The Second Computational Motor Control Workshop at Ben-Gurion University of the Negev

June 7, 2006, W.A. Minkoff Senate Hall, BGU
Marcus Family Campus, Beer-Sheva, Israel

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

Program

8:20-8:50 Registration, poster placement and coffee
8:50-9:00 Greetings – **Dr. Opher Donchin**, head of the organizing committee, BGU
9:00-9:10 Opening remarks – **Prof. Rivka Carmi**, BGU president

The Nature of Movement

Chairperson: Prof. Gideon Inbar, EE, Technion
9:10-9:40 **Prof. Emilio Bizzi** - McGovern Institute for Brain Research, Massachusetts Institute of Technology
Keynote speaker under the auspices of the Kreitman Foundation Distinguished Visitors Program
Learning and consolidation of motor tasks
9:40-10:10 **Dr. Benny Hochner** - Depart of Neurobiology, Hebrew University, Jerusalem
Motor control of goal directed movements in the flexible arms of the octopus
10:10-10:40 **Prof. Jerry Loeb** - Department of Biomedical Engineering, University of Southern California
Biomimetic integration of sensorimotor neural prostheses

Perception and Action

Chairperson: Prof. David Golomb, Physiology and BME, BGU
11:30-12:00 **Prof. Anatol Feldman** - Department of Biomedical Engineering, University of Montreal
The referent body configuration and principle of minimal interaction: solutions to redundancy problems in motor control
12:00-12:30 **Dr. Tzvi Ganel** - Department of Behavioral Sciences, BGU
Hemisphere and skill determine vulnerability to visual illusions during grasping
12:30-13:00 **Dr. Mark Wessinger** - Department of Psychology, University of Nevada, Reno
Modal and amodal processing is task- and modality-specific

Representation

Chairperson: Dr. Opher Donchin, BME, BGU
14:30-15:00 **Prof. Sandro Mussa-Ivaldi -** Northwestern U. and the Rehabilitation Institute of Chicago
The adaptive representation of time and space
15:00-15:30 **Dr. Dana Cohen** - Gonda Brain Research Center, Bar-Ilan University
Spike timing during typical movements
15:30-16:00 **Prof. Haim Sompolinsky** - Racah Institute of Physics, Hebrew University
Motor trajectories: a dynamical-systems perspective

Coding

Chairperson: Prof. Tamar Flash, Weizmann Insittute
16:30-17:00 **Prof. Moshe Abeles -** Gonda Brain Research Center, Bar-Ilan University
What is coded in neurons of the motor cortex?
17:00-17:30 **Prof. Maarten Frens -** Department of Neuroscience, Erasmus Unversity
Cracking the complex spike code

The Alpha Omega and the SenseGraphics Awards for the best posters.
The NanInstuments Travel Award.

Motor Adaptation

Chairperson: Dr. Amir Karniel, BME, BGU
18:30-19:00 **Dr. Jim Patton -** BME, Northwestern U. and the Rehabilitation Institute of Chicago
Exploiting the natural capacity to adapt for motor teaching and rehabilitation
19:00-19:30 **Dr. Robert Scheidt** - BME, Marquette University
Independent control of trajectory and final equilibrium position predicts asymmetric transfer of learning and systematic extent errors in reaching
19:30-20:00 **Prof. Claude Ghez -** Department of Neurology, Columbia University
Separate early and late updating mechanisms assure accuracy of trajectory and final position in reaching

Being in the desert leads us to ask questions about
Origins of things, the timeless beauty and strength of
Nature, the fragility and limits of human life and creativity

Dear friends:

On Thursday the 8th of June, we are going for a trip to the Negev, the Israeli desert. We will begin with a short hike to the biggest oasis in the area "Ein - Ovdat", and after the hike we will go to Ben Gurion's grave which is located on a beautiful viewpoint. There, we will hear about the connection between Zionism and desert life. Later, we will have a lunch full of desert tastes. After lunch, we will take a special hike through Havarims Gulch, and see the desert survival methods of the Nabatians – the lords of the desert. Finally, we will enjoy the desert sunset on the way back to the university.

Meeting time: 10 A.M. (after breakfast)

Meeting place: In front of the Paradise Hotel

What to bring: back pack, 3 liters of water, sunscreen, a hat, comfortable clothes and shoes, and some snacks.
Cost: 150 NIS per person

(We will be back approximately at dinner time)

See you then…
Eitan (the tour guide)

Foreword

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.

Sponsors:

- The President, Ben-Gurion University
- The Rector, Ben-Gurion University
- The Dean of the Faculty of Health Sciences, BGU
- The Dean of the Faculty of Humanities & Social Sciences, BGU
- The Zlotowski Center for Neuroscience, BGU

Advisory Committee:

- Opher Donchin, Ben-Gurion University
- Amir Karniel, Ben-Gurion University
- Rich Ivry, Berkeley
- Stephen Schall, University of Southern California
- Dana Cohen, Bar-Ilan University
- Tamar Flash, Weizmann Institute

Best Poster Award Committee:

- Amir Karniel, Ben-Gurion University
- Dana Cohen, Bar-Ilan University
- David Golomb, Ben-Gurion University
- Gideon Inbar, Technion – Israel Institute of Technology

Talks

Learning and consolidation of motor tasks

Emilio Bizzi
McGovern Institute for Brain Research, Massachusetts Institute of Technology
Keynote speaker under the auspices of the Kreitman Foundation Distinguished Visitors Program

A number of recent studies have demonstrated that when networks of neurons are repeatedly exposed to sensory-motor associations, learning of motor tasks occurs. The iterative sensory-motor processes lead to the establishment of internal models of the controlled dynamics through a gradual change of the synaptic strength of the neurons of cortical and sub cortical motor areas. The resulting internal models are embedded in the newly formed connectivity of groups of neurons, and the activity of these neurons generate the neural impulses necessary for the execution of the learned motor task.

Motor control of goal directed movements in the flexible arms of the octopus

Benny Hochner
Dept. of Neurobiology and Center for Neuronal Computation, Hebrew University, Jerusalem, Israel

Controlling goal-directed movements by flexible arms raises complex problems due to the virtually infinite number of degrees of freedom (DOF). I shall describe how the octopus copes with these complex control problems and give two movements as examples; the arm extension with which the octopus reaches for a target, and a fetching movement with which the octopus brings a grasped object to its mouth. Kinematic analysis and EMG recordings in freely behaving animals help elucidate the control strategies and the neural control mechanisms involved in these movements. I will show that the octopus simplifies motor control by dramatically reducing the number of DOFs to be controlled and by using relatively simple motor programs which are mainly based in the peripheral nervous system of the arm itself.

Biomimetic integration of sensorimotor neural prostheses

Gerald E. Loeb
Department of Biomedical Engineering, University of Southern California

Bidirectional neural interfaces with the central and peripheral nervous system make it possible to attempt to restore reach and grasp function to patients with paralyzed or amputated arms. I will review briefly the designs, characteristics and current status of these interfaces, but focus mostly on the larger challenges in sensorimotor control that arise from their integration into functional systems. At one extreme, we can use conventional servocontrol to turn the limb into a robot whose end-point position in space is controlled explicitly by whatever source of voluntary command signals is available. At the other, we can try to create a spinal-like regulator that mixes more natural command signals with distributed sensory feedback to produce a limb that behaves more like a biological arm, interacting with loads and perturbations according to its intrinsic biomechanical properties and emergent reflex responses. Clinical acceptability of any prosthetic system will depend on the ability of clinicians to configure it for patients and for patients to learn to use it effectively. Building such complex systems and surgically implanting their command and feedback interfaces is an enormous undertaking. Therefore, we have developed a comprehensive modeling and virtual reality environment in which conceptual neural prostheses can be simulated, engineers and patients can experience their behavior in real-time, and adaptive control schemes can be trained ad libitum without endangering patients.

The referent body configuration and principle of minimal interaction:
Solutions to redundancy problems in motor control

Anatol Feldman
Department of Physiology, University of Montreal, Canada

In studies on decerebrated cats (Matthews 1959; Orlovsky and Feldman 1972) and intact humans (Asatryan and Feldman 1965), it has been found that the nervous system controls motor actions by changing the threshold positions at which motoneurons begin to be recruited. The notion of threshold control underlies the λ model that describes the *fundamentals* of action, perception, and learning. Depending on the level of consideration, the threshold position can be referred to: a single motoneuron, neuron or muscle (e.g., *threshold muscle length*, λ); muscles spanning a single joint (*threshold joint angle*) or several joints (*threshold arm configuration*, *threshold position of the hand, threshold aperture of fingers*, etc.); and all skeletal muscles (*threshold body configuration*). Moreover, muscle activation thresholds can be associated with an external frame of reference and thus define the *threshold localisation of effectors or the whole body* in the environment. Thus, motoneurons and other neurons have the capacity to *recognize* when the centrally established threshold position matches the actual, physical position, generate the activity in proportion to the difference between them and signal about this difference to muscles and other neurons. Threshold variables can also be considered as referent points or origins of the respective spatial frames of reference. For example, the threshold body configuration is also called the referent body configuration since it represents the origin of a spatial frame of reference in which all-possible body configurations are represented by points. Thereby the difference between the actual and the referent configuration of the body is a global factor influencing the activity of all muscles, regardless of their biomechanical function. Threshold control implies that neither motor commands (muscle activation patterns), nor mechanical variables (movement trajectories, velocities, accelerations and forces) are programmed for motor actions: the motor commands and mechanical output automatically *emerge* following the difference between the physical (P) and the referent (R) positions of the body. Threshold control also implies that the behaviour of the neuromuscular system is guided by a simple principle: given a referent value of the physical variables at the task-specific level, the system tends to diminish the activity and interactions between its elements as well as between theses elements and the environment in order to reach, if possible, an equilibrium state. In this state, the difference between the P and R values becomes minimal, in the limits determined by internal and external constraints. This process is a manifestation of the *principle of minimal interaction* in the functioning of the neuromuscular system (Gelfand and Tsetlin 1971). It guides the motor action:

Motor action= minimization of $|P-R|$

Threshold control remains unique in providing a solution to the classical posture-movement problem in motor control. It also offers an unexpectedly simple solution to the problems of multi-muscle and multi-joint redundancy, as illustrated by simulations of arm reaching, sit-to-stand movement, and walking. Other optimality criteria (smoothness, EMG or torque minimization, Pontriagin's optimality, etc.) are likely partial manifestations of the more fundamental principle.

Hemisphere and skill determine vulnerability to visual illusions during grasping

Tzvi Ganel
Department of Behavioral Sciences, BGU

Some studies have shown that visual illusions, which have a robust effect on perceptual judgments, have little effect on the scaling of grip aperture during grasping. Other studies have reported contradictory findings, however, showing that both perceptual judgments and grasp can be affected by the same visual illusion. To test for factors determining vulnerability to visual illusions in object-targeted movements, right and left handed subjects reached out and grasped objects with either their dominant or their non-dominant hand in the context of visual illusions. Both right and left handers were unaffected by the illusion when grasping with their right, but not with their left hand, suggesting a left-hemisphere specialization for visually-guided actions. Furthermore, illusions affected grasping with the right hand when motor task difficulty was increased. These findings show that Visuomotor mechanisms in the left hemisphere play a crucial role in the control of action and that the engagement of these mechanismsdepends on how skilled the action is.

Modal and Amodal Processing is Task-and Modality-Specific

C.M.Wessinger 1 ,K.Lenzi 1 ,J VanMeter 2
1 Dept.of Psychology,Univ.of Nevada,Reno,NV,USA;2 Ctr.for Molecular and Functional Imaging,Dept.of Neurology, Georgetown Univ.Med.Ctr., Washington,DC,USA

We investigated modal and amodal processing of illusory and categorical information in visual and tactile domains. The illusory study investigated whether or not visual illusions are perceived tactilely using behavioral techniques. There is ongoing debate as to why we experience visual illusions. Are illusions mistakes or byproducts of perception? In light of such debate, visual illusions are often used as a tool to help us better understand how our visual system processes and interprets form information in the world around us. This raises another interesting question - are illusions experienced in other modalities? We process and interpret form information in other modalities. Do we also experience illusions in other modalities? If so, are these illusions amodal or modality-specific? We can use touch to distinguish forms -such as telling the difference between a dime and a quarter. We can also make mistakes –such as choosing a penny instead of a dime. Are these mistakes simply that –mistakes? Or are they processing byproducts? Better yet-are they illusions? Using well-known visual illusions we investigated how such illusions might be experienced tactilely. Initial analyses indicate that these illusions are indeed experienced in the tactile domain, suggesting that such illusions are general byproducts of our perceptual systems trying to understand the world around us. Interestingly, these illusions were experienced differently in each modality, suggesting that these illusions are modality-specific, and occur while organizing and interpreting the world. The categorical study investigated perceptual and conceptual processing of categorical information in the visual and tactile domains using behavioral and neuroimaging techniques. Stimuli consisted of MR-compatible toy animals and tools. Participants were asked to name (perceptual processing)or retrieve the output associated with each item (conceptual processing).The output for animals was the sound the animal makes while for tools it was how the tool is used. The data demonstrate modality specific early sensory processing in primary and association sensory regions that is likely occurring prior to stimulus identification, and modality non-specific (amodal)processing in the left inferior frontal lobe that is likely occurring concurrent with stimulus identification, as well as an increase in activation intensity and scope that is likely related to accessing higher-order conceptual information. These studies indicate that initial interaction with, and interpretation of, the surrounding environment is primarily modality driven, as evidenced by both studies. One interesting finding specific to the illusion study is that illusions do occur in multiple modalities, and are likely byproducts of what are generally very efficient and accurate perceptual processing heuristics. However, data specific to the categorical study indicate that additional processing involves common, amodal, brain regions. Taken together, these studies indicate that modal and amodal processing systems are employed as we interpret, react to, and interact with, the world around us.

The adaptive representation of time and space

Sandro Mussa-Ivaldi
Northwestern U. and the Rehabilitation Institute of Chicago

Space and time are the most basic concepts of Physics. While relativistic ideas about space and time are very sexy, and for good reasons, I will focus on the most classical notions of Euclidean space and a simultaneous events, that remain quite applicable to everyday life experiences. If one makes the reasonable assumption that we interact with the world through a system of neural signals (sensory, motors and more) one needs also to observe that these signals are not inherently endowed with metric and temporal properties of the ordinary space and time in which organisms exist. The ability of the nervous system to represent fundamental properties of space and time depends on adaptive mechanisms that reconstruct Euclidean metric and simultaneity from signals that are neither Euclidean nor simultaneous. I will present some recent experimental studies that address these issues and that have practical implications for the development of adaptive human-machine interfaces.

Spike timing during typical movements

Dana Cohen
Gonda Brain Research Center, Bar-Ilan University

Neurons are noisy entities yet a prolonged movement practice during motor skill learning leads to stereotypical performance with low variability. To understand neural coding, we must understand how inaccurate neural activity gets translated into the performance of accurate movement. For that purpose rats were trained for over 2 months to move left and right in response to specific auditory cues. Neural activity from motor cortex was recorded using chronically implanted microelectrode arrays. Analyzing the data, we aimed at finding neuronal features that will match the behavior. This means that the distance between these features will be smaller when movements are similar and larger when movements are different. We looked at a range of features: firing frequency during movement, time to first spike after movement initiation and firing order across neurons. Any clear relationship between the similarity across movements and the similarity across neural activity during the movements is considered evidence of a role for that feature in the performance of stereotyped movements. Such a finding would support the overarching hypothesis that neuronal variability is countered by having neuronal networks that are sensitive to specific features of their input. The significance of these results in relation to theories of variance control in optimal feedback models will be discussed.

Motor trajectories: A dynamical systems perspective

Haim Sompolinsky
Racah Institute of Physics, Hebrew University

In this talk I will discuss issues that arise when the motor system is analyzed from a dynamical system perspective. These issues include: (1) the characteristic features of the repertoire of movement trajectories and their hierarchical organization. (2) The dynamic mechanisms for selection and control of these trajectories. (3) The origin of the broad time scales exhibited by the motor system.

I will discuss a joint work with Uri Rokni that addresses these issues. In this study we assume that the brain uses a general-purpose pattern generator to transform static commands into basic movement segments. The system has the following key elements: an internal oscillator which controls the overall rhythm of the movement; frequency and amplitude modulation by external inputs; temporal integrators that determine the final muscle activation patterns; concatenation of movement segments into complex but smooth trajectories. The model accounts for the basic features of natural movements. I will discuss the implementation of this model by neuronal networks and its experimental predictions.

What is coded in neurons of the motor cortex?

Eran Stark[1], **Rotem Drori**[1,2], **Itay Asher**[1,2], **and Moshe Abeles**[1,2,3]

1Department of Physiology, Hadassah Medical School, The Hebrew University of Jerusalem, Jerusalem 91120, Israel; [2]The Interdisciplinary Center for Neural Computation, The Hebrew University of Jerusalem, Jerusalem 91904, Israel; [3]Gonda Brain Research Center, Bar-Ilan University, Ramat-Gan 52900, Israel

An important question in neuroscience is how the motor cortex controls arm movements. The classical model of movement direction control by means of a population vector has been modified and challenged. To a large extent, the controversy arises from interdependencies between various movement features. When several features are interdependent at a given point in time or at distinct points in time, neural activity related to one feature appears to be correlated with other features. Thus, techniques that simultaneously consider multiple features cannot account for delayed interdependencies between the features. The result is an ambiguity regarding the encoded movement features.

For instance, during continuous drawing like movement of monkeys, correlations between the directions of velocity and acceleration vectors may be low at zero delay, yet they are maximal at time delays of ±150 ms. Ambiguity ensues: does the neuron encode acceleration at zero delay or velocity at a time delay of 150 ms? We resolve this ambiguity using a novel statistical method based on partial cross-correlations. The method was applied to two monkeys performing continuous movement tasks while recording with 8 microelectrodes from both motor and pre-motor areas. In the analysis we resolved correlations between firing rate, and three movement features: position, velocity and acceleration, at all possible delays from -300 up to + 300 ms. Most units were related to one or more kinematical feature.

Supported in part by grants from ISF and DIP.

Cracking the complex spike code

Maarten Frens
Department of Neuroscience, Erasmus University

Climbing fibers (CF) that project to Purkinje cells (PC) of the cerebellar flocculus are known to respond to rotational optic flow and can be classified on the basis of their direction selectivity. In the rabbit, PCs in different parasaggital zones receive CF input that is tuned to either horizontal 135°-axis (HA) or vertical axis (VA) rotation. In the present study we revisit the directional and temporal tuning properties of floccular PCs. We compare the spatiotemporal tuning of CF input, recorded extracellularly as complex spikes (CS), with that of the parallel fiber input of the PC as signaled through its simple spike (SS) activity. Current theory of cerebellar learning predicts that the tuning of CS activity is anti-correlated with the tuning of SS activity, because CF input causes attenuation of coincident parallel fiber synaptic input. We developed a novel experimental protocol in which a subject is placed in a panoramic computer-generated visual scene that can be rotated about any axis. By using 3d white noise to drive this optokinetic stimulus and employing standard reverse correlation techniques we could resolve both the temporal as well as the directional tuning of a cell with high accuracy in relatively short time. It is the first time that such a stochastic stimulus has been used to characterize and map the spatiotemporal tuning of complex and simple spikes in the cerebellar flocculus. The directional tuning of the CS signal can be classified as HA or VA tuned as described in the literature. Surprisingly, the directional tuning of the SS signal is in many cases not the mirror image of the CS preferred axis. Most cells show a systematic relative tilt between the preferred axes of the CS and SS signal. In some cases the SS preferred axis is completely different from the CS preferred axis and could even be tuned to more than one preferred axis. The temporal tuning of the CS signal is fairly uniform, integrating the visual stimulus about 100-150 ms, while the SS signal has typically longer integration times.

Exploiting the natural capacity to adapt for motor teaching and rehabilitation

James Patton
BME, Northwestern U. and the Rehabilitation Institute of Chicago

New developments of robotic devices can safely interface with humans to facilitate the motor learning process. Learning can be induced in a variety of creative and new ways with these new technologies, allowing for new possibilities in training a person for teleoperation or for helping patients recover their ability to move after a brain injuries such a stroke. Several scientific studies will be presented/discussed on robotic teaching and rehabilitation that point to the future of this new field.

Independent control of trajectory and final equilibrium position predicts asymmetric transfer of learning and systematic extent errors in reaching

Robert Scheidt[1,2] and Claude Ghez[3]
[1]*Biomedical Engineering, Marquette University*
[2]*Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University*
[3]*Center for Neurobiology and Behavior, Columbia University College of Physicians and Surgeons*

Models of voluntary limb movements have often emphasized exclusive planning and control of either movement endpoints or trajectories in reaching. However, using separate tasks to assess each of these possibilities, we find that trajectory and endpoint are planned in parallel and independently. In learning visuomotor rotations, subjects showed limited transfer of adaptation between trajectory and endpoint tasks and learning showed different generalization patterns. Specifically, trajectory adaptation generalizes about initial hand location whereas endpoint adaptation generalizes about the shoulder. Unexpectedly, we observed asymmetric transfer of movement extent across tasks. After trajectory task practice, endpoint task movements were accurate whereas after endpoint task practice, trajectory task movements became increasingly hypermetric after peak hand acceleration.

Here we describe forward dynamic simulations of hybrid feedforward control of hand trajectory and final equilibrium position in reaching. A trajectory controller generated elbow and shoulder torques to produce reaches with linear hand-paths and bell-shaped speed profiles (Shadmehr and Mussa-Ivaldi, 1994). Trajectory task movements were composed using a smooth sequence of out and back reaching movements (Gottlieb, 1998). A second controller specified equilibrium positions with both joint stiffness and viscosity (Lacquaniti et al., 1993) centered at the target for the endpoint task, and/or at the return point for the trajectory task. Based on our kinematic data, the development of equilibrium positions at the goal and home targets were assumed to begin at peak outward and inward acceleration, respectively. We also assumed that the trajectory controller achieves nominal trajectories through error-driven adaptation, but is uninformed of control signals generated by the positional controller.

We examined how movement kinematics are influenced by increased joint stiffness and viscosity due to limb stabilization (Gomi and Osu, 1998). With endpoint stabilization, feedforward torques calibrated during trajectory task training must be reduced initially (due to increased joint stiffness) and increased later in movement (due to increased joint viscosity) to achieve an ideal trajectory. Failing to do so only results in minor deviations from path linearity and speed profile symmetry. In contrast, application of feedforward torques that compensate for increased limb impedance, as would occur during endpoint training, resulted in hypermetria when endpoint stabilization was no longer required. This replicates the behavioral data collected in our trajectory task. Furthermore, adaptation of either trajectory or endpoint controllers predicts observation of limited transfer using the performance measure used in our psychophysical study. Thus, accurate movement requires feedforward motor commands to account for changes in muscle mechanical properties induced by increased co-contraction during movement. By failing to do so, our human subjects provide compelling psychophysical evidence supporting independent control of trajectory and final equilibrium position in reaching.

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Temporal and visuospatial information increase spatial accuracy in reaching by improving final position planning.

Claude Ghez, M.D.
Columbia University Center for Neurobiology and Behavior

Our recent observation that trajectory and endpoint are adapted independently raised questions about how the two controllers are temporally coordinated and the role of visuospatial information to spatial accuracy. To disentangle these effects we examined single and reversal (slicing) movements to a common target made from 4 locations in different directions in the horizontal plane under different conditions. We examined the effect of timing cues by instructing subjects to either (1) move after target and tone presentation or to (2) synchronize movement termination or reversal with the target and tone, both occurring at a predictable time. We also examined the effects of (3) prior vision of initial cursor location and (4) feedback of cursor trajectory. Kinematics, and spatial distributions of points reached at movement endpoints (or reversals) and at peak velocity (velocity-point) in these tasks were compared ones in (5) a simple 'ballistic' task. Here subjects aimed a 0.5 kg mass at the same targets, but released it at movement midpoint.

In all conditions the spatial distributions of velocity-points were elliptical and aligned with movement direction. As expected, for ballistic movements ellipse areas expanded from peak velocity to final endpoint. This expansion was reduced or absent in other tasks, indicating neuromuscular control of final position. Endpoint areas (precision) of both reaches and slices were significantly reduced when final position (or reversal) was to be synchronized with the auditory cue. However, the shapes of the endpoint distributions differed between reaches and slices. In reaches ellipse eccentricity was markedly or distributions became circular, while in slices the reversal and velocity ellipses had similar eccentricities. In reaches, visual feedback did not change endpoint precision at the onset of stabilization but vision of the initial position alone increased both accuracy and precision. Surprisingly, in slices visual feedback reduced systematic errors resulting from inertial anisotropy, but did not change precision: Without feedback, variations in mean extent mirrored directional variations in peak acceleration and velocity, which were present in all conditions.

When switching from previous reach training, both ballistic and reversal movements became hypermetric.

The present results fit our hypothesis that reaching is achieved through separate planning of trajectory and final equilibrium position, each based on estimation of different state variables. We now find that accurate performance also depends on precise temporal coordination of the two controllers. Extent errors made after transferring from reach to slice and push support the idea that the trajectory controller is not informed of the intended final equilibrium state (Scheidt, this volume). However, the postural controller appears informed of the intended trajectory, compensating for inertial effects on acceleration and speed. We hypothesize that this is achieved by adjusting impedance at the final position. Initial position and visual feedback both provide critical state information for this control. Maximal spatial accuracy is achieved when aiming of movement and interception of the moving hand by the postural controller can be timed to a common temporal signal.

Posters

Motor representations of well-practiced handwriting versus novel motor sequences of graphomotor output: an fMRI study

Meirav Balas1,2, David Manor2,3, Nir Giladi1,4, Avi Karni2,3
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[2]The Brain Behavior Research Center, University of Haifa, Israel
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Background: In humans and monkeys extended motor practice was shown to result in the recruitment of additional M1 units into a local network specifically representing the trained motor sequence. It was proposed that M1 might code not just for simple, single, movements, but rather for complex movement sequences. The proposal is that the representation of well-practiced handwriting sequences is effector-dependent because it relies on the activation of low-level motor areas (e.g., M1), rather than high-level ones, for fluent performance. Unpracticed writing sequences may require more activation of high-level areas (e.g., the SMA) and depend less on M1 based fluency. Neuro-imaging studies indicate that controlled, novel handwriting is associated with kinematic non-fluency and shows increased neuronal activity in brain regions that contribute to sensorimotor control and integration and attentional processes. Nevertheless, the above results are confounded by the fact that writing with the practiced (dominant) and non-practiced (non-dominant) hands was compared.
Aims: to study the differences between the representation of well-practiced, native hand-writing and the novel writing using the writer's dominant hand.
Method: Thirteen healthy participants performed two tasks inside a 3T (GE Excite HD) fMRI scanner. In task A, the participants wrote 18 common Hebrew words using either the Hebrew alphabet (Hebrew writing) or similarly constructed common Hebrew words but in the Latin alphabet (Heblatin writing) in a random order. In task B, the participants completed three incomplete visual stimuli by drawing round shapes: the letters, "ס", in the word **סוס**, the numbers "ס" in the number string 974**0**1**0**, and eyes, "ס", in a schematic drawing of a face, in a random order. These conditions require the production of the same graphomotor output, but in different contexts. The SPM2 second level (one sampled) comparison was used.
Results: Task A: while the primary motor area was activated in both handwriting types, the Heblatin writing triggered additional activations in high-level motor areas (e.g., lateral and medial pre-motor areas) that are known to be involved in the planning of new, untrained, motor sequences. Task B: writing zeros activated significantly more of the lateral pre-motor cortex contralateral to the writing hand as well as the ipsilateral cerebellum, compared to writing the letter. There was also more activation in the bilateral pre-cuneus, the posterior intra-parietal sulcus and dorsal occipital areas. However, there was more M1 hand-area activation in writing the letter as compared to zero. Both conditions activated the bilateral posterior superior temporal gyrus including the planum temporale, but in a non over lapping manner. Drawing eyes resulted in significantly more activation, compared to letter writing, in the lateral pre-motor and the SMA as well as more activation in M1. In contrast, letter writing activated more of bilateral parietal and occipital areas, the right superior temporal sulcus and the bilateral DLPFc.
Conclusions: Our results suggest that the motor system is highly sensitive to the context in which a given motor path is executed, as well as to the level of experience with the target movement.

Random Perturbation as an Enhancement to Treatment of Children with Cerebral Palsy

Simona Bar-Haim[1, 2], Netta Harries[2], Mark Belokopytov[2], Jacob Kaplanski[1]

[1]Faculty of Health Sciences, Ben-Gurion University of the Negev, Beer-Sheva, [2]Motion Analysis Laboratory, Assaf-Harofeh Medical Center, Zerifin.

Background and Purpose: Within a dynamic system approach, motor behaviors can be considered to be organized in stable states called attractors. The motor behavior of children with cerebral palsy (CP) can be considered in terms of stiff attractors that prevent movement flexibility. We hypothesized that the use of random perturbations (RP) would weaken stiff attractors, introduce flexibility and enhance effects of physical treatment. The objective was to evaluate the contribution of RP to gross motor function and mechanical efficiency (ME) during intensive physiotherapy in children with CP.

Participants: A convenience sample of 20 children with CP (mean age 8.2, range: 5.9-12.9 yr) were matched by age and gross motor function level and randomly assigned to structured intensive treatment (SIT) or to SIT+RP groups.

Methods: Groups received one month of daily treatment. RP was applied by engine-induced random passive cycling for upper and lower limbs for up to 10 min in a 90-min treatment session. Gross Motor Function Measure and ME during stair-climbing were measured before and after treatment.

Results: Gross Motor Function Measure scores increased similarly by about 1.0 in each group. However, external work and ME increased significantly more in SIT+RP than SIT. The increase in ME in SIT+RP was independent of the level of motor function at baseline.

Discussion and Conclusion: The addition of a small amount of RP in children with CP may have weakened previously established stereotypical motor patterns and introduced flexibility, thereby improving mechanical efficiency of a complex motor task. RP may enhance the effects of intensive treatment, but this needs to be confirmed in future studies.

Gait Kinematics - Intersegmental Coordination Law An Analytic Approach

Avi Barliya[1], Claire L. Rother[2], Martin A. Giese[2] and Tamar Flash[1]

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The *Law of Intersegmental Coordination* is a well known kinematic law that correlates between the elevation angles of the lower-limb (thigh, shank, foot) during locomotion (Borghese et. al, 1996). This correlation reduces the number of degrees of freedom of the lower limb to two and hence, the elevation angles covary along a plane in the space defined by the three joint angles. The properties of the plane that constrains the time course of the elevation angles have been extensively studied and its orientation was correlated with gait velocity and energy expenditure (Bianchi et. al, 1998). We have developed a mathematical model that explains what requirements the time course of the elevation angles must fulfill in order for the angular covariation to be planar. Moreover, an analytical formulation is proposed for both the orientation of the plane and eccentricity of the nearly elliptical shape that is produced on this plane. The normal to the plane and the eccentricity of the ellipse are given only in terms of the amplitudes of the first harmonics of each of the segments' elevation angles time course, and the phase shifts between these harmonics.

Presenting the limb behavior by means of coupled (in terms of their phase shifts) simple oscillators may shed some light on the interactions between the controlling CPGs. It is implied by the model precisely how each two segments in the limb interact, and how a change in gait velocity, which is mainly reflected in a change in phase shift between the segments, affects the orientation of the plane.

Additionally, an intersegmental coordination pattern was found also for the upper-limb when the upper arm, forearm and the hand angular rotations during natural gait pattern are considered, expressed in a strong linear correlation in the angular space between the movements of these segments. Thus, angular covariation is represented by a line in 3D angular space, rather then by the planar loop which was observed for the lower-limb.

The implications with respect to neural control of locomotion and other motor activities will be further explored.

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Analysis of 3D reaching motion using Geometric Algebra

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Geometric algebra integrates quaternions into a more powerful mathematical system combining their advantages with those of conventional vector calculus. The enhanced mathematical power combined with simplified representations give way to new perspectives not always readily apparent using other representations. For the representation of rigid body motion geometric algebra is an isomorphic approach to screw theory offering computational advantages with respect to quaternions and rotation vectors. We have harnessed the power of geometric algebra to examine three dimensional reaching movements.

A reaching task is fully specified in space by the distance and direction of the target. If the wrist is kept rigid such a task is executed using four degrees of freedom: the three degrees of freedom of the shoulder and one degree of freedom of the elbow (elbow pronation-supination is of no relevance to such a task). The redundant degree of freedom determines the positioning of the elbow relative to the target. An "*arm triangle*" is defined as a triangle whose sides are the upper arm, the forearm, and the distal vector connecting the wrist and the shoulder. In analogy to the description using joint angles, the arm movement can be fully determined by describing the change in the shape of the *arm triangle* together with its rigid rotation about the shoulder. A plausible strategy for reaching and pointing movements is to maintain a zero rotation angle around the distal vector of the plane containing the *arm triangle*. Such a policy is efficient since rotation of the triangle while maintaining zeros rotation of its plane is equivalent to a parallel transport along a geodesic.

We evaluated the rotation angle around the distal vector of the *arm triangle* plain for radial motions (movements towards targets along the line connecting the target and the shoulder) and frontal plane reaching motions (movements towards targets within a fixed frontal-parallel plane relative to the trunk). For the radial condition, the database includes two subsets of movements performed towards targets located at shorter and longer distances from the shoulder with 48 different final locations but one starting region. For the frontal plane condition, the database included movements within four such frontal planes and four different initial points within each plane. The results support the zero plane rotation angle strategy since the rotation angles of the *arm triangle* plane for all types of movement are very small (mean torsion angle <7 deg for radial movement and <5 deg for frontal plane movements) with an exponential distribution.

Contrary to reaching and pointing movements, during grasping movements the positioning of the hand relative to the target object is constrained by the orientation of the object prescribing acceptable rotation angles of *arm triangle* plane. Due to the availability of additional degrees of freedom at the wrist and hand the controller must still solve a redundant inverse kinematics problem. Our future experimental work will focus on grasping movements and the strategies employed for the choice of the *arm triangle* plane rotation angle.

Applying the Euler-Poisson Equation to obtain piecewise smooth optimal hand trajectories

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We consider the minimum acceleration criterion with constraints (MACC, Ben-Itzhak and Karniel submitted) for point to point reaching movements as well as for movements through via point. To find the optimal trajectory we developed an algorithm based on an extended method of the Euler-Poisson equation. The trajectory is a piecewise third order polynomial, continuous in displacement, velocity and acceleration, and piecewise constant in the jerk. We compare the results of this criterion to the observed trajectories.

For a reaching movement with flexible object (a mass and spring), it was previously suggested that the integral of the squared crackle (fifth derivative of displacement) of the object is minimized (minimum crackle criterion, Dingwell et al. 2004). In this case, we used our method to obtain the minimum jerk trajectories. For two conditions of movements with flexible object presented in Dingwell et al. 2004 our model can be fitted to better predict the hand trajectory than the minimum crackle criterion.

Spatial, cognition related characteristics of mouse open-field behavior

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In previous studies of Open-Field behavior in rodents, it was shown that rats alternate between progression and stopping. Stopping behavior is organized around preferred locations established by rats in the open field (home bases and principal places, which are characterized by high number of visits and high cumulative time spent in them). In the present study, we examine the cognitive constraints on stopping in the open-field in mice. This is done by examining dynamics of visiting behavior to locations. A visit is defined as either passing through the location or stopping there. We estimate the probability of stopping at a location as a function of the number of previous visits to that location. This estimate can be regarded as a measure of the familiarity of the mouse with the location. A comparison of 3 inbred strains shows that, one strain (CZECHII/Ei) exhibits an overall increase in probability, another (DBA/2J), exhibits a fixed probability, and a third strain (C57BL/6J) shows a mild increase in this probability.
The strain difference is not due to change in the rate of stopping, which remains constant in time in all 3 strains.
An increasing probability of stopping at a certain location is likely to reflect a memory of the history of visits to that location. This feature appears therefore to be a cognition-related measure of open-field behavior. The poor performance of DBA mice coincides with previous reports of impaired spatial memory due to hippocampal dysfunction in this strain.

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Does the kinematics of wild mouse locomotor behavior exceed that of laboratory inbred strains?

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The noisy and relatively erratic nature of rodent free locomotor behavior presents a challenge for the precise measurement of its kinematics. By using robust smoothing and by segmenting the animal's trajectory into intrinsic modes of locomotion we obtain high-quality data on trajectory kinematics. This allows us to phenotype mouse behavior on the basis of its kinematic features.

An interesting question is the relationship between the kinematics (e.g., speed, acceleration, curvature) of the laboratory inbred mouse strains (*M. laboratories*) and that of their wild ancestors. It is commonly believed, often in the absence of hard evidence, that the repertoire of wild mice exceeds by far, in terms of magnitude and variability of kinematic measures, the behavior of the classical inbred strains. Having measured the locomotor behavior of eight of the commonly used laboratory inbred strains, two wild-derived inbred strains and a group of first-generation-in captivity local wild mice (*Mus musculus domesticus*), we show that contrary to common belief, wild-mouse locomotor behavior is moderate, both in terms of kinematic values and in terms of their variability, being embedded within the multidimensional data space spanned by laboratory inbred strains. The implication could be that whereas natural selection favors moderate and constrained locomotor behavior in wild mice, the inbreeding process tends to generate, in many of the features, extreme and more variable behavior. Be it as it may, this study illustrates how kinematic data and a computational approach can contribute to the classification of complex free animal locomotion.

Coordination of steering in a free trotting quadruped

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Typically, locomotion has been studied by restricting the animal's path and/or speed, focusing on stride and step kinematics. Here we incorporate measurements of the legs and trunk in the support and swing phases, during trotting with various speeds and path curvatures. This paradigm releases the animal from the confines of the treadmill and runway into the open space. The diagonal step, a new unit of locomotion, is defined by regarding the line of support between diagonal legs as a frame of reference for the description of the swinging diagonal's dynamics. This analysis reveals that during free locomotion the mouse uses 3 types of steps: fixating, opening, and closing steps. During progression along a straight path, the mouse uses fixating steps, in which the swinging diagonal maintains a fixed direction, landing on the supporting foreleg; during progression along a curved path the mouse uses opening and closing steps alternately. If two steps of the same type are performed in succession, they engender an abrupt change of direction. Our results reveal how steering with the swinging diagonal, while using a virtually bipedal gait, engenders the whole repertoire of free locomotor behavior.

The relationship between action observation and motor learning

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It has been shown that action observation can replace practice during motor learning to some extent. This effect is may be mediated through the mirror system, a group of neurons in the brain activated by both action observation and action execution. In addition, activation of the mirror system is greater when observing familiar actions as opposed to unfamiliar actions.

Based on these results, we sought to understand the effects of action observation on motor learning during different phases of acquisition of expertise in a new motor skill. We developed two motor skills whose mastery requires between two and three days, and tested the effects of observation of the skill on different days of training. Our working hypothesis is that action observation's effect on performance will be greatest when observing a skill with which one is familiar but which has still not been mastered completely.

Subjects are divided into groups in which they practice one of two juggling skills: 2 ball juggling or devil sticks, for 3 days. On each day, subjects perform three 10 minute practice blocks interleaved with two 10 minute observation blocks. In the practice blocks, the subjects practice the appropriate skill, while in the observation blocks, they perform a behavioral task which requires them to watch video of a model performing one of the tasks. In addition, in control groups, subjects watched videos of the alternative task (the one they were not practicing). By measuring the subject's performance before and after the observation blocks, and comparing the performance of experimental groups to control groups, we hope to describe the way action observation efficacy changes during acquisition of a motor skill.

Key words: Action Observation, Mirror System, Mirror Neurons, Motor Learning, Juggling.

Estimating wall guidance and attraction in mouse free locomotor behavior

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In this study, we estimate the influence exerted by the wall of the Open Field on the trajectory of the mouse. The wall exerts two types of influence on the mouse's path: one of guidance and one of attraction. The guiding influence is expressed by the tendency of mice to progress in parallel to the wall. This tendency wanes with increasing distance from the wall but is observed at large distances from it. The more parallel the mouse is to the wall the higher is its speed, even when distant from the wall. This association between heading direction and speed shows that the mouse controls its heading in reference to the wall. It is also observed in some blind strains, revealing that wall-guidance is not based exclusively on vision. The attraction influence is reflected by movement along the wall and by the asymmetry between speed during movement toward, and during movement away from the wall: sighted mice move faster toward the wall, whereas blind mice use similar speeds in both directions. Measures characterizing these influences are presented for five inbred strains, revealing heritable components that are replicable across laboratories. The revealed structure can lead to the identification of distinct groups of genes that mediate the distinct influences of guidance and attraction exerted by the wall. It can also serve as a framework for the decoding of electrophysiological data recorded in free moving rodents in the Open Field.

Info-Gap Filter for Control and Estimation

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The neuro-control system is subject to severe uncertainty – a fact that makes it very difficult to extract the command signals delivered to the motor system aiming for a desired trajectory.
Recent studies in the field of biological movement have tried to use optimality principles in order to derive estimators for the laws governing the system behavior. Most of these estimators are based on the assumption that the system dynamics equations or the noise accompanied the command signals are all known up to small deviations. However the uncertainty which exists within the system parameters can be severe, and the optimal estimators aiming to predict the system behavior lack robustness.
Thus it can be hypothesized that the online control and estimation executed by the nervous system has a certain way to cope with this uncertainty rather than the standard optimization process. In order to examine this hypothesis I chose to utilize the Info-Gap approach [1] for decisions made under severe uncertainty. In my work I exploit the Linear-Quadratic- Gaussian framework to construct a new controller $u_t = \pi(\hat{x}_t)$ which is robust to uncertainty within the noise in the plant dynamics. The robust controller is chosen based on a *robustness function* curve led by the principle of achieving higher robustness values than those satisfied by the optimal Kalman control law. The robustness function expresses the greatest level of uncertainty at which a certain performance requirement is satisfied. In our case the performance requirement is set to be $x_t^T Q_t x_t + u_t^T R u_t \leq R_c$,which means that the quadratic cost function cannot exceed a certain value.

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Modeling the Ongoing Cortical Dynamics Inherent in the Local Field Potential in the Motor Cortex

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Understanding the role of the motor cortex in volitional movements requires a model which can predict the neuronal activity around a given movement, in a single trial. However the inter-trial variability has been found to be much larger than the average response. Furthermore, this variability has been shown to correlate with behavioral responses. In a series of studies, Arieli A. and colleagues have shown that a large portion of this variability can be accounted for by the spontaneous (*ongoing*) network state before the trial begins.

To examine the nature of this ongoing activity and its relation to behavioral trials we modeled the dynamics of the ongoing network states in motor cortex inherent in the local field potentials, from simultaneously recorded multi-electrodes in behaving monkeys. We used the LFP as a measure of the network state, as it is believed to reflect the synaptic activity from a large ensemble of neurons in the vicinity of the microelectrode.

We trained a linear dynamical system with gaussian noise (Kalman Filter), using the LFP signal from one electrode as our *observations*, and learned to predict the LFP signal of another electrode—our *states*. After training the model on data taken from periods of ongoing activity (when the monkey is resting from the task and not moving the manipulandum), we tested the model on the trial-by-trial fluctuations (single trial minus average) during reaching trials. Our model significantly outperformed the correlations inherent between the electrodes. Thus the statistics of the ongoing activity can account for a portion of the inter-trial variability during trials. We examined the stationarity of these statistics by training the model on data from different parts of the day, as well as, from different epochs of ongoing activity. In addition, we examined the predictive power of the model on data segments with oscillations in specific frequencies (e.g. gamma-band oscillations), or on limited frequency bands of the LFP signal.

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Interfacing

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When learning to control an external device that responds to hand movement, hand movement becomes skilled, the process becomes automatic, awareness of the hand movement is reduced and after extensive practice, the perception that the device itself responds to the motor commands may develop (assimilation). We present a computational model that aims to capture this process and preliminary experimental results which are consistent with our model.

Our model is based on the simultaneous formation of differing representations for the practiced task. Such an approach has been taken by Logan for cognitive tasks (1988), Ahissar and Hochstein for visual tasks (1997), Nakahhara and Hikosaka for sequence tapping tasks (2002), Criscimagna-Hemminger et al for adaptation to force perturbations (2003), and recently by Wang and Sainburg for visuomotor tasks (2004).

We develop our model for the task of learning to move a cursor that is controlled by hand movement under a visuomotor rotation. We differentiate between two possible representations of the task, one that uses information from the hand (indirect), and one that does not (direct). In our model task, a plausible indirect controller uses input from attempted hand trajectories and the resulting cursor trajectories in order to form a representation of the mapping between the two. We note, however, that in this task, hand trajectory (position and direction) is uniquely mapped to cursor trajectory, and therefore this task can be controlled without information from hand, based solely on information from cursor trajectory alone. Such a direct controller uses input from the neural commands and the resulting cursor trajectories in order to form a representation of the mapping between the two.

Our model makes the assumption that the indirect controller can be trained faster, while the direct controller attains better performance. An optimal controller will therefore train both controllers simultaneously. In early stages of training the output of the indirect controller is used for execution of the task. However after prolonged training, the direct controller outperforms the indirect controller, and task is executed based on the output of the direct controller. We term this transition interfacing and note that since information from hand is removed from the control loop of the task, it is a computational correlate to the notion of automaticity and assimilation of the cursor.

We present a set of experimental results supporting the first part of the learning in which the indirect mapping is being employed.

Perception of Time Delay: How does the Human Motor System Learn Time Delay Disturbances?

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"How does the human brain represent time" is an open question. Recent findings suggest that in many cases the motor system does not adapt to forces that depend explicitly on time, and lead to the speculation that our brain might be unable to utilize temporal representation. However, earlier studies suggesting the existence of explicit time structures in the Central Nervous System were not yet proven false. Moreover, adaptation to delayed visual feedback was recently studied with positive results.

In order to control movements from a distance, e.g. in tele-operation, the human sensori-motor system has to overcome unavoidable communication delays; understanding the representation of delay by the brain could be useful for such applications.

This dissertation focuses particularly on delayed force perturbations. We explore the ability of the brain to adapt to a delayed viscous force field, and the manner in which this adaptation is achieved.

We planned and conducted experiments of delayed force perturbations in a task of reaching movements, aimed to answer the proposed questions. The experimental results were compared with the predictions of three alternative models proposed for approximation to time delay. One of the models consists of actual delay representation; the second includes a state-based approximation; and the third – no adaptation to time delay. The results demonstrate clear adaptation to the delayed force perturbations, but the evidence regarding which model is most probable for the perception of time delay – delay representation or state approximation – is ambiguous.

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Effects of Brain Stimulation on Motor Performance & Learning: A Systematic Exploration

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Deep brain stimulation (DBS) has demonstrated a high rate of success in ameliorating Parkinson's disease (PD) symptoms, though its mechanism of action is not currently understood. We use a wrist robot to test whether DBS restores overall motor performance levels of PD patients. In 2001 Krebs et al found a difference in the learning rates of PD patients (off medication) and age-matched controls during a task involving skill-transfer (or task-switching). We use a wrist robot to test whether DBS obliterates this difference in learning rates between the PD and the control groups.

HYPOTHESIS I: Deep-brain stimulation restores *motor performance* levels of Parkinson's disease patients to those of healthy peers.

HYPOTHESIS II: Deep-brain stimulation restores *learning rates* of Parkinson's disease patients to the levels of healthy peers *during task switching*.

METHODS: 16 subjects (8 PD patients with implanted STN DBS, mean age 67.8±7.1yr; 8 age-matched controls (AMC), mean age 68.6±8.4yr) participated in the study. Patients were studied both with stimulation turned ON and turned OFF. They used a wrist robot to perform a point-to-point reaching movement as they followed a visual cue presented on a computer screen. The task was first performed in the absence of forces, then in the presence of a curl force field (force perpendicular to velocity), and finally in the presence of a reverse field (skill transfer; performed by the AMC and the DBS ON groups only).

RESULTS: HYPOTHESIS I: Using most of the performance measures it is possible to differentiate the DBS ON group from the AMC group to a 5%-significance level, but not DBS ON from DBS OFF, despite trends showing that the DBS ON group performs better than the DBS OFF for all performance measures. HYPOTHESIS II: Trends indicate that the AMC group learns at a higher rate during the skill-transfer phase than patients with DBS. However, it is not possible to differentiate the DBS ON group from the AMC group to a 5%-significance level, using most performance measures.

CONCLUSION: Trends are showing that DBS improves performance levels for PD patients; Trends also indicate that the control group learns faster than the DBS ON group during task switching, suggesting that DBS does not fully restore motor learning abilities for PD patients. One should regard these results with appropriate caution, as those trends do not reach a 5%-significance level. Likely, this is due to the small number of subjects who have so far participated. We are currently recruiting and testing more subjects to reach our initial target of 20 PD patients and 20 age-matched controls.

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Noise, smoothness and the two-thirds power law

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The two-thirds power law, an empirical law stating an inverse non-linear relationship between the tangential hand speed and the curvature of its trajectory during curved motion, is widely acknowledged to be an invariant of upper-limb movement. It has also been shown to exist in eye-motion, locomotion and was even demonstrated in motion perception and prediction. This ubiquity has fostered various attempts to uncover the origins of this empirical relationship. In these it was generally attributed either to smoothness in hand- or joint-space or to the result of mechanisms that damp noise inherent in the motor system to produce the smooth trajectories evident in healthy human motion.

We show here that various types of noise, including white noise, also obey the power-law. Analysis of signal and noise combinations suggests that trajectories which were synthetically created not to comply with the power-law are transformed into power-law compliant ones after their combination with low levels of noise. Furthermore, there exist colored noise types that drive non-power-law trajectories to power-law compliance and are not much affected by smoothing. Last, preliminary experimental results suggest that the variance inherent in the human motor system, which could be said to be due to correlated noise, could significantly influence the power-law compliance of upper-limb movement signals.

These results suggest caution when running experiments aimed at verifying the power-law or assuming its underlying existence without proper analysis of the signal and noise relationship. Moreover, the power-law phenomenon might be derived from a combination of smoothness-inducing mechanisms and correlated noise inherent in our motor system.

Perception of stiffness through bilateral teleoperation

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Bilateral (force reflecting) teleoperation allows human operator to control the movement of a distal robot while receiving force feedback. The finite traveling speed of information in the transmission line generates an unavoidable delay which may reduce the performance and even cause instability. A prominent application of teleoperation is telesurgery, in which perceiving accurately the stiffness of the tissue might be crucial for diagnosis and operation. Numerous studies explored the performance and stability of bilateral teleoperation techniques however, the perception of stiffness through these systems was scarcely addressed.

In this study we explore the influence of delay on the perception of stiffness, and try to understand the mechanism which the brain may employ to distinguish between surfaces' stiffness.

In our first study (Pressman A, Karniel A, Mussa-Ivaldi FA SFN, 2005, Biorob 2006) we found clear over-estimation of delayed stiffness and considered various models. In this work subjects moved the whole arm probing a spring like surface.

Here we considered movements in which the elbow is on the table and movements in which the palm is fixed on the table. We also considered stiffness estimation without boundary where the subjects are probing stiffness without moving out of the object, i.e., the hand is always touching the object and feel some no-zero force. We used an Augmented Reality with haptics system (Reachin® system) to experimentally test the perception of delayed stiffness by human subjects. We employed a forced choice technique in which subjects were asked to choose the stiffer between two virtual surfaces presented to them by probing the surfaces with PHANTOM® Desktop™ haptic device. An elastic force (proportional to penetration to the surface) was simulated with or without delay.

We reproduced our first results about overestimation of stiffness for the spring-like surface, however for the case in which subjects probed a liner spring without boundary we found clear under-estimation of the delayed stiffness.

The difference in the estimation of surfaces with and without boundary will be discussed and possible estimators to explain the experimental results will be presented. We also discuss the possible effect of using the wave-variables technique (Niemeyer & Slotine, 2004) on stiffness estimation in bidirectional teleoperation.

Understanding the human motor control system and the brains strategy to perceive mechanically manipulated objects is essential in order to develop efficiently and effectively the telemanipulation systems of the future.

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Movement Imitation via Visual Similarity

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In movement imitation observed movements are mapped into similar executed movements. An open question is the type of space in which the similarity between movements is determined. Existing approaches have suggested a motor space [1] or a supra-modal, abstract space [2]. In this work we take a different approach: we focus on a visual space, treating imitation as a problem of maximizing the visual similarity between observed and executed movements. Using a visual space allows as to circumvent the 'correspondence problem' – the mapping between the motor space of the demonstrator and the motor space of the imitator.

We developed and tested a computational model of movement imitation. Our goal was to provide a proof-of-concept for the idea of imitation via visual similarity. Our model provides a general solution to the problem of movement imitation, requiring only a forward kinematic model of the imitator.

Our model has two main components. First, given a new pose of the demonstrator we search in the motor space of the imitator for the pose that will maximize the visual similarity between the poses of the demonstrator and the imitator. The search is performed using standard optimization algorithms. We use a forward model of the imitator, converting a set of motor commands (e.g. joint angles) to the resulting image of the imitator. In practice, we use a graphical simulator of the imitator. The second component is the visual similarity function, measuring the similarity between the silhouettes of the demonstrator and the imitator.

We have developed and tested our model using three scenarios: (1) virtual-virtual: imitating a virtual humanoid with another virtual humanoid, (2) real-virtual: imitating a real human with a virtual humanoid and (3) real-robot: imitating a real human with a 5-DOF robotic arm. Results from the three scenarios will be presented.

The proposed method suggests a new approach to robotic movement imitation. In addition, successful movement imitation via visual similarity in robotic might suggest a new candidate for the mechanism underlying human movement imitation.

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Gesture Language for Man-Computer Interfaces

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The goal of this research was to develop and implement a gesture-based language and an interface as an alternative to the traditional keyboard, menu, and direct manipulation interfaces.
The first step of the research involved the definition of a gesture-based language. The main purpose of the language is to use it in interactions with objects in a virtual reality environment. In considering gesture-based interaction with a computer, it is important to understand the role of gesture in human-to-human communication. Hence, our research was based on psychological and anthropological studies in this field. Sign language research was also used as a source of information. On the other hand, gesture-based language must adopt relevant linguistic concepts.

Hence, in the language design process, we relied on notions derived from computational linguistics and natural language processing.
Finally, we wished to include gestures that are easy to perform. In choosing such gestures we relied on ergonomics and on biomechanical research of hand movements.
For the implementation of the gesture-based language, 15 dynamic gestures were used. These gestures were recorded using the CyberGlove device (23 sensors). For a successful interface with the computer, a novel approach to gesture recognition was suggested. In particular, a classifier based on information theory techniques was developed. The classifier takes into account kinematic features of finger movements. For each gesture a template containing the set of most informative features was constructed. The set was extracted from the entire input data using mutual information criteria. In this classifier, applied to our data set, a recognition rate of 100% was achieved.

Are parabolas movement primitives? Are movements represented by an equi-affine metrics? Geometric and neurophysiological studies.

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In this study we have analyzed the kinematic properties of monkey scribbling movements and the underlying activities of motor cortical units recorded over several consecutive experimental sessions.

We showed earlier that a parabolic segment is the unique common geometric template of both the constrained minimum-jerk and the two-thirds power-law models that is invariant under arbitrary equi-affine transformations. The kinematic analysis of well-practiced monkey drawing movements and their decomposition into basic parabolic strokes has yielded 3-4 different clusters of parabolic segments, each cluster being defined in terms of the direction of the main axis of the parabola. Parabolas are known to have zero equi-affine curvature and to be geodesics that maximize the equi-affine length in equi-affine plane (Handzel and Flash, 1999).

The comparison of the monkey trajectories during which the monkey did or did not receive a reward has indicated that receiving a reward influences the characteristics of the monkey drawings, thus suggesting that the scribbling strategy that the monkey has adopted following sufficient practice is based on a reward-related decision which movement primitive to generate. We define a movement primitive as an indivisible movement stroke that cannot be intentionally stopped after it has been initiated. During several experimental sessions, the monkey tended to decelerate and stop at a specific part in the workspace after it had received a reward at certain locations. The corresponding movement paths between the rewarding times and the end of the stroke resembled parabolic segments. We found that the activity of several motor and dorsal premotor cortical units was influenced by receiving a reward.

To analyze the neuronal data, several techniques were applied. Using the partial cross-correlation method (as in Stark et. al., 2006) we found that equi-affine velocity was represented more strongly than the Euclidian speed in the activity of several recorded units.

HMM modeling was used in order to implement an unsupervised state-dependent segmentation of the neural activities obtained from a number of recording sessions. Movement segments corresponding to the identified states of neuronal activation resulted in clusters of similar geometric shapes, most of them parabolic. In one such recording session, the segments were also related to the time of getting reward.

Thus, both behavioral and neurophysiological analysis supports the notion that parabolic segments constitute geometrically defined motion primitives subserving the construction of scribbling movements. We have also provided the first direct evidence for the possibility that equi-affine geometry is used in the neural coding of arm movements.

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Keywords: decision-making; geometry; HMM; metric; models of biological motion; motion primitives; motor cortex; motor learning; parabolas; partial cross-correlation; segmentation.

The transition from a closed to an open kinetic chain exercise: A biomechanical and physiological view

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Introduction: It has been reported that triathletes experience a loss of coordination during the transition from cycling to running. When researching this phenomenon, Chapman and Hodges (1) detected an altered EMG pattern of the Tibialis Anterior. This pattern was found similar to the typical EMG pattern of cycling, showing that cycling has a direct influence on the following running phase. Our belief is that during the transition phase, the movement is not optimally controlled by the CNS, and reflex activity is impaired. Under such conditions, the athlete is more susceptible to injuries.

Objective: Finding the parameters that influence the adaptation phase between the two tasks will give us a better understanding of the CNS, and how it copes with a transition from a closed to an open kinetic link exercise. On a more practical note, optimal parameters which minimize the transition phase can be used in the design of external devices such as insoles.

Methods: A model developed by Derrick, Caldwell and Hamill (2) was adapted. Measurements of corresponding input-GRF, and output-the location of the leg's center of mass are taken. Using parameter estimation, the stiffness and damping parameters can be found.

In order to validate the model, a signal composed of GRFs of cycling followed by running was fed to the MATLAB realization of the model. The output was further studied using wavelet analysis. EMG signals measured from athletes conducting 20 minutes of cycling followed by running were also wavelet analyzed.

The model can be verified if the transition time from the EMG corresponds to the transition time of the model simulation.

Results: Preliminary results show the stiffness and damping parameters differ between the subjects and the tasks. EMG data analysis exhibits clear adaptation phase.

Conclusions: Further work needs to be done concerning the matching of measured and simulated adaptation times.

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The Point of No Return in Planar Hand Movements: An Indication to the Existence of High Level Motion Primitives

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Previous psychophysical studies have sought to unravel whether the processes of movement engagement and termination are dissociable, whether stopping an action is a generic process, and is there a point in time in which the generation of a planned action is inevitable ("point of no return"). Moreover, recent surface EMG studies have attempted to locate the anatomical locus in the central and peripheral nervous system beyond which the intended action must be produced. It is not clear yet, however, whether the action of stopping is merely a manifestation of low-level, dynamic constraints, or is it also subject to high-level, kinematic plan. In the present study, stopping performance was studied while 10 subjects, who generated free scribbling movements looking for the location of an invisible circular target, were requested unexpectedly to impede moving. Temporal analysis of the data shows that in 87% of the movements, which superseded the stop cue, the tangential motion velocity profile was not a decelerating function of the time but exhibited a complex pattern that comprised of one, or more, velocity peaks. Furthermore, geometrical analysis shows that the figural properties of the path, generated after the stop cue, were part of a repetitive geometrical pattern. Altogether, these findings imply that the "point of no return" phenomenon in humans reflects a high level, kinematic plan and may serve as a new operative definition for the notion of motion primitives.

Kinematic features of locomotor behavior in chimeric mice with various proportions of intact Purkinje cells in the cerebellum.

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Genetic lesions that affect cerebellar function display graded levels of ataxia dependent on the severity and specific cerebellar cell types involved. We have combined the use of experimental chimeras of the cerebellar ataxic lurcher (Lc/+) mutant with a robust and replicable behavior analysis approach (SEE, software supported Strategy for the Exploration of Exploration) to determine the influence of cerebellar Purkinje cells on the kinematics of locomotor behavior.

Lurcher chimeras (with various proportions of ataxic lurcher and Wildtype cells) provide a useful animal model in which we can generate mice with varying numbers of Purkinje cells that then can be correlated with behavior.
SEE provides an analysis of natural behaviors in a large circular arena yielding several dozens of kinematic measures (endpoints) of free locomotion.

We have assessed locomotor and exploratory behavior of Ataxic (Lc/+), Wildtype (+/+), and Chimeric (LCx) mice using SEE endpoints and correlated them with cerebellar Purkinje cell numbers. In this manner we determined the contribution of Purkinje cell function to the expression of relevant kinematic behaviors.

Our results show that many kinematic measures differentiate between Wildtype and Ataxic mice. In particular, acceleration during progression segments is lower in the ataxic mice, and the mean speed of movements during investigation of the proximal environment (scanning movements) is higher in the ataxic mice.

Plotting the magnitude of the kinematic measures against the number of Purkinje cells in the cerebellum reveals that the transition between normal and Ataxic behavior is threshold dependent, occurring at around 10% of the normal Purkinje cell number in Wildtype mice. The results also suggest that different measures require a different number of intact Purkinje cells for achieving Wildtype values: for example, total distance traveled per session and path curvature require a smaller number of these cells, while acceleration and mean speed of scanning movements require a larger number.

Optimal Control Theory Predicts Complex Patterns of Neural Activity Observed in the Primary Motor Cortex

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What determines the specific pattern of activation of primary motor cortex (M1) neurons in the context of a given motor task? We present a systems level physiological model describing the transformation from the neural activity in M1, through the muscle control signal, into joint torques and down to endpoint forces and movements. The redundancy of the system is resolved by biologically plausible optimization criteria. The model explains neural activity at both the population, and single neuron, levels. Due to model's analytic tractability and mechanistic explicitness, it provides intuition as to the most salient features of the system, as well as a possible causal explanation of how these determine the overall behavior. Moreover, it explains a large number of recent observations, including, the temporal patterns of single-neuron and population firing rates during isometric and movement tasks, narrow tuning curves, non-cosine tuning curves, changes of preferred directions during a task and changes of preferred directions due to different experimental conditions.

Robust satisficing approach to neural decoding

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One of the challenges of Brain Machine Interfaces is estimating the transformation from neural activity to motion parameters. This transformation is highly uncertain since it may change during the operation of the Brain Machine Interface. In addition neural activity contains large amount of "noise", which hinder the estimation of motor signals.

It is customary to use simple linear models since other methods, including non-linear neural networks and Kalman filters, do not provide consistent improvements. While linear regression techniques are well developed, their applicability to problems with severe uncertainties is still a challenge.

Linear regression is usually performed to derive a model that can be used to make predictions of the future, and should therefore be designed to confront future surprises.
In particular, standard regression techniques are based on optimizing performance for data used to estimate the model – "past data", but they may fail to provide high, or even acceptable, performance for new observations which comprise noise and surprises- "future data". A common way to treat noisy data is Regularization Techniques. But the choice of the regularization technique and parameter is not easy under severe uncertainties.

Here we develop an alternative regression methodology based on satisficing rather than optimizing the performance criterion while maximizing the robustness to uncertainties. This approach may facilitate comparison and selection of proper regularization technique and regularization parameter to provide the highest robustness to future uncertainties. The technique is developed in the framework of information-gap theory, which describes uncertainties as unbounded family of nested sets of measurements parameterized by a non-probabilistic horizon of uncertainty.

The technique is demonstrated for predictions of movement velocity from neuronal data from cortical motor areas during experiments with Brain Machine Interfaces. We demonstrate that the robust-satisficing solution is different from the optimal least squares solution and provides higher robustness to uncertainties.

Central control of stereotypical movements of the octopus arms

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The nervous system of the octopus is uniquely divided into a centralized brain and an elaborated peripheral nervous system. Several lines of evidence suggest that a significant part of the arm motor functions are rather autonomous, both in processing sensory information and in executing stereotypical arm movements (e.g. Sumbre et al. 2001). To understand the control relationships between the central brain and the peripheral nervous system of the arms, micro-wire electrodes were implanted in the higher motor centers (basal lobe system) and glued to the brain capsule allowing recording and micro-stimulation in freely behaving animals.
Stimulations led to a variety of whole body movements. To understand the central control of arm movements here we analyzed the centrally evoked arm extensions. Stimulating widely spread loci throughout the higher motor centers, induced arm extensions simultaneously in several arms. This result suggests that individual arms are not somatotopically represented at the level of the higher motor centers. Typically for arm extension the evoked movements involved a forward propagation of a bend along the arm, ruling out the possibility that the stimuli activated directly the arm’s muscles. As in natural arm extensions, the evoked ones were confined to a single linear plane and had bell shaped velocity profiles with an invariant accelerating phase. In a sharp contrast to the triggered extensions obtained in denervated or amputated arms (Sumbre et al. 2001), the accelerating part of the centrally evoked movements usually continued only as long as the stimulation train was on, and thus the duration of the centrally induced extensions were positively correlated with the duration of the stimulating train (R^2 0.746, $F_{(1,13)}$= 38.261, $P<0.0001$, n=15).
Taking together these results suggest that while the peripheral extension motor program is centrally controlled, an additional ‘gating mechanism’ (which is open as long as the stimulation train is on) adjusts the movement duration.
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