivocerebellar signals are modulated by violation of "safety" expectations

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The cerebellum is known to be essential for motor learning, often studied using the classical eyeblink conditioning paradigm, in which a benign conditioned stimulus (CS; e.g., a tone), which by itself does not elicit a behavioral response in the naive animal, is followed, usually with a fixed interval, by a noxious somatosensory unconditioned stimulus (US; e.g., a periorbital airpuff). Following repeated paired CS+US presentations, the cerebellum learns to elicit a conditioned motor response (e.g., a blink), that precedes the onset of the US. The US signal is mainly conveyed to the cerebellum by the inferior olive (IO) nuclei, and it has been suggested that IO signals constitute "error signals", in the sense that they report the occurrence of unexpected sensorimotor events. However, it is not known whether such expectations could affect IO responses independently of conditioned motor responses. Therefore, in the present study we sought to determine whether the presentation of a CS may modulate the neural representation of noxious somatosensory stimuli in the IO, and whether this modulation depends on the CS's emotional/motivational valence, assigned through previous non-motor learning. Anesthetized rats were subjected to emotional learning sessions in which the CS either predicted the occurrence of a noxious electric shock (CS+) or its absence (CS-). Following learning sessions, we recorded responses of IO populations and single IO neurons to facial airpuffs from the cerebellar cortex (as climbing fiber responses and complex spikes, respectively), and compared responses in airpuff-alone trials to responses in trials in which the airpuff was preceded by a CS. We observed that CS-presentations were significantly more likely to modulate airpuff-evoked IO responses than CS+ presentations, suggesting that IO signals may contain information regarding the violation of "safety" expectations.

Perception of biological motion and the Default Mode Network

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Previous studies suggested that observed motion kinematics is utilized by the brain for social-cognitive processing. High-level social-cognitive functions such as self-referential processing and theory of mind have been attributed to the Default Mode Network (DMN). Here we used functional MRI to examine whether the DMN is sensitive to parametric manipulations of observed motion kinematics. DMN structures presented distinct activity and connectivity in response to observed natural vs. unnatural kinematics. These differences were evident only when the motion was performed by a human-like avatar, and not when it was displayed as abstract motion, devoid of human form features. These findings are the first to implicate involvement of the DMN in perception of biological motion, presenting evidence of sensitivity to kinematics and form of external stimuli. We further examined whether connectivity between DMN and other brain structures is affected by motion features. Connectivity between a subgroup of DMN structures and the Superior Temporal Sulcus (STS) showed selectivity only to motion kinematics, whereas connectivity between the complementary subgroup of the DMN and visual areas was sensitive to form or to the interaction between form and kinematics. It is possible, then, that the DMN resonates and integrates different aspects of observed motion. This information may support high-level social-processing in the DMN.

Intrinsic muscle design: influence on human motor control

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A key aspect of understanding human movement is the interaction of the control strategy with the musculoskeletal system. In the last decades, numerous approaches and modeling studies concerning the control of posture and movement have been developed. There are simple torque-driven models ignoring intrinsic muscle-tendon properties (e.g. Kawato 1990, Sainburg et al., 1999). More complex, second-order linear spring-damper-inertia (KBI) models take the visco-elastic characteristics of the muscle-tendon-complex into account (e.g. Gomi & Kawato 1997, Popescu, Hildler & Rymer 2003). These visco-elastic properties arise from muscle-tendon characteristics like the force-length or force-velocity relation of the contractile element and the non-linear elasticity of the tendon. In the KBI model, such an elastic tendon element is missing. Therefore, in vivo dynamics of the musculoskeletal system cannot be adequately described using this kind of stiffness-damping-inertia model.

Recent studies have shown that Hill-type musculoskeletal models can be used as well-established biomechanical actuators to perform fast goal-directed single-joint arm movements (Kistemaker & Rozendaal 2011, Kistemaker et al. 2006, Song et al. 2008). In general, such kind of models takes into account the non-linear activation dynamics, non-linear visco-elastic muscle properties and non-linear elasticity of tendons. As it has never been investigated, we address the question which characteristics are relevant/necessary for actuators to perform fast goal-directed arm movements.

In our simulation study, the human arm (upper & lower arm, elbow) is modeled by a non-linear musculoskeletal model with two degrees of freedom and four lumped muscle-tendon complexes. Each muscle-tendon complex model consists of biochemical activation dynamics and four biomechanical elements: a contractile element (CE) with force-length and force-velocity relation, a parallel elastic element (PEE), a series elastic element (SEE) and a serial damping element (SDE) (Haeufle et al. 2014). The motor control system is represented by a combination of feedforward and feedback-controller (Kistemaker et al. 2006). We compared the effect of different mathematical representation of the biochemical and biomechanical model parts on movement speed in fast goal-directed arm movements. Already exchanging the mathematical model of the biochemical activation dynamics (Zajac 1989 vs. Hatze 1977) revealed significant differences in peak arm speed. Exchanging the models of the biomechanical structures also influences arm kinematics. We discuss the implications of these results for motor control simulation studies.

The Effect of Space Variant Delay on Proprioceptive Space Recalibration

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Because we live in a dynamic world, space can be described as events that occur simultaneously in different locations. From this point of view, one could wonder how breaking the simultaneity between events would affect our representation of space.
Recent experiments[1] demonstrated that after subjects experience a delay between the hand and paddle movements during a virtual game of pong, their representation of hand location has been recalibrated. In the light of these results, we proposed the hypothesis that disturbance of the simultaneity between the proprioception modality and other (visual and haptic) sensory modalities in a non-uniform manner within the pong arena, would result in a non-uniform deformation of space which grows according to the incline direction of the temporal perturbation.
In order to test this hypothesis we have developed a new experimental protocol which is based on the game of Pong and is administered in a virtual reality environment. The subjects hold the handle of the robotic device (6 DOF PHANTOM® Premium™ 1.5 haptic device) with their right hand while looking at a screen that is placed horizontally above this hand. During the adaptation part of the experiment, the virtual paddle is delayed with respect to the movement of the hand controlling it. The amount of delay is determined according to the horizontal location of the subject's hand, gradually increasing toward one hemispace- from right to left; from left to right; or with no delay in any location within the arena in the control condition.
Our preliminary results imply for differences in the extent of targets overshoot following adaptation to delay between the different conditions of spatial direction of increasing delay. This asymmetry might be attributed to mechanical constraints and to differences in hand dynamics while acting on different sides of space, or to right hemisphere dominance for the distribution of spatial attention[2].

This study may contribute to the understanding of how the brain represents time and space while controlling motor tasks, and to help in the continuous research and development of new rehabilitation techniques, specifically for impairments related to space representation such as in hemispatial neglect syndrome.
Acknowledgment- The study is supported by the Binational United States Israel Science Foundation. Grant no. 2011066.

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Decoding of Hand Kinematics from a Non-Invasive Brain-Computer Interface

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Several neurological disorders can lead to severe motor disabilities or even cases of locked-in syndrome. In order to overcome these physical limitations, brain-computer interfaces aim at restoring motor or cognitive functions by acting as communication pathway from the brain to an external device such as a computer. It has been assumed for a long time that inherent limitations of non-invasive interfaces would prevent them from being used to decode limb movements. However several researches conducted in the last few years proved that assumption wrong. In this study, we aim at using convolutional neural networks (CNN), a gradient-based learning method which has been extensively used in image classification problems, for decoding hand kinematics from EEG. Subjects were instructed to perform random reaching movement while gazing at a cross displayed on the monitor in front of them. EEG signals were recorded from 64 channels and synchronized off-line with the kinematic data acquired through a Phantom haptic device. The experiment comprised 20 trials of 1 minute each, separated by a period of rest. Hand kinematics were then decoded off-line using a CNN and the results were compared to those obtained with a linear decoder. Both decoders reached reasonably high performance in single trial decoding (each trial was decoded using a different decoder). However, the linear decoder failed to achieve the same level of performance in multi-session decoding (a decoder was trained and used across multiple sessions), indicating that the model is time-dependent: it does not provide a stable mapping between the brain signals and the kinematic data and thus appears to be inadequate for long-term control of brain-computer interfaces. The CNN successfully overcame these limitations and reached high performance even in multi-session decoding. We have showed in this study that non-invasive interfaces can be used to decode hand kinematics with reasonably high accuracy. However it seems that the linear decoder fails to capture time-invariant features from the signal. In order to overcome this issue, the CNN model offers promising results. The next step of this study will be to perform on-line decoding of hand kinematics.

Awareness of sensorimotor adaptation to visual rotations of different sizes

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Previous studies on sensorimotor adaptation revealed no awareness of the nature of the perturbation after adaptation to a 30° rotation of visual feedback or after adaptation to gradually introduced perturbations. However, assessment of awareness by means of questionnaires, as done in those studies, can be problematic. Thus, the present study used the process dissociation procedure, known in the field of cognitive psychology, to measure awareness and unawareness indices. We were interested in determining whether degree of awareness depends on the magnitude of the visual rotation. We further wished to determine if it can be manipulated by providing the subjects with an explicit strategy before adaptation.

To this end, two groups of subjects (explicit and implicit) performed alternating blocks of center-out reaching movements under null and adaptation conditions. Adaptation was to 20°, 40° and 60° cursor rotations in different adaptation blocks. The order of blocks was randomized between subjects. After each adaptation block the process dissociation procedure consisting of an inclusion and an exclusion condition was conducted. During inclusion condition subjects were asked to perform the task the same way as during the adaptation block and during exclusion they were asked to refrain from using what was learned and instead perform movements as during the baseline block. We determined an awareness index by subtraction of performance during the exclusion from performance during the inclusion condition and an unawareness index from the performance during the exclusion condition. Analysis of variance (ANOVA) of the adaptation performance revealed no significant differences between groups for the last third of each adaptation block. A further ANOVA of the awareness index with the factor Rotation Size (20°, 40°, 60°) yielded significant effects of Group and of Rotation Size. Post hoc analysis showed a significant increase of awareness from 20° to 60°, but no difference between 40° and either 20° or 60°. For the unaware index statistical analysis revealed a significant effect of Rotation Size only. Contrary to the awareness index, smaller rotations produced more unaware adaptation as confirmed by post hoc analysis. Our results suggest that aware and unaware states are differentially involved during adaptation to different perturbation sizes and awareness can be manipulated by instructions. Since it has been shown that gradual, i.e. unaware, and sudden adaptation are based on different neural correlates, it is possible that distinguished neural networks are differentially involved in adaptation to varying perturbation sizes.

Environment and its impact on State Representation during a Blind Tracking Task

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Effective interaction with the external world is predicated on an integration process of various sensory inputs (visual, proprioceptive, etc.), that maintains an internal representation of environment dynamics. However, given the different propagation times of sensory inputs, the fact that we perceive multisensory events as happening at the same time is probably the outcome of an active reconstruction processes that accounts for these discrepancies.

In this study we hypothesize that the temporal integration processes that are driven by simultaneity affect our sense of space and state of motion, and in particular, its proprioceptive representation. We test this hypothesis using a virtual game of pong in which the movement of the controlled paddle is delayed with respect to the subject's hand. Previous results indicated that prolonged exposure to the delayed environment is corrected in a way that brings about subjects to display movement overshoots during a blind reaching task (in which the visual feedback of the cursor is absent) towards spatial targets1. In another set of experiments, we observed a tendency for a stronger spatial recalibration when the delay was increasing gradually throughout the adaptation session rather than abruptly2. Nevertheless, the effects described in all of these experiments could be either the result of changes in proprioceptive estimates or in the representation of hand dynamics. To differentiate between these explanations, we proposed testing subjects in a blind tracking task following the pong delay adaptation. During this task, subjects are requested to follow a visual target going along a specific path with no visual feedback of their hand location. We analyze subjects' performances by examining the interaction between target and hand movements. Such interaction should be influenced in a different manner for proprioceptive remapping and for changes in the representation of arm’s dynamic.

We believe that the understanding of how the brain represents time and space during the performance of a motor task, and the extent of the effect of gradual and abrupt time perturbation on state representation, have important implications on developing novel rehabilitation techniques for motor impairments, specifically those related to disruption of space representation such as in hemispatial neglect syndrome.

Acknowledgment- The study is supported by the Binational United States Israel Science Foundation. Grant no. 2011066.

EEG recorded error related neural responses during continuous 3D motion

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Error-related neural responses (ERNRs) of motor execution and outcome errors during continuous motion, executed by users, are of major interest both for understanding error processing in the brain and for facilitating early error detection and correction in Brain-Computer Interfaces (BCI). Motion outcome errors occur when the goal of the intended movement is not achieved. Motion execution errors occur when an unexpected movement was performed instead of the intended. Execution errors are related to interface miss-interpretation of the user intent or miss-calibration of the user's internal motion models. Previous invasive research based on electrocorticography (ECoG) recordings have shown that it is possible to detect a clear ERNR signals in response to execution and outcome errors during controlled agent motion and differentiate between them. The purpose of this study is to characterize and compare ERNRs due to execution and outcome errors during continuous 3D motion, in non-invasive electroencephalogram (EEG) recordings. During the experiment the subject plays a virtual 3D Tennis game in multimodal immersive virtual reality with haptic feedback. When a user misses the ball, it is counted as an outcome error event. In 34% of the instances, the approaching tennis ball unexpectedly changes its' direction of motion. This is distinguished from the previous and is counted as execution error event. The change in motion direction happens at multiple points and is unpredictable. When the user hits the ball it is counted as a "hit" event and used as a reference. The experimental results show well-defined event related potentials (ERPs) which are characterized by a positive component, but have different waveform profiles depending on the conditions. The "Hit", outcome error and execution error events related components at Cz electrode are characterized, respectively, by positive peaks of the following latencies, amplitude and source localization: (1) Latency of 225 msec, amplitude of 7.8 μV, vicinity of Broadman area (BA) 6&24; (2) Latency of 263 msec, amplitude of 4.9 μV, vicinity of BA 11&10; (3) Latency of 300 msec, amplitude of 12.8 μV, vicinity of BA 7&5. Results are providing a basis for EEG based discrimination between two types of errors and non-error. These ERPs can be used to improve the efficiency of non-invasive EEG based Brain-Computer Interfaces.

Motor markers of ADHD player in a 3D immersive virtual word.

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Individuals with symptoms of attention-deficit/hyperactivity disorder (ADHD) consistently demonstrate subtle abnormalities on motor development and performance. Studies have shown slower performance on timed motor tasks (Piek et all 1999), greater variability in speed of task performance (Castellanos & Tanock 2002; Gilden 2007) and poor fine motor performance. (Pitcher Piek & Hay 2003).

A wide body of evidence indicates that atypical motor development in individuals with ADHD may be a biomarker for the disorder, appearing to run in parallel with, and be closely associated with the behavioral deficits of the disorder.Recent views suggest that the association of ADHD with other symptoms may not only be due to superficial effects (such as inattentiveness) but rather due to a shared etiology (Fliers et al, 2009; Martin, Levi Piek & Hay 2006).

Motor tasks, that have been used for evaluation of ADHD motor performance, have usually been measured coarsely; by duration of total task time or number of errors. In our experiment we tried to measure kinematic movements in high temporal and spatial resolution. To this end, we used a controlled 3D virtual environment, combined with a phantom haptics robotic arm. Using the phantom allowed us to obtain fine measures of hand movement in precise temporal resolution. Subjects freely played a virtual tennis game, using the phantom as a racket. Their movements and the locations of the tennis ball were continuously recorded and analyzed.

Differences in patterns of hand motion were found between normal and ADHD groups in speed acceleration and jerk. A notable difference was found in the pattern of tracking the tennis ball. It seems that ADHD players performed more corrections to their movements suggesting more overshoots in ball tracking, and limited motor control.

Structural Brain Changes Induced by Practicing a Novel Motor Task with a Body-Machine Interface

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Motor skill learning (acquisition, retention, and refinement of motor skills) relies on the capability of the nervous system to create new patterns of neural activation for accomplishing new tasks or for recovering motor functions lost to disability.

Learning-induced structural changes of cortical and subcortical areas have been reported to occur in both gray and white matter. Using voxel-based morphometry, cross-sectional studies have identified regional differentiation of gray matter volume between expert and non-expert performers in a variety of activities. Here, we used diffusion tensor imaging
(DTI) to investigate learning-induced changes in brain connectivity following training with a body-machine interface (BMI), where subjects learned to use the bilateral simultaneous movements of their shoulders and upper arms to control a cursor on a computer screen to solve different tasks. Eleven subjects performed two visuo-spatial tasks over nine sessions. We aimed at identifying white matter changes by comparing fractional anisotropy (FA) values pre and post bilateral upper extremity motor skill training in unimpaired participants. Before the start and within 2 days of the completion of training, whole brain DTI data were acquired. Motor training increased FA values in the posterior and anterior limbs of the internal capsule, the corona radiata, and the body of the corpus callosum by 4.19% on average indicating white matter microstructure changes induced by activity-dependent modulation of axon number, axon diameter, or myelin thickness. These changes correlated with motor performance and may underlie the functional reorganization associated with motor skill learning and suggest that there is a possibility to investigate the neural substrates responsible for the reorganization of residual motor ability after spinal cord injury. This information will potentially aid in enhancing clinical strategies in physical rehabilitation and facilitate the learning processes related to assistive devices used in impaired subjects.

Relation between perceived effort and the electromyographic signal in low effort activities; implementation on human-machine interfaces

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Hand-based human–machine interfaces are complex tasks that involve repetitive or sustained movements and postures of the hands that can lead to overuse syndromes of the musculoskeletal system. Consequently, it is important to minimize the physical effort that occurs at these interfaces. The evaluation of physical effort can be performed either by subjective evaluation of the relative perceived effort (e.g., Borg scale) or objective physiological measurements (e.g., electromyography-EMG). The relation, however, between these two measures has not been sufficiently studied for localized low-effort activities. This study investigated the relation between EMG and Borg ratings, as well as the issue of gender differences during low-effort activity of forearm muscles. Nine females and nine males performed eight different hand gestures (localized low-effort activity), during which EMG signals were recorded from six forearm muscles and Borg ratings were obtained. On average, women rated the gestures as less effortful than the male subjects and also demonstrated a higher positive correlation between the EMG and Borg ratings. Furthermore, the linear model that was fitted for predicting the Borg ratings based on gender and the combined activity of muscles provided R-squared value of approximately 0.3.

Effectiveness of Split Belt Treadmill training on physical activities and motor functions of adolescents with Cerebral Palsy – a matched control trial.

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Background: the objective of this study was to assess whether the efficacy in increasing physical activity is greater with split treadmill (ST) training than the regular treadmill training (TT) in adolescents with cerebral palsy (CP).

Children with CP are challenged by motor function and mobility for their lifetime.

This disability is often thought of as non-progressive. While the neural lesions are not progressive, the levels of independent function and mobility most often deteriorate once the child enters adolescence.

Walking flexibility depends on both feedback and feed-forward control to respond to unexpected changes in the surface. ST training creates an artificial asymmetrical walking task. Adolescents with CP adapt to ST training; however, the generalization of this adaptation to natural everyday environments has not yet investigated.

Research question: Is the new approach of training on a ST more effective than the currently employed TT in adolescents with CP?

Methods: twenty-four teenagers with CP were matched according to age and GMFCS level II and III. Each participant underwent 30 intervention sessions, twice a week over 15 weeks.

Each subject underwent an evaluation at baseline and immediately post-intervention to measure functional parameters and Center Of Pressure pattern.

Results: The ST training group showed an improvement in the Growth Motor Functional Test. However, a more significant improvement was observed in all functional parameters for the regular TT. In addition, the center of pressure during walking shows improvement in symmetry and ability to adapt while walking on a ST.

Discussion: There is an improvement in symmetry during walking on a ST; in addition, improvement in adaptation throughout the treatments. This result indicates the existence of adaptation processes during walking on a ST.

Moreover, treatment protocol with the impaired leg walking at fast speed is more efficient. Lastly, improvement in functional performance was shown.

Conclusion: learning by trial and error while walking on a ST induces a new walking pattern in adolescents with CP, suggesting it as a tool for rehabilitation.

There is need for further study in order to obtain a deeper understanding.

Ongoing control of trajectory segments is revealed by shortening movement preparation time

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The timed response (TR) reaching task was designed to study the independent control of movement direction and amplitude by examining the effect of the shortening of movement preparation on the performed trajectories (Ghez et. al., 1988). Nevertheless, in curved trajectories direction and magnitude are intertwined and controlled variables are likely to differ. Fifteen subjects made reaching movements to four targets presented 15 cm from the origin, while avoiding obstacles presented halfway between the start and end-point targets. Subjects initiated the obstacle avoidance movements in synchrony with a predicted auditory signal. Targets were presented at two different time points before the auditory cue (25ms or 350ms), imposing short and long preparation time conditions. While reaching the targets in both conditions, movements in the short condition showed increased initial directional variability, and increased deviation from the axis connecting the initial hand position and target location. Additionally, the distributions of initial trajectory directions in the short condition showed less target sensitivity, suggesting the existence of an initial task-insensitive default plan (prior) in the short condition. We applied a geometrical segmentation of the trajectories and found that while all movements were composed of a long central parabolic segment that was followed by a shorter straight segment; the onset of the parabolic segment was correlated with the subject's reaction time only in the short condition. These results suggest that the motor system utilizes “segmented control” in order to adapt to the uncertainty in the location of the target. We further examined the time course of movement specification using a minimum jerk model, by estimating the end point of the movement at each point along the trajectory based on its derivatives. We found that in the short time condition the time point where the predicted end-point reached the final target was achieved significantly (~80ms) later, compared to the long time condition. Thus, the initial part of the short preparation time condition movements contained significantly less kinematic information regarding the position of the target and may correspond to a default or target-insensitive motor plan that requires a shorter preparatory time. The findings from both approaches show that in the absence of sufficiently long preparation time, subjects compensate for the lack of complete specification by adjusting the onset and the parameters of the subsequent movement portion on the fly.

Basic and Applied research: procedural learning in young children and its contribution to academic skills

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(A) Procedural memory plays a major role during early childhood, when many new skills are acquired. Previous studies of age-related differences in skill acquisition mainly focused on skill learning within a single practice session. Here we studied developmentally the training, memory consolidation and long-term retention of a simple grapho-motor ('invented letter') task (ILT) using a digitized tablet. A block of the ILT is composed of spaced identical 2-segment graphic symbols. The performance of 20 kindergarteners, 20 second-graders and 20 adults on the task indicated that adults outperformed children in both speed and accuracy. However, there were larger training gains among children than among adults. Furthermore, children and adults showed similar consolidation (off-line) enhancement in speed 24 hours post-training that was retained two weeks later. Decomposing performance into writing time and non-writing (space) time suggested that both components showed 24-hours enhancement in all 3 age-groups. Five-yr.-olds, however, lost the enhancement in space-time by retention testing. These data suggest improved retention with age. In spite of similar enhancement, amalgamation of task units stabilizes better with age.

(B) Procedural learning is a core skill that has not been studied yet in the context of academic achievements. In a longitudinal study, procedural learning of 56 children in kindergarten and grade two was assessed using the invented letter task (ILT). The ILT is a simple letter like task, typical of children's activities and is performed on a digitizing tablet. Speed and accuracy of performance were measured at four time points: pre-training (baseline), post-training, 24 hours post-training (consolidation) and two weeks post-training (retention). Writing speed, writing legibility and academic achievements in math were tested concomitantly and the following year. Reading and spelling were assessed in the following year as well. Stepwise regression indicated that among the level of performance of the baseline, consolidation and retention testing, the consolidation phase performance showed the highest predictive value. The ILT contributed significantly to the prediction of writing speed in the first and second year and of writing legibility, math, reading and spelling in the second year. Our findings suggest that procedural learning, specifically the consolidation performance assessed using the invented letter task, may be used in early school years to predict later academic achievements.

Intensive locomotor adaptation training in Cerebral Palsy patients improves both adaptation rates and performance variability

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Cerebral Palsy (CP) results from an insult or an injury to the developing brain before birth or in early childhood causing physical disability and a-typical motor patterns such as asymmetrical walking. Consequently, rehabilitation treatments for CP patients should address both the motor disability and the possible control impairments over the damaged system. To examine the interaction between these components in a rehabilitation-like treatment protocol, we studied the dynamics of step-asymmetry during a longitudinal locomotor adaptation task. Six teenagers with CP were exposed to 30 sessions of adaptation to a novel split-belt treadmill over four months. Aged and gender matched controls were exposed to 10 sessions of adaptation. Adaptation rates and motor variability were computed throughout the adaptation sessions by analysing the asymmetry and the variability of the center-of-pressure (COP). Compared to controls, CP patients showed slower adaptation (e.g., reduction in COP asymmetry) in the first session ($p<0.05$) and higher COP variability ($p<0.001$). By the last session, CP subjects adapted significantly faster ($p<0.01$) and showed a marked reduction in COP variability ($p<0.001$). To examine the improvement of CP patients at the control level, we modelled the data using a dual-state state-space model, assuming that locomotor adaptation is driven by a fast and a slow adaptation processes. Results showed that initially, CP subjects relied mainly on the slow stable process and the contribution of the fast process during initial adaptation was negligible. With practice, both the learning rate and the contribution of the fast liable process significantly increased. In addition to the changes in learning rates, the single subjects' fits to the models improved, pointing to the reduction in COP variability with training. To incorporate the improvement in adaptation with the changes in variability, we used a Bayesian state estimation model with a single state. Results showed that the improvement in learning can be explained by an increased sensitivity to prediction errors due to the reduction in observation noise, rather than by changes in state uncertainty. Our results suggest that the impaired adaptation of CP patients is primarily a result of their variable performance, and not of an impairment in state estimation. Thus, effective rehabilitation of CP patients should rely on two interacting processes: adaptation of a-typical motor patterns through shaping and reduction in variability through repetition training.

Resting state functional connectivity in the thalamo-cortical pathway predicts retention of motor memories

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Locomotor adaptation is an experimental paradigm developed for studying the control mechanisms of locomotion, and for designing novel rehabilitation strategy for neurological patients with asymmetric walking patterns. Using this paradigm, others and we have recently shown that locomotor adaptation patterns can be retained long after the initial learning, suggesting the formation of long-term motor memories following initial adaptation, and a possible utility of this paradigm for rehabilitative treatments. Despite the robust retention of the adaptive patterns, we currently know very little about the neuroanatomical basis of learning and retention of locomotor patterns.

In the current study, we study the relationship between locomotor adaptation and the connectivity patterns within the locomotor execution network, measured during fMRI resting state scans. We were specifically interested in asking how does functional connectivity between regions of interest changes following learning, and whether baseline connectivity levels are indicative of the ability of subjects to learn and retain novel patterns. Fifteen subjects participated in a protocol of 3 days. In the first day, they did a baseline treadmill session with no adaptation (both belts of the treadmill moved at the same speed), and then moved to the MRI scanner and underwent anatomical, functional and structural MRI. In the second day, subjects did a split-belt treadmill adaptation and then underwent the same MRI protocol as they did in the first day. On the third day, subjects performed only behavioural session of adaptation-washout-readaptation protocol.

We found that the functional connectivity between the leg areas in the thalamus and motor cortex in the first day (pre-training) was correlated with the retention of the motor task in the third day (post-training). Moreover, we detected a significant change in functional connectivity between the leg areas in the cerebellum and the motor cortex following motor adaptation (when comparing pre and post training scans).

Our results provide two main findings: First, to the best of our knowledge, we are the first to show that connectivity within the thalamo-cortical network can predict consolidation of motor learning. Second, we extended previous results showing that cerebellar-cortical network plays a major role in locomotor adaptation by showing specific changes in connectivity following locomotor training. Taken together, we provide evidence that locomotor learning and retention is affected by the connectivity patterns between cortical and sub-cortical motor areas.

Directional tuning in human brain following visuomotor adaptation

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What happens to directional tuning when reaching movements are dissociated from their visual feedback by rotating the visual field. Do neural populations in motor system areas remain tuned to the reaching direction or shift their tuning according to the visual rotation?

We recorded simultaneous movement kinematics and fMRI activity while subjects performed 'out and back' reaching movements to four targets spaced 45° apart. The experiment included three conditions: 1) Baseline – visual and motor mapping were matched. 2) Rotated – the cursor movement was rotated by 45° with respect to the hand movement. 3) Washout – the visual and motor mappings were matched again. A multivariate classification algorithm was trained to identify movement direction according to voxel-by-voxel fMRI patterns in each of several brain areas.

The direction of movements was successfully decoded with above-chance accuracy rates in multiple motor and visual areas when training and testing the classifier on trials within each condition (i.e. within-condition decoding). However, when training the classifier on baseline trials and decoding rotated trials, motor brain areas including primary motor cortex (M1), dorsal premotor cortex (PMd), and supplementary motor area (SMA) exhibited above chance decoding for the original movement direction (as in the baseline condition) while visual brain areas including early visual cortex and superior parieto-occipital cortex (SPOC) exhibited above chance decoding for the rotated visual target location rather than the actual movement direction. Most interestingly, decoding levels in the anterior intraparietal sulcus (aIPS), an intermediate visuomotor area, were at chance level for both visual and motor aspects, suggesting that directional tuning in this area was altered by the visuomotor adaptation. Farther analysis of the decoding in the aIPS reveals dual tuning to the visual and the motor targets. We interpret these results to suggest that in humans, like monkeys, directional tuning of low level motor areas is not affected by visuomotor adaptation, which seems to alter directional tuning in higher parietal areas such as aIPS.

The effects of emotion on interaction during walking

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In everyday life humans regularly socially interact with each other, often forming groups, where coordination and synchronicity play very important roles. The individuals forming such groups bring their unique emotional tendencies to the group and the interaction among those individuals results in behavior that goes beyond the tendencies of the group members. Such expressions of emotion and their recognition by others play a major role in the human social interaction. In our work we examined emotional interactions by studying their effects on locomotion when two people walking in the same vicinity interact with each other. We designed a paradigm not dissimilar from everyday group interactions, where we simply asked two actors to assume specific emotional states (anger, fear or neutral) and walk together. From these simulated interactions we were able to identify the influence each emotion has on the locomotion kinematics of the observer and more importantly, the effect on the metrics of interactions between the actors. Our investigations led us to the conclusion that the emotions of the interacting walkers affect their apparent role within the group. More precisely, the anger emotion can be consistently associated with *leading* behaviour, the fear emotion with *following* behaviour and the interaction between identical emotions results in *cooperative* behaviour. The effects of other modalities, such as dialogue or the transitivity of the emotion, do not affect the overall role within the group. However, they do influence the synchrony between the interacting parties. Hence account all the dimensions of interaction to interpret the actual effects of emotions on locomotion.

Differentiating sensory goals from motor actions in the human brain

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To achieve a certain sensory outcome, multiple actions can be executed. For example, in order to draw a circle one can perform a clockwise or counter-clockwise pen trace. Thus the same sensory goal can be achieved by different motor actions. Using fMRI, we examined the neural networks that dissociate sensory goals from motor actions. Subjects (n=12) controlled a figure on the screen by performing pen traces on an MR compatible digital tablet using their right hand. In order to move the figure in a certain direction (e.g. horizontal) they had to perform either congruent (horizontal) or incongruent (vertical) pen movements on different trials. This design allowed us to dissociate sensory goals (moving the figure in a certain direction) from the underlying motor actions (horizontal/vertical pen traces). Using multi-voxel pattern analysis (MVPA) and a whole brain searchlight strategy, we found that activity patterns in left (contralateral) motor and parietal cortex, and also right (ipsilateral) motor cortex significantly discriminated direction of pen traces regardless of intended figure movement. Furthermore, activity patterns in right superior parietal lobule and pre-motor cortex, and also left fronto-polar cortex significantly discriminated sensory goals (horizontal vs. vertical figure movement) regardless of underlying pen traces. Together, these results highlight the role of ipsi-lateral motor cortex in coding movement directions, and point to a network of brain regions involved in high order goal representation that is dissociated from specific motor plans.

Optimal Trajectories of Via-Point Reaching Movement using Minimum Acceleration with Constraints Criteria

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Over the last three decades there has been a long going debate regarding how we generate hand motion. One suggestion to answer this question is to describe the trajectory as a solution of an optimization problem which minimizes a given cost function. Minimization of state variable derivatives such as hand jerk, were suggested to explain simple point-to-point reaching movement as well as complex motions. An example for such a complex motion is the via-point reaching movement where the movement is forced to pass through a given point prior to the end point. Recently, a minimum acceleration criterion with a constrained maximum jerk (MACC) was suggested as a fundamental criterion governing simple reaching movements. Here we apply this criterion to analyze the complex via-point reaching movement.

We derive the mathematical model using the previous MACC-based solution and the optimal conditions for an interior-point constraint suggested by Bryson and Ho (1975). Similar to the MACC-based model for point-to point reaching movement, our model is based on a piecewise constant control signal suggesting an intermittence control approach to generating motions. We compare our model predictions to other models which are based on continuous control signals and further link its intermittent nature to the generated EMG signals.

Intersegmental Coordination in Straight-Ahead and Circular Gait, Eyes Open and Closed is Modulated by Parkinson's Disease but Complies with the Law of Planar Covariation

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Objectives: To investigate the influence of Parkinson's disease (PD) on intersegmental coordination and the interaction with circular walking, visual feedback, disease severity and dopaminergic medication

Background: The 3 lower limb segmental angles covary forming a loop that lies on a 2-dimensional attractor plane, (Lacquaniti et al., 1999) even under very different biomechanical contexts (e.g., walking backwards). The plane orientation varies with gait speed as well as other conditions, pathologies and species.

Methods: We analyzed the gait of 11 male patients with PD (64 ± 9 years-old) treated with levodopa in both the 'off-medication' state (motor UPDRS: 34 ± 9, H&Y range: 2.0 – 3.0) and the 'on-medication' state (motor UPDRS: 24 ± 8, H&Y range: 2.0 – 2.5), and 12 healthy male controls (63 ± 9 years-old) matched for age, weight and height. Subjects performed gait trials with both straight-ahead and circular paths, eyes open and blindfolded. Linear mixed models analysis was applied to test the main effect of group (PD-on versus controls and PD-off versus controls separately) and 2-way interaction effects of group with vision, path and leg.

Results: Elevation angles of both patients and controls covaried with high planarity. Plane orientation was significantly rotated in both PD-off: 19.1 ± 0.71^{o} (standard error), $F_{(1,191)}=6.4$, $p<.05$, and PD-on: 19.9 ± 0.54^{o}, $F_{(1,189)}=18.5$, $p<10^{-4}$ versus Ctrl-PD: 17.3 ± 0.6^{o}, was not modified by vision, path or leg and was negatively correlated with disease severity ($r=-0.3$, $p<10^{-5}$) with no interaction with medication.

Conclusions: The high planarity of elevation angle covariation in PD, even under conditions of increased gait task complexity, suggests that it emerges from oscillatory properties of spinal central pattern generators which are robust to significant neuronal and biomechanical perturbations. The correlation with disease severity and lack of interaction with medication suggest that dopamine-mediated compensatory mechanisms underlie the covariation pattern change.

Intact Savings in Patients with Cerebellar Degeneration

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When a visuomotor rotation is introduced between movements of the limb and visual feedback, cerebellar ataxia patients show large adaptation deficits, consistent with the hypothesis that the cerebellum is critical for sensorimotor adaptation. While the patients are aware of their movement deficits and often acknowledge the large and persistent errors that occur after a perturbation is introduced, they do not readily make use of explicit strategies to compensate for their inability to adapt. However, if provided with an explicit strategy to counter the rotation, their performance is immediately restored. This raises an interesting question: Are patients with cerebellar ataxia able to spontaneously develop and apply explicit strategies to improve motor performance?

We had a group of patients with cerebellar degeneration (n=16) perform a 8cm center-out reaching task in which color cues were used in indicate trials where feedback was veridical (white) and trials where the feedback was rotated by 45° (red). The participants were instructed that when the cue was red, "something weird will happen." The session began with 40 baseline trials in which feedback was veridical. This was followed by a mixed block of 48 trials, composed of 40 rotation trials and 8 veridical trials, with the latter interleaved at irregular intervals. After a 64 trial washout block with all veridical feedback, the participants completed another mixed block of 48 trials and finished with a final washout block. This design allowed us to assess strategy use by comparing performance on the two types of cued trials, as well as savings by comparing performance on the initial trials of the second rotation block relative to the first rotation block.

Similar to controls, the patients showed a clear separation of performance on the trials with veridical and rotated feedback, indicating that, when cued, they were able to develop and apply a compensatory strategy to offset the rotation. There was, however, a tendency for their performance on rotation trials to be less successful than controls. In contrast, the patients showed the same degree of savings as the control participants in the second rotation block. These results suggest dissociations between adaptation, strategy use, and savings, with cerebellar dysfunction affecting adaptation and strategy use, but sparing savings. The latter finding is consistent with the idea that savings in visuomotor adaptation tasks results from the recall of a previously acquired action plan.

Motor Neuro-Kinemes: Identifying the neural ‘building-blocks’ of human complex movements

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Previous studies have been successful in extracting muscle synergies and decomposing point-to-point movements into sub-movements. Yet, further mathematical and electrophysiological tools are needed to unravel the neural representations of movements as well as the mechanisms underlying the successful combination of movement primitives into complex movements. In this preliminary study, we first used Support Vector Machine (SVM) to classify Electroencephalography (EEG) signals recorded during various complex movements (drawing two-step shapes). Across 8 subjects, power in low gamma band (30-45Hz) allowed significant classification of drawn shape (61% accuracy, chance level = 33%). Next, we trained a Hidden Markov Model (HMM) using combinations of gamma-band power from two single-step movements to classify gamma-band power recorded during real two-step complex movements. This yielded significant classification accuracy (52%), allowing us to classify the neural representation of complex movements based on the representation of movements primitives. Furthermore, we were able to correctly predict acceleration of complex movements with 78% performance accuracy based on the neural signal during a primitive movement. More data is necessary to assess whether it is possible to obtain real-time estimation of intended hand motion, based on the neural data. Such estimation could be used in the future, for instance, to control sophisticated Brain-Machine Interfaces (BMIs).

Decomposition of an error signal for sensory motor learning

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Performance-based feedback has long been known to be critical for motor learning (Trowbridge and Cason 1932). In visuomotor rotation tasks, sensory-prediction error signals are thought to drive motor learning (Tseng et al 2007). Recently, it has been shown that reward-based feedback, conveying only task success, can also drive learning; however, it is insufficient for sensorimotor adaptation to occur (Izawa et al 2011). This raises an interesting question: What is the necessary information in cursor feedback that drives sensorimotor adaptation? Cursor feedback contains two error components, direction and magnitude, but it remains unclear how these components contribute to learning. In the current study, we decompose this error signal into its components to determine their role sensorimotor adaptation.

Thirty-six participants trained to overcome a 45° rotation in a center-out reaching task. The experiment was divided into three blocks: baseline, rotation, and washout. The participants were equally divided into three groups receiving different components of endpoint feedback: *magnitude*, *direction, or magnitude plus direction* error. In the *magnitude plus direction* condition, the endpoint error signal consisted of a line connecting the virtual cursor location to the center of the target. In the *magnitude* condition, the length of the line was veridical but the direction changed randomly across trials. In the direction condition, the direction of the line was veridical but the magnitude changed randomly across trials.

There were no group differences during the no-rotation baseline block. Participants in all groups showed significant learning (magnitude plus direction: 43 ± 2°, magnitude: 29 ± 6°, direction: 29 ± 5° SE) during the rotation block. The magnitude plus direction group showed faster and more complete learning than either the magnitude ($p = 0.03$) or direction ($p = 0.02$) groups. Following the rotation block, participants were instructed to aim directly at the target and all visual feedback was removed. Aftereffects were present in all groups, but the *magnitude plus direction* group showed the greatest aftereffect with respect to baseline. However, if the aftereffect is computed relative to asymptotic learning in the rotation block, then the differences in the aftereffects are no longer significant. Thus, it appears that either component of the error signal, *magnitude* or *direction*, is sufficient to induce sensorimotor adaptation. The minimal amount of error information that is necessary to induce sensorimotor adaptation remains an open question.

Quadra-pedal coordination of human walking during asymmetric conditions

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Introduction: Quadra pedal coordination of gait in humans is not fully understood. The objective of the present study was to better understand the inter relations between the rhythm movements of all four extremities while walking.

Methods: 6 healthy adults (30.9 ± 2.8 yrs) walked on split-belt treadmill as follows: **(A)** 2min self-selected speed; **(B)** Incremental speed increase of the left belt to 150% of baseline ; **(C)** 4min walk with uneven belt speeds; **(D)** incremental speed increase of the right belt; and **(E)** 2 min walking in maximal speed (tied belts). Gait analysis was with three-dimensional optoelectronic analysis system.

Results: During condition **(C)** Left Stride Length(LS_L) increased by 24.1± 3.3% (SEM; p<0.001) and Right Stride Length(RS_L) decreased by 8.6± 2.1% (p<0.001). During condition **(E)** LS_L and RS_L stabilized on about 19% increase as compared to **(A)**. Arm swing amplitude(AS_A) was decreased significantly during the maximal split belt condition (e.g., Right_AS_A = 49±1 cm) as compared to baseline condition (55±2 cm) and these values were preserved in the fast tied belt condition (49±1 cm). Stride- and arm swing cycle- time- variability as well as the values of the phase coordination index (PCI – a measure that quantifies bilateral coordination) values did not change significantly.

Conclusions: Despite the limited number of subjects, the present findings point to the suggestion that movement rhythmicity and inter limb coordination are the primary control features which are preserved during locomotion adaptation, while movement scaling is differentially controlled to allow this preservation.

Stronger mu suppression for consciously perceived actions

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Passive observation of actions performed by others has been shown to elicit neural responses in various regions of the motor system that are also active during overt execution of the same actions (i.e. mirror neurons). Whether conscious recognition of actions is necessary to trigger mirror neuron activity, or alternatively this response is automatic, is unknown. Here we examined whether activity in motor cortex depends on the degree of conscious perception of actions.

We manipulated the level of conscious perception by using a modification of the Continuous Flash Suppression (CFS) paradigm. The CFS display consisted of target videos presented to one eye and a masking video presented to the other eye. The target videos depicted one of three different hand movements or a non-human biological movement. At the end of each trial, participants reported which action was presented together with their confidence level on a scale from 1 to 4. Suppression of power in the electroencephalogram (EEG) 8-13 Hz frequency range (Mu rhythm suppression) in the left and right central sites (C3 and C4 respectively) was used as an index for mirror neuron activity during observation. .

Participants reported full recognition of actions in 41% of the trials and no recognition on 36% of the trails. In the rest of the trials, confidence levels were intermediate. In agreement with previous studies, when no masking was displayed, Mu suppression was stronger during observation of Human vs. Non-Human actions *($t(13)$ =* 1.664*, $p = 0.06$ in C3 and in C4)*. During observation of Human actions, Mu suppression was stronger in the Recognized compared with Unrecognized trials *($t(13) = 2.283, p<0.02$ in C3 and $t(13) = 0.66, p = 0.26$ in C4,* N=14*)*. Importantly, during observation of Non-Human action, Mu suppression was not significantly different across recognition levels *($t(7) = 1.04, p = 0.46$ in C3 and $t(7) = 0.238$, $p = 0.41$ in C4 ,* N=8*)*.

Our results show that exposure to actions that are invisible to conscious perception produces lower mirror activity relative to the same actions consciously perceived. This effect is more robust during observation of Human vs. Non-human actions suggesting it is not a global effect of recognition level. This data supports the notion that the intensity of mirror neuron responses during observation of human actions depends on the level of conscious perception of the observer.

The Effect of Conflicting Virtual Scenery on Leveled and Inclined Gait

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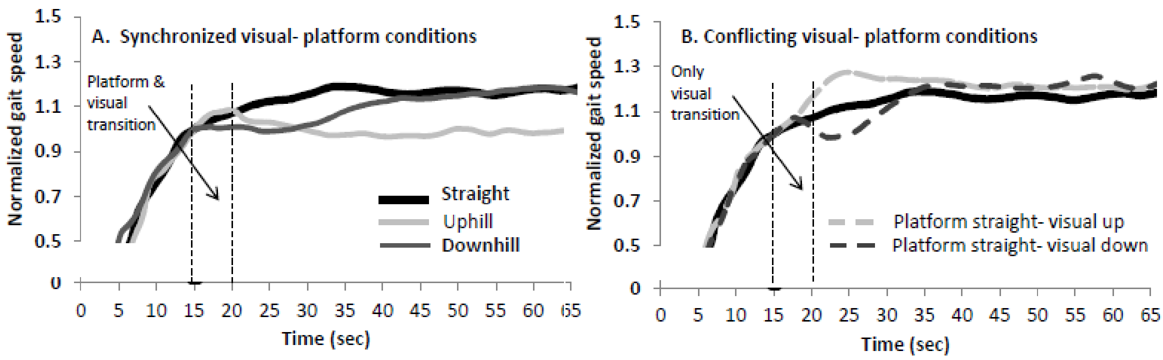
Introduction: The effects of visual flow on gait were studied mainly in relation to gait speed control. Our objective is to study the effects of visual scenery related to path inclination on gait. We hypothesize that visual cues related to path inclination during treadmill walking will trigger gait modulation, even in the absence of actual inclination.

Methods: Seven healthy adults walked on treadmill embedded in virtual reality environment in a 'self- paced' mode. Uphill/downhill walking simulation was created when the platform was pitched up or down along with synchronous elevation of the projected road scenery. After walking straight and level (15 s), the condition either did not change or changed in : (A) synchronized visual-platform manipulation (SyncVPCs); or (B) conflicting visual-platform conditions (ConflVPCs).

Results:

When the platform inclination changed in concurrent with the visual field, the subjects slowed their gait in uphill walking, and first slowed, but soon after resumed their normal speed in downhill walking (Fig 1A). In both conflicting conditions (Fig 1B), the visual illusion generated responses representing increased of effort in the case of uphill walking, and the start slowing related to the start of downhill walking.

FIG 1:



Averaged gait speed from all subjects.

Conclusions: Conflicting visual flow related to path inclination can modulate gait speed, even when no change in actual inclination occurs, a finding that underscore the role of visual input in gait control. It remains to be seen if this, seemingly transient effect, can be utilized to facilitate gait rehabilitation programs.

Grasping virtual objects

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As the world becomes increasingly dominated by portable electronics such as tablets and smartphones, actions we perform are more frequently directed at virtual objects, presented on a screen, rather than at real objects. The purpose of the current study was to gain better understanding of the nature of the kinematics that underlies such virtually-based interactions. We rely on recent evidence suggesting that when people grasp real objects, their trajectories are analytic in nature. That is, they can act without being influenced by Weber's law, a fundamental psychophysical principle governing visual perception. Nevertheless, it is not yet clear to what extent actions performed toward virtual objects violate Weber's law, and obey "real-life" kinematics rather than relative rules of visual perception. To address this issue, we asked participants to grasp and to make perceptual size estimations of virtual possible and impossible objects, which lack coherent pictorial depth. The results showed that grasping trajectories toward virtual objects were affected by Weber’s law, showing a linear increase in the Just Noticeable Differences (JNDs) with object's size. Additionally, grasping trajectories toward the virtual objects were affected by configural, perceptually-driven aspects of the visual scene. Conversely, some kinematics of the grasping trajectories were still dissociated from perceptual estimations, showing that normal grasping movements can still be performed toward virtual objects. These findings provide novel evidence that actions toward virtual objects are hybrid in nature such that they are affected by perceptual factors as well as by real-world kinematics.