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

June 11, 2009, W.A. Minkoff Senate Hall, BGU
Marcus Family Campus, Beer-Sheva, Israel

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

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

Program

Sunday – Wednesday, June 7-10, IAS-ISF workshop in Jerusalem – see www.as.huji.ac.il

Wednesday, June 10 Welcome Dinner

Thursday, June 11

8:20-8:50 Registration, poster placement and coffee

8:50-9:00 Greetings – **Dr. Amir Karniel**, head of the organizing committee, BGU

9:00-9:10 Opening remarks – **Prof. Rivka Carmi**, President, BGU

Principles of motor control

Chairperson: Prof. Gideon Inbar, Technion, Israel

9:10-9:40 **Prof. Kenji Doya** – Neural Computation Unit, Okinawa Institute of Science and Technology, Japan
Multiple representations and algorithms for motor learning and control

9:40-10:10 **Prof. Olivier Sigaud** – Institut des Systèmes Intelligents et de Robotique Université Pierre et Marie Curie, Paris, France
An Operational Space Control Approach to Motor Learning

10:10-10:20 Discussion

10:20-11:00 Posters and coffee

Laws of motor control

Chairperson: Prof. Ferdinando A.(Sandro) Mussa-Ivaldi, Northwestern University, Chicago

11:00-11:30 **Prof. Kurt Thoroughman** – Washington University, St. Louis
The delta rule, adaptation, and human motor behavior

11:30-12:00 **Prof. Tamar Flash** – Weizmann Institute of Science, Israel
On desired trajectories and compositionality: geometry, kinematics and dynamics

12:00-12:30 **Dr. Tzvi Ganel** – BGU
Weber's law in grasping

12:30-12:40 Discussion

12:50-14:40 **Posters and lunch**

Action-perception coupling

Chairperson: Prof. Anatol Feldman, U. Montreal, Canada

14:40-15:10 **Prof. Pieter Medendorp** – Radboud University Nijmegen, The Netherlands
Spatial constancy mechanisms in perception and action

15:10-15:40 **Prof. Randy Flanagan** – Queen's University, Ontario, Canada
Representations of objects used in action and perception

15:40-16:10 **Prof. Jeroen Smeets** – VU University, Amsterdam, The Netherlands
Combining depth cues for arm movements

16:10-16:20 Discussion

16:20-16:30 **The Alpha Omega, Sensegraphics and NanInstuments Best poster and Travel Awards**

16:30-17:00 Posters and coffee

Physiology of motor control

Chairperson: Prof. Eilon Vaadia, Hebrew University, Israel

17:00-17:30 **Dr. Opher Donchin** – BGU
Combining theory and experiments in our approach to the cerebellum

17:30-18:00 **Prof. Stephen Scott** – Queen's University, Kingston, Ontario, Canada
Statistical models of the limb in primary motor cortex

18:00-18:30 **Prof. Tim Ebner** – University of Minnesota, Minneapolis, USA
Searching with an Electrode for Internal Models in the Cerebellum

18:30-18:40 Discussion

20:30 **Dinner and discussion**

Friday, June 12, 9:00-14:00, Desert hike

Guide – Eitan Krokovski

Dear Colleagues,

In what has now become a tradition, we wish to invite you to participate in the fifth annual **Ben-Gurion University Workshop on Computational Motor Control** on **June 11, 2006**, in the W. A. Minkoff Senate Hall at Ben-Gurion University of the Negev, Beer-Sheva, Israel. The following information is also available on our website: http://www.bgu.ac.il/cmcw

This year we are also having **a companion meeting** titled **Israel Motor Days in Jerusalem** on **June 7-10**, which will require a separate free registration at http://www.as.huji.ac.il

Thank you for your attention,
Opher Donchin and Amir Karniel
donchin@bgu.ac.il; akarniel@bgu.ac.il

Winter in the Negev

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.

Best Poster Award: The award committee will choose the best poster(s) which will be announced at the end of the day. The Best Poster Award Committee: Opher Donchin, Ben-Gurion University, Sandro Mussa-Ivaldi, Northwestern University – Chicago, and Anatol Feldman, University of Montreal - Canada.

Dinners: We will have a festive welcome dinner on the evening of June 10, before the workshop. 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 90 NIS per person. We will also have a more modest dinner and discussion in the evening following the workshop. Subsidized cost (other than speakers and chairmen) will be no more than 50 NIS per person.

Tour to the Negev: On Friday, June 12, we plan a trip to the Negev, cost per-person will be no more than 150 NIS (approx. $40), registration and payment (cash only) to the trip will be done during the morning of June 11 at the workshop registration desk. Price includes the cost of lunch.

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

The desert in motion

 Photo: Ilya Borovok, Google Earth

The desert hike

Dear friends:

On Friday the 12th of June, we will continue the CMCW tradition and enjoy an "experiential taste" of the Negev desert. This year we will tour the "Great crater," a unique natural phenomenon that is one of seven of its kind in the world.

Our visit in the Crater will take us on a journey through time including fossil trees, a water spring, colorful sandstone and beautiful view points. We will have lunch at a homestead a few minutes of drive from the desert town of Yerucham.

Meeting time: 08:45 A.M. Bus leaves at 9:00 A.M. sharp.

Meeting place: The Golden Tulip Hotel

*What to bring: Back pack, sunscreen, a hat, comfortable shoes and clothes, bathing suit beneath-**optiona**l if there will be water in the spring.*

Cost: 150NIS

We will return to the Golden Tulip at approximately 14:30 P.M., and from there the bus will continue to Tel Aviv.

See you then
Eitan (the tour guide)

Talks

Multiple representations and algorithms for motor learning and control

Kenji Doya

Okinawa Institute of Science and Technology

Motor control skills can be represented in multiple spaces, such as visuospatial or somatosensory spaces, using multiple algorithms, such as model-free reinforcement learning and model-based sequence planning. We will first review the motor control studies and present a working hypothesis that the cortico-basal ganglia loop realizes model-free reinforcement learning and its combination with the internal models implemented in the prefrontal cortex and the cortico-cerebellar loop can implement model-based sequence planning. Different sub-loops of the cortico-basal ganglia and cortico-cerebellar loops are recruited for learning and control using different representations. We will then present our on-going work to test such hypotheses. In the "grid sailing" task, subjects moved the cursor on a 5x5 grid to a goal position by sequentially pressing three keys either with or without a few seconds of delay period after the goal presentation. The behavioral result showed that the subjects utilized pre-learned internal models that predict the result of imaginary actions during the pre-start delay period. The functional brain imaging result showed that the network linking the prefrontal cortex and the anterior part of the basal ganglia are activated during the model-based sequence planning.

References:

Doya K (1999). What are the computations of the cerebellum, the basal ganglia, and the cerebral cortex. Neural Networks, 12, 961-974.

Hikosaka O, Nakahara H, Rand MK, Sakai K, Lu X, Nakamura K, Miyachi S, Doya K (1999). Parallel neural networks for learning sequential procedures. Trends in Neurosciences, 22, 464-471.

Bapi RS, Miyapuram KP, Graydon FX, Doya K (2006). fMRI investigation of cortical and subcortical networks in the learning of abstract and effector-specific representations of motor sequences. Neuroimage. 32, 714-727.

Doya K (2007). Reinforcement learning: Computational theory and biological mechanisms. HFSP Journal, 1(1), 30-40. Free on-line access:http://dx.doi.org/10.2976/1.2732246

Rodrigues A: (2008). Model-free and model-based reinforcement learning strategies in the acquisition of sequential behaviors. Master's thesis, Nara Institute of Science and Technology.
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An Operational Space Control Approach to Motor Learning

Olivier Sigaud

Institut des Systèmes Intelligents et de Robotique Université Pierre et Marie Curie, Paris, France

I will present a motor learning model based on Operational Space Control, first at the velocity kinematics level and then at the dynamics level. I will show that motor adaptation capabilities can be modeled with a simple forward dynamics model learning process. Finally, I will explain how Reinforcement Learning processes can be included into the model to give account of a wider range of phenomena.

The delta rule, adaptation, and human motor behavior

Kurt Thoroughman

Washington University, St. Louis

Many theories of neural adaptation arise from the classic delta rule, which postulated learning of appropriate interneuronal connections based on a minimization of error. This presumption led to theories that postulated weight changes dependent on both the real value of error and on the tuning curves of the presynaptic neurons. I will review the development and impact of the delta rule on theories of motor adaption, consider the inability of these theories to explain behavior measured in our lab, and posit new theories of learning that enable more flexibility in the learning process.

On desired trajectories and compositionality: geometry, moving coordinate frames and kinematics.

Tamar Flash

Dept of computer Science and Applied Mathematics
Weizmann Inst. of Science, Rehovot, Israel.

In recent years, several research studies have argued against the notion that movement generation involves planning and representation of desired trajectories and motion plans. Although these studies have suggested instead that movement generation involves the use of optimal feedback control schemes, most of these studies have not provided sufficient evidence against the idea that the brain does indeed store and represents preferred motion plans, based on both ontogeny and/or learning through skill acquisition. Moreover, most of the arguments against the existence of desired trajectories were based on studies dealing with 2D reaching movements for which the goal of the movements is simply to reach an external target and not to move along prescribed movement paths. Here I will discuss observations derived from a series of behavioral and modeling studies focusing on 2D hand drawing and locomotion trajectories. These studied have demonstrated that the velocity profiles of the generated trajectories are rather stereotypical and that movement speed is tightly dependent on the geometrical characteristics of the generated movement paths. To account for these observations, I will describe the results from recently combined theoretical and experimental studies (Bennequin et al., in press).
These studies were aimed at examining several fundamental questions with respect to the planning and representation of complex trajectories and to account for the kinematic and temporal invariants characterizing these walking and drawing movements. The observed invariants include the isochrony principle and the coupling between movement speed and curvature, partially captured by the two thirds power law. The new theory aims at suggesting how the brain selects movement duration and what the nature of the underlying motion primitives is.
The new theory is based on the notion that motor timing emerges as a result of the use of a tensorial mixture of several geometries where in each geometry movement time is proportional to a measure of distance specific to that geometry. These geometries are the Euclidian, affine and equi-affine geometries and the mathematical approach employed for predicting specific trajectories for given paths is based on the Cartan's moving frame method. Evidence for the plausibility of the proposed theory and its implications with respect to neural motor representations will be described and the possibility of combining this theory with models based on optimality principles will also be discussed.

Bennequin, D., Fuchs, R. Berthoz A. and Flash, T. (2009) "Movement timing and invariance arise from several geometries", Plos Computational Biology, In Press.

Weber's law in grasping

Tzvi Ganel

Ben-Gurion University of the Negev

According to Weber's law, a fundamental principle of perception, sensitivity to changes in magnitude along a given physical dimension decreases when stimulus magnitude increases. In other words, the increment needed in order to detect a change - the Just Noticeable Difference (JND) - is smaller for weak stimuli compared to stronger stimuli. Although Weber's law governs human perception for visual dimensions, including visual length, there have been no attempts to test its validity for visually-guided action rather than for perception. Based on the notion that visually-guided action and perception are mediated by distinct neuroanatomical systems, we hypothesized that Weber's law does not necessarily hold for visually-guided action. In order to test this idea, we asked observers to either grasp or make perceptual estimations of length for objects varying in length. These measurements served to measure the JND of these two functions of vision. For perceptual tasks, we found that the JND increased with object size in accordance with Weber’s law. For grasping, however, the JND remained invariant across different sizes of objects, violating Weber’s law. In a series of follow-up experiments, we tested the presence of Weber's law in memory-based grasping and in grasping under open-loop conditions. We also found evidence for overall increased resolution for object size in grasping as compared to perception. Our findings reinforce the presence of a basic dissociation between the way object size is computed for perception and for action.

Spatial constancy mechanisms in perception and action

W.P. Medendorp

Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, The Netherlands.

When we navigate through the environment, complex changes occur in the optic flow that hits the retinas in the back of our eyes. Yet, we are not aware of these continuous changes in retinal input; instead we perceive the world as a seamless, stable reality and have an integrated sense of where we are. This ability requires continuous monitoring of intervening movements and subsequent computations that combine this information with (remembered) visual input. Recent studies on the retinal image shifts caused by rapid eye movements have suggested that the brain corrects for these perturbations by remapping the neural image. But eye movements are a simple, special case as compared to challenges faced by the brain to keep spatial constancy and produce suitable motor plans during real-life motion, such as head, trunk and whole-body movements. Can the remapping hypothesis also explain the effects of body translations, like when walking or driving a car, on the perceived location of objects in both direction and depth? Does the remapping hypothesis also apply in interception, when representations of moving targets must be maintained during self-motion? This talk will address these and related questions. I will outline the results of recent studies testing the mechanisms for spatial constancy in more challenging conditions, involving other eye movement systems (vergence), other modalities (body movements), and in dynamic environments (moving targets).

Representation of Object using in Action and Perception

Randy Flanagan

Department of Psychology and Centre for Neuroscience Studies, Queen's University, Canada

Skilled object manipulation requires the ability to estimate, in advance, the motor commands needed to achieve desired sensory outcomes as well as the ability to predict the sensory consequences of the motor commands. Because the mapping between motor commands and sensory outcomes depends on the physical properties of grasped objects, the motor system must have knowledge (i.e., an internal model) that enables the prediction of these properties. The first part of this talk will deal with the how this knowledge is acquired and represented. Recent work suggesting that object dynamics can be flexibly represented in different coordinates frames will be discussed. A number of recent studies, including our own, have provided evidence that representations of objects used to guide action are distinct from representations of the same objects used to make perceptual judgments. The second part of the talk will describe experiments showing that representations of object weight, used when lifting objects, are independent and distinct from representations used when judging weight in a perceptual task. The question of why people maintain separate representations for action and perception will be addressed.

Combining depth cues for arm movements.

Jeroen Smeets

VU University, Amsterdam, The Netherlands

Information about the world is in general redundant. We have several modalities (e.g. vision, touch), and within a modality various attributes (e.g. egocentric position and allocentric size) and for a single attribute various cues (in vision for instance retinal cues such as linear perspective and binocular disparity). How do we decide how to use these sources of information? A key to understanding is to realise that subjects might want to perform optimally, i.e. as precise as possible. The choice of attribute to control might be based on precision. For instance, given the sensory resolution, grasping will be more precise if it is based on position information than on size information (Smeets & Brenner, 2009). If multiple cues are available, it has been argued that we use a weighted average of the available cues, and that we choose the weights in such a way that the variance in the weighted average is minimal. If this strategy of 'optimal combination' would be used, one would expect that precision is independent of whether the cues specify the same value or are in conflict. This is indeed the case (Muller et al., 2009). Furthermore, if the cues are in conflict, optimal combination predicts that it would not matter which cue is veridical. We here show that the latter is not true: systematic errors can lead within a few trials to a change in cue weights. We conclude that systematic errors play an important role in the choice of cue weights, and that optimal behaviour entails more than reducing variance.

Muller CMP, Brenner E, Smeets JBJ (2009) Testing a counter-intuitive prediction of optimal cue combination. Vision Res 49: 134-139

Smeets JBJ, Brenner E (2008) Grasping weber's law. Curr Biol 18: R1089- R1090

Combining theory and experiments in our approach to the cerebellum

Opher Donchin

Ben-Gurion University of the Negev

By examining adaptation, substantial progress has been made towards understanding how reaching movements are controlled and theories have been developed about how the different parts of the brain interact in producing this control. I will examine, specifically, the role of the cerebellum in the control of reaching movements and the extent to which it can be seen as part of a larger control framework. Based on theoretical considerations, results from healthy human subjects, and cerebellar patients, I will argue that the two different parts of the cerebellum that represent the forelimb have different roles in the control of the limb. I will argue that it is possible that one of them is responsible for predictions at the level of abstract goals while the other is responsible for assisting in the translation of those goals into specific motor commands.

Statistical models of the limb in primary motor cortex

Stephen H. Scott, Tim Lillicrap

\Centre for Neuroscience Studies, Queen's University, Kingston ON K7L 3N6 Canada

The activity of primary motor cortex (M1) neurons recorded in non-human primates during sensorimotor tasks show consistent preferences at the population level for certain directions of hand movement and combinations of joint torques. Where do these biases in preference come from, and what is their functional significance? It has been hypothesized that these preferences may develop as a result of biases in spatial experience, e.g. from having more experience reaching away and toward than left or right, akin to how orientation biases are thought to emerge in primary visual cortex (V1). But, it is known that upper limb muscles show trends in their distribution of preference similar to those observed for M1 neurons, so it also seems reasonable to hypothesize that the observed biases are related to the mechanical and anatomical properties of the limb. My presentation will describe whether and how the organization of recurrent neural networks trained to perform sensorimotor tasks were influenced by prior experience and different anatomical and physiological features of the musculoskeletal system. Our results demonstrate that the influence of biased spatial experience is small. On the other hand, we found that limb geometry (i.e. the geometric mapping from joint-angles to hand position), and the existence of bi-articular muscles (i.e. muscles which span both shoulder and elbow joints) created biases in preference that parallel the patterns observed in recorded M1 neurons. This suggests that the physical properties of the limb have a profound impact on neural processing in M1.

Searching with an Electrode for Internal Models in the Cerebellum

Tim Ebner, Siavash Pasalar, Alexander Roitman, and Angela Hewitt,

University of Minnesota.

Feed forward control and estimates of the future state of the motor system are critical for the control of limb movements. One framework for generating these predictive signals is based on the central nervous system implementing internal models. Internal models provide for representations of the input-output properties of the motor apparatus or their inverses. The cerebellum has been hypothesized to acquire and store internal models of the motor apparatus. The results of functional imaging and transcranial magnetic stimulation studies in normal subjects support this hypothesis. The deficits in patients with cerebellar dysfunction have been attributed to a failure of predictive feed forward control and/or to accurately estimate the consequences of motor commands. Furthermore, the computation performed by cerebellar-like structures is consistent with predicting the sensory consequences of motor commands. However, there have been limited studies that directly test whether neurons in the cerebellar cortex have the requisite signals compatible with either an inverse or forward internal model. Our previous study in the monkey performing manual pursuit tracking under various force fields and loads demonstrate that the simple spike discharge of Purkinje cells does not encode the dynamics-related signals required to be the output of an inverse dynamics model. However, recent studies of Purkinje cell firing during both tracking and reaching movements show that these cells have several of the characteristics expected of the output of a forward internal model of the arm. These include a robust representation of limb kinematics that leads the movement and is largely independent of the motor task. Purkinje cell simple spike discharge also encodes the requisite error signals. Therefore, the evidence suggests that the cerebellum is involved in integrating the current state of the motor system with internally generated motor commands to predict the future state.

Posters

Sorting Cerebellar Purkinje Cell's Spikes

Yoav Aminov and Opher Donchin

Ben-Gurion University of the Negev

Motor Learning Laboratory, Biomedical Engineering Department, Ben-Gurion University. Many studies in the field of neuroscience depend on the analysis of neuronal spiking activity recorded under various behavioral conditions. Recent advances in available acquisition systems allow recording of hundreds of channels simultaneously, and the reliability of these data critically depends on accurately identifying the activity of individual neurons. However, there is still much to do in the field of developing efficient and reliable computational methods for classifying neuronal spiking activity, or in other words – spike-sorting algorithms.

One limitation is the use made by most spike sorting systems on the linear principle components analysis (PCA). An alternative that has been suggested [R. Quian Quiroga, Z. Nadasdy and Y. Ben-Shaul, 2004] is to use a wavelet transform to generate spike features. We tested whether this approach could improve spike sorting in the specific context of identifying simple and complex spikes in cerebellar cortex. Using an existing spike sorter developed at Masters MC, Rotterdam, we compared spike sorting perfomrance on real and simulated data collected from cerebellar cortex. Our findings indicate a substantial improvement when using the wavelet transform in preference to the PCA for selecting spike features.

Key words: spike-sorting, action potential, extracellular neural recordings, spike detection, spike classification, cerebellum, PCA, wavelets transform, probabilistic neural network.

Forward model adaptation is not sufficient for force field adaptation in optimal feedback control

Jonathan Aprasoff and Opher Donchin

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

Optimal feedback control (OFC) has become popular in recent years as a model of motor control. Computational models based on OFC framework reproduce experimental results involving force field perturbations of reaching movements. For instance, using optimal control it was possible to explain the curved trajectories that people produce in force fields, a result that was not predicted by earlier models.

The site of plasticity during adaptation to force fields is still being debated. There are reasons to believe the cerebellum is the main site of adaptation, but the motor cortex and other areas have also been suggested as important alternatives. The OFC model ascribes to the cerebellum the estimation of future state; that is, it predicts that the cerebellum calculates a forward model. Naturally, when movements are made in altered dynamics, the forward model must adapt to incorporate the new dynamics. It is not clear, however, whether such adaptation is sufficient to produce optimal trajectories in the new dynamics. In order to test this question, we fitted an OFC model with a linear adaptive forward model.

Our results show that forward model adaptation alone cannot account for the production of optimal trajectories under force field perturbations. Thus, if OFC is a reasonable representation of the motor control system in the CNS, cerebellar adaptation alone is insufficient. We conclude that the motor cortex, the proposed site of the feedback controller, also takes part in adaptation.

This research was supported by the Binational Science Foundation.

Sensory feedback alters the computation of directional signals by the motor cortex

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Learning new motor skills entails the ability to incorporate relevant information for adapting movements to novel environments. Indeed, humans use different strategies when adapting to a novel dynamic load depending on the available sensory feedback. Yet, the mechanism by which motor cortex incorporates feedback to control actions during adaptation remains unknown. Here, we examined neurons' activity in motor cortex when monkeys reached for a visual target and adapted to force-fields with or without visual feedback. We found that the activity of subpopulations of cells was preferentially enhanced or reduced depending on their directional tuning. While this was observed under both feedback conditions, the final output - the population directional signal - was altered by feedback via differing proportions of modulated cells. This may account for the influence of feedback on the choice of learning strategy. Furthermore, the results provide electrophysiological evidence for the neuronal elements involved in computing motor outputs and explain previous results related to neuronal tuning and to the nature of generalization of learning in humans.

This work was supported in part by the US-Israel Binational Science Foundation (BSF), by the Israeli Science foundation (ISF), and special contributions by the Rosetrees Trust and the Ida Baruch fund. EV is the Jack H. Skirball Chair of Brain Research.

Exploring the Rhythmic Nature of Handshake Movement and a Turing-like test

Guy Avraham, Shelly Levy-Tzedek and Amir Kaniel

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

We design a Turing-like handshake test, for motor intelligence, administered through a telerobotic system. Instead of asking the subject whether the other party is a person or a computer program, we employ a forced-choice method that asks which of two systems is more human-like. By comparing the developed model with a weighted sum of human and artificial systems, we construct a psychometric curve and extract a quantitative grade for the artificial system in terms of similarity to the human handshake. The test subject is engaged in a task of holding a robotic stick and interacting with another party (human, artificial, or a linear combination of the two).

In this poster we present initial results on the rhythmic nature of the human handshake. Human movements can be classified as rhythmic or discrete. Participants (3 young adults) were asked to perform handshake motions when holding the stylus of a Phantom® haptic device which enabled us to track their position. We analyzed their motions in terms of smoothness, harmonicity, frequency and amplitude. We found that the handshake motion is rhythmic in its nature rather than discrete.

Based on these results, we hypothesized that a robotic handshake model which implements the rhythmic characteristic of the motion would be perceived as more human-like than a model that lacks this characteristic.

Our preliminary results suggest that a mechanical model of a handshake that includes a rhythmic power source is perceived as more human-like than a passive model that lacks it.

Further iterations of the Turing-like handshake test are expected to unravel additional basic properties of human perception and motor interaction, with important implications for medical diagnostics, artificial limbs, telerobotics and medical robotics.

We intend to organize a computer tournament during one of the next Annual BGU Computational Motor Control Workshop to compete on the best simulated handshake and the best discrimination program to develop a controller for the PHANTOM® Desktop™ that will generate handshake behavior indistinguishable from that of the human handshake.

This research was supported by the Israel Science Foundation (grant No. 1018/08). SL is a Kreitman Foundation postdoctoral fellow.

Expression of emotions in human locomotion – Effects of speed

Avi BARLIYA*[†], Lars OMLOR[‡], Martin A. GIESE[‡], Alain BERTHOZ[§], Tamar FLASH[†]

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Keywords: locomotion; coordination; kinematics; intersegmental; emotion

Emotion manifests itself in various aspects of human behaviour. Emotion is accompanied with facial expressions, changes in voice tones, body expressions and several physiological parameters such as sweat and heart-bit rate. In this study we focus on how the kinematics of locomotion is affected by different emotions. The space of kinematics parameters by which locomotion can be characterized is rather large.
We focused on a compact representation of locomotion properties through the use of the inter-segmental law of coordination (Bianchi et al., 1996). The law states that during human locomotion the elevation angles of the thigh, shank and foot do not evolve independently of each other during the gait cycle but form instead a planar pattern of co-variation. That phenomenon is highly robust and has been extensively studied. Particularly, the orientation of the plane has been correlated with changes in speed of locomotion, and with reduction of energy expenditure as speed increases. An analytical model that explains the conditions underlying the emergence of the plane and predicts its orientation, reveals that it suffices to look at the amplitudes of the elevation angles of the different segments along with the phase-shifts between them (Barliya et al., 2009). Given its success in accounting for the features of neutral locomotion, the model was used to investigate the influence that different emotions (happiness, fear, sadness and anger) have on the kinematic features of human locomotion.
We were interested in characterizing the effects that the different emotions have on the parameters that directly determine the orientation of the inter-segmental plane and on the forms of the leg segments angular rotation profiles. We present here the results of our study which was conducted in two subject groups: professional actors and subjects with no training in acting. Emotions were found to strongly affect the kinematics of locomotion.
Emotion, however, is also known to affect speed of movement. We therefore suggest a method that can be used in establishing whether changes in the inter-segmental coordination patterns are simply a by-product of changes in speed or whether they reflect additional modification in the locomotion patterns that can be directly attributed to the emotional state.

Acknowledgments:
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A simple and accurate onset detection method for a measured bell-shaped speed profile

Lior Botzer and Amir Karniel

The computational motor control laboratory,
Department of Biomedical Engineering, Ben-Gurion University of the Negev, Israel

Motor control neuroscientists often measure the trajectories of the limb and extract the onset of the movement for various purposes. The gathered trajectories are often aligned relative to the individual movement onset before the movement features are extracted and their properties are inspected. The onset detection is performed either manually or automatically, typically by selecting a velocity threshold which tends to bias the onset detection point. We present here a new simple onset detection algorithm which is more accurate than the conventional velocity threshold technique. The proposed algorithm is based on modeling of the initial phase of the bell-shaped movement, and a simple regression. An important outcome of the suggested method is its ability to estimate the initial motor command before feedback sensory loop modifies the trajectory; hence it can be used to measure at the same time also adaptation rates during typical motor control experiments such as visuomotor rotation or load/grip force experiments.
We demonstrate the performance of the suggested method and compare it to motor control experts manual detection as well as velocity threshold technique using simulated minimum jerk trajectories and recorded reaching movements.

Acknolwdgements: The computational motor control laboratory is supported by: the National Institute for Psychobiology in Israel; the Ministry of Science, Culture and Sport, Israel, and by the Ministry of Research, France; the United States - Israel Bi-national Science Foundation (BSF), Jerusalem, Israel; and the National Science Foundation (ISF), Israel.

Impairments in motion perception and motor imagery in patients with Parkinson's Disease

Eran Dayan[1,2], Rivka Inzelberg[3,4] and Tamar Flash[1]

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There is ample evidence for shared representations in perception, imagery and action in neurologically healthy individuals. However, the precise nature of the internal representations that are shared between these different domains is still unclear. One experimentally-derived view posits that the properties and constraints characterizing movement generation are also manifested during motion perception and motor imagery.

A prototypical example for an interplay between motor production and visual perception concerns the so called "two-third power law", a prominent motor invariant describing the strong relation that exists between the kinematics of motion and the geometrical features of the path, followed by the hand during planar drawing movements. The two-thirds power law characterizes a wide variety of movement generation tasks, but also seems to constrain visual perception of motion. An example for similar constraints in movement generation and motor imagery concerns the so called " isochrony principle", which refers to the observation that movement of different extents have nearly the same duration. The principle of isochrony characterizes hand and arm movements, but also seems to apply to motor imagery.

The aim of the present study was to assess whether motor invariants, such as the two-thirds power law and the isochrony principle, also constrain motion perception and motor imagery in patients with PD. In the first experiment, patients with PD, as well as age-matched controls were asked to observe the rotation of a dot around an elliptical path and to modify its velocity until it appeared to move in the most uniform manner. As in previous reports controls tended to choose as most uniform movements which were close to obeying the two-thirds power law. Patients with PD, on the other hand, displayed a much more variable behavior, choosing on average, movements which were closer to moving at a constant Euclidean velocity.

In the second experiment patients with PD, as well as age-matched controls, were asked to imagine themselves moving their dominant hand, along elliptical paths of different sizes, while reporting the onset and offset of the imagined movements (thus allowing us to quantify the imagined movement duration). While controls indeed displayed isochronous imagined movement times, the patients' imagery performance deviated considerably from the principle of isochrony.

Thus, our results demonstrate impairments in motion perception and imagery in patients with PD. Recent theories on the role of the Basal Ganglia in motor timing can possibly account for these irregularities. Alternatively these impairments may reflect similar impairments in motor production.

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Evidence for a memory consolidation phase in letter-string handwriting before and after puberty

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INTRODUCTION: Robust practice-dependent performance gains can be expressed after a critical post-training interval (delayed, consolidation-phase, gains) when learning non-language skills. These delayed gains are prone to interference by subsequent experience for a few hours post-training; with interference more pronounced after puberty. We tested whether a post-training memory consolidation phase occurs in a handwriting task.

METHODS: 103 participants, 9, 12 and 17-year-olds, practiced the writing of a non-sense, pronounceable, letter string (160 repetitions) within a single session. Half the participants in each age-group were given a second session, two hours later, in which the reversed letter-string was practiced.

RESULTS: There were significant gains in writing speed within-session, but also significant delayed gains, without additional practice, which were expressed by 24 hours post-training. The delayed gains constituted shortened in-air times, i.e., shortening of the movement times between the letters of the trained string, but not in the actual, on-ground, writing times. These gains were more susceptible to interference by subsequent practice on the reversed letter-string in the 17-year-olds compared to the 9 and 12-year-olds.

CONCLUSIONS: Our results indicate the existence of an effective consolidation phase in learning a handwriting sequence both before and after puberty. However, the ability to co-consolidate different, successive, writing experiences may diminish after puberty, as has been recently shown in a non-language motor sequence learning task (Dorfberger et al, Plosone, 2007). The results support the notion that similar procedural memory consolidation processes may subserve the establishment of long-term memory for non-language tasks and handwriting skills.

Control and variability of isometric forces generated by the arm

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Control of the endpoint force generated by the arm is required for many day-to-day tasks. While the control of force magnitude has been studied in depth (e.g. Newell & Carlton, 1998), there has been little research into the control of force direction. In this study, subjects were asked to produce and hold for 5 seconds a prescribed isometric force on a handle with the arm in the horizontal plane, with feedback provided on a computer monitor. Both the magnitude and direction (one of 8 equally spaced directions) were specified. The arm was constrained such that the forces resulted from torques produced only about the shoulder and the elbow. The arm posture was selected such that the joint torques used to produce the force could be calculated.

Similar to previous studies of unidimensional force production, the standard deviation of the force magnitude was found to increase approximately linearly with the increase in force magnitude.
Unexpectedly, the standard deviation of the direction of force production (measured as an angle) decreased as the force magnitude increased.

In general, high covariation was observed between the two joint torques involved in the force production. Additionally, the forces in the left-right and front-back directions showed non-zero correlations.
However, the force magnitude and the force perpendicular to the prescribed direction showed very little correlation. This independence of the force magnitude and the force perpendicular to it, suggests that these may be coordinates used in the neural planning of force production.

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Movement timing and invariance arise from several geometries

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One long-established characteristic of both human planar hand trajectories and locomotion is the coupling between velocity and curvature, captured by the *two-thirds power law*, which stipulates a local relation between geometry and kinematics. Another long-known principle observed for different movements is *global isochrony*, which implies that the overall movement duration does not scale with movement size. No previous models of motor control were able to capture, let alone reconcile, these two empirical principles.
The two-thirds power law was recently shown to be equivalent to moving at a constant equi-affine speed. The research described here aims at understanding the relationship between movement kinematics and timing and various geometries in much broader terms, where different geometries here refer to different groups of planar transformations. We are especially interested in magnitudes that remain unchanged, or are *invariant* under these transformations. The most basic invariant of any geometry defines a distance measure, also termed *arc-length*, along curves. We focus on constant-speed movements (i.e., movements in which equal arc-lengths according to a specific geometry are traversed during equal durations of time) and propose here that the duration and compositionality of movements result from a tensorial combination of constant-speed movements according to the *Euclidian*, *equi-affine* and *affine* geometries, where each of these geometries has a different influence on the total velocity.
We tested our hypothesis on three different data sets: drawing elliptical curves, tracing complex figural forms (cloverleaves, lemniscates and limaçons) and locomotion along the same curved paths. Our model successfully accounted for the kinematics and temporal features of the recorded movements. Size scaling and the stretching transformations belong to the group of affine transformations, meaning that regardless of an increase or decrease in size movement duration will remain nearly the same. This may explain the tendency towards isochrony. We found that equi-affine geometry is the most dominant one during both hand movements and locomotion. This could explain why the two-thirds power law describes the kinematics rather successfully. In drawing, affine geometry has a lesser though still important role and Euclidean geometry has an almost negligible role while we discovered that Euclidian geometry has a central role in locomotion, whereas affine geometry has a small but important role, mainly when passing through inflection points. The underlying strategy used for selecting particular combinations of the different geometries for different paths still remains to be completely understood.

Reference: Bennequin D, Fuchs R, Berthoz A & Flash T (2009) *Movement timing and invariance arise from several geometries*. PLoS Computational Biology, in press.

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Rhythmicity as a Function of Movement Frequency

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The literature on rhythmic movements suggests that there exists a continuum of rhythmicity, along which movements can be classified, rather than simply being classified as either rhythmic or discrete. It has been suggested that the index of difficulty (ID, as defined by Fitts 1954) of the movement determines the resultant rhythmicity of the movement (Buchanan JJ, Park JH, Shea CH. Exp Brain Res 175:710-25, 2006). We tested whether a more fundamental movement parameter – its frequency – affects the degree of movement rhythmicity.

The protocol consisted of 6 blocks of trials. 12 participants were presented with a display of the phase plane of their forearm motion; the horizontal axis displayed angular position and the vertical axis displayed angular velocity. The six blocks of trials were differentiated by the velocity of the forearm movement, while the amplitude was kept the same across all trials, resulting in 6 target movement frequencies.

Harmonicity, a measure of how harmonic a movement is, divides the experimental blocks into two distinct groups: the movements in the two blocks with the lowest frequencies are of a discrete nature, while those in the other four are highly harmonic.

Mean squared jerk ratio (MSJR), a measure of relative rhythmicity (Hogan N, Sternad D. Exp Brain Res 181: 13-30, 2007), also distinguishes between the four higher-frequency movements, and the two lower-frequency movements.

Accuracy across the experimental blocks supports the separation into two groups: there appear to be two speed-accuracy tradeoff functions; one at the lowest two movement frequencies, and the other at the four higher frequencies.

Our results suggest that movement frequency determines the rhythmicity of the movement in a spatio-temporally defined task. Movements can thus be classified into two distinct types – "pseudo rhythmic" or "truly rhythmic" (Levy-Tzedek S. PhD Thesis, MIT. 2008) – based on the frequency at which they are performed.

This finding offers a more fundamental explanation of the underlying cause for the varying degrees of movement rhythmicity than the previously suggested task ID. Moreover, by suggesting a more fundamental underlying cause, this explanation encompasses the previously suggested explanation, while not being limited only to the task's ID.

Fitts' Law predicts prolonged movement times at higher movement IDs. These, in turn, correspond to lower movement frequencies. While the decreased rhythmicity of movements with higher IDs can be explained by the increased task ID, we demonstrate here that a more fundamental movement parameter – its frequency – can predict the rhythmicity of the movement.

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Perception of Nonlinear Stiffness

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Information transfer in bilateral teleoperation systems suffers unavoidable delay caused by the distance between the operator and distant robot. The effects of delay on the system were widely studied in the context of stability and recently with an increasing attention to the effect on the human operator and his/her perception of mechanical properties.

In our previous studies we explored perception of stiffness in delayed environment, and found that subjects interacting with delayed elastic force fields tend to underestimate the stiffness if they do not move across the field's boundary, and overestimate the stiffness when they move across the elastic field boundary. A model based on a convex combination between regression of force-over-position (FOP) and position-over-force (POF) according to the relative fraction of probing movements completed outside and inside the field best predicted our behavioral results (Nisky, Mussa-Ivaldi, Karniel, "A Regression and Boundary-Crossing-Based Model for the Perception of Delayed Stiffness," IEEE Transactions on Haptics, 1(2) 73-83, 2008).

In the current study we explore the generality of the proposed models in prediction of stiffness perception, where nonlinear force fields are applied. In order to find an appropriate nonlinear force position relation we designed a simulation of interaction with different force fields. We designed a piecewise linear position dependent force field, with stiffness levels randomly chosen around a fixed stiffness level, which predicts different estimation of stiffness generated by the POF and FOP models.
Based on simulation results, we hypothesize that human subjects will overestimate the stiffness of the nonlinear elastic force field if they will cross the boundary during probing. We present preliminary results and assess the ability of models to predict subjects' answers.

Understanding the computational model underlying the perception of mechanical properties of virtual environments is important for designing good teleoperation systems, efficient medical simulators as well as other realistic virtual haptic environments.

Proximodistal gradient in the perception of delayed stiffness

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Intuitively we feel that our fingers are more dexterous than our shoulder, and that shoulder muscles must be stronger than finger muscles. Indeed, there is evidence for discrepancy in the control of proximal versus distal joints. There are different control loops for distal and proximal muscles in the cerebellum and in reflex pathways. It is well established that in primates the corticospinal tract mediates fine movements of the distal muscles, whereas reticulospinal connections are widely assumed to be responsible for coordinated gross movements of proximal muscles. A similar anatomical difference is likely underlies the human proximodistal gradient in positional accuracy, opposite gradient in maximum controllable force and resolution of force control, and gradients in residual motor functions after stroke and hemispherectomy. In the current study we explored whether a proximodistal gradient exists in the perception of delayed stiffness.

In our previous studies we explored perception of stiffness in delayed environment, and found that subjects interacting with delayed elastic force fields tend to underestimate the stiffness if they do not move across the field's boundary, and overestimate the stiffness when they move across the elastic field boundary. A model based on a convex combination between regression of force-over-position and position-over-force according to the relative fraction of probing movements completed outside and inside the field best predicted our behavioral results (Nisky, Mussa-Ivaldi, Karniel, "A Regression and Boundary-Crossing-Based Model for the Perception of Delayed Stiffness," IEEE Transactions on Haptics, 1(2) 73-83, 2008).

In the literature regarding the proximodistal gradient one can find evidence that the shoulder tends to employ force control while the wrist tends to use position control. Therefore, based on our previous study, we hypothesize that force-over-position would better predict the perception of stiffness in wrist while position-over-force will better predict the perception during probing with the shoulder.

We present the framework for exploring perception of delayed stiffness when probing is executed using movement with different joints. We found a statistically significant proximodistal gradient in the amount of underestimation of delayed stiffness in the transition between probing with shoulder, elbow, and wrist joints. Moreover, there was statistically significant gradient in optimal weighting between force-over-position and position-over-force regressions for prediction of subjects' answers, but no statistically significant effect of joint on probing movements' ampletude, duration, and velocity. Therefore, we suggest that the observed gradient in perception reveals a proximodistal gradient in control: proximal joints are dominated by force control, whereas distal joints are dominated by position control**.**

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Evidence for spatiotopic representation of saccadic targets in the human cortex.

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Various brain regions, such as the frontal eye fields (FEF), supplementary eye fields (SEF), and the intraparietal sulcus (IPS), are known to be involved in eye movement planning and execution in both humans and primates. But the reference frame in which these regions code saccades is still under debate. Recently, new multivariate classification methods have been used to assess the reliability of distinctive spatial patterns of the fMRI response (SPfR) in the visual cortex. We apply similar methods here to study the spatial nature of representation of memory-based saccades in cortical regions. Human subjects performed a memory guided saccade task in which equal-amplitude saccades were executed from several starting points in various directions. We find that the SPfR in the FEF and IPS is positively correlated when saccades with the same vector of movement are repeatedly executed. Interestingly, the SPFR in the right posterior IPS is positively correlated when saccades made to same destination point, even when the vector is different. This imply on destination based (in at least head-centred coordinate frame) representation in this region. Such a representation could provide a common reference frame to encode the motor plans of both eyes and limbs. Relation to hemi-spatial neglect and spatiotopic Inhibition Of Return (IOR) are discussed.

Real-Time Closed Loop Deep Brain Stimulation of the Globus Pallidus Internal Segment as a potential novel treatment for Parkinson`s disease

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While synchronized neuronal oscillations in the basal ganglia (BG) and in the primary motor area (M1) of the cerebral cortex of Parkinson's disease (PD) human patients and 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP) treated primates have been demonstrated, their role as the neuronal correlate of PD symptoms has been challenged. Out of the motor symptoms of PD, which include bradykinesia, muscle rigidity and tremor, it is the latter that is considered to be the hallmark symptom of the disease. Due to the similarity in the nature of the oscillatory activity recorded from the musculature and the CNS, it has been suggested that the oscillatory neuronal activity either drives the tremor or vice versa. However, the neuronal oscillatory activity is concentrated at approximately double tremor frequency (10-12 Hz) and only to a lesser extent at tremor frequency (4-6 Hz). Several studies have argued that the clinical alleviation of PD symptoms provided by Deep Brain Stimulation (DBS) is achieved by the disruption of the abnormally synchronized oscillatory activity in the cortico-BG loops. Since our previous study indicated that the oscillatory activity at tremor frequency originates by the way of sensory feedback, we focused on the activity at double tremor frequency and tried to optimize DBS therapy by specifically targeting this pathological activity. Using a dedicated real-time Digital Signal Processor chip running custom software, we initiated a stimulatory burst in the Globus Pallidus Internal Segment (GPi) of two MPTP-treated African Green monkeys (Cercopithecus aethiops aethiops) after a 80 millisecond delay from the identification of M1 or GPi burst, thus targeting the next ~10-12 Hz oscillatory burst of the GPi neuronal activity. This stimulation paradigm was compared to several "open loop" paradigms: standard DBS (130 Hz single pulse), 10 Hz oscillatory bursts, 10 Hz single pulse and a control closed loop session recorded on the previous day. Our preliminary results indicate that DBS employing the closed loop paradigm was more successful in both disrupting the ongoing GPi oscillatory activity and alleviating the motor symptoms of the animals, as compared to the open-loop paradigms. We therefore suggest that future DBS treatment should be based on closed rather than open loop architecture.

Representation of dynamic and kinematic parameters of wrist flexion in the human brain

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Both dynamic and kinematic movement parameters affect neural activity in the primate motor cortex. To dissociate their relative contribution to human brain activity, we measured BOLD responses as subjects performed well-defined wrist flexion movements.

In the first, block designed experiment, we aimed to characterize the representation of movement dynamics while controlling kinematic parameters. 13 right-handed subjects were trained to make repetitive isolated movements of their right or left wrists against flexion loads of 0.5, 1 or 2 kg in separate blocks. As trained, flexion position profile and peak velocity did not differ between the load conditions. However, activity strength within the sensorimotor cortical network (areas M1, PM, SMA and S1) increased monotonically with the load. Consistent with this, a direct contrast between the activation elicited by the lightest and heaviest loads during wrist movements revealed a voxel cluster within S1, in which medium load movements led to an intermediate BOLD response. Consistent with some single-unit studies in primates, this shows that the BOLD signal throughout the sensorimotor cortical network increases monotonically with the force exerted.

To characterize the complementary representation of kinematics while controlling for movement dynamics, we carried out a second, event-related experiment. Nine right-handed subjects repeatedly moved their dominant wrist against a 0.5kg flexion load. Movement distance, duration and velocity were varied systematically between three or four conditions. We found that movement extent and duration both contributed similarly to the M1 BOLD response, while peak movement speed was largely irrelevant. Thus, large-amplitude actions (in time or space) lead to an increased BOLD response.

Taken together, our results show that both kinematic and dynamic parameters of single-joint movements influence BOLD activity in the human sensorimotor cortex.

Adult age-related differences in the structure of postural variability in manual pointing

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Depending on its structuring in relation to the movement goal, execution variability in systems with abundant degrees of freedom (DOF) may reflect flexible or perturbed control. Previous research indicate that task-specific organization of movement variability may be affected by adult aging (Latash & Anson, 2006; Latash, 2008)

We studied adult age-graded differences in the structure of postural variability in manual pointing using two approaches for quantifying task-specific coordination multi-DOF systems: the uncontrolled manifold method (UCM; Scholz & Schöner, 1999) as well as the randomization method (RM; Müller & Sternad, 2003). Twelve older (70-80 years) and twelve younger (20-30 years) participants completed a total of 120 pointing trials to two different targets presented according to three schedules: blocked, alternating, and random.

The groups were similar with respect to basic kinematic variables, end point precision, as well as the accuracy of the biomechanical forward model of the arm. The structure of variability was assessed at five characteristic time points of the movements: start, 10%, 50%, 90%, and end. Following the UCM apporach, goal-equivalent and non-goal-equivalent components of postural variability (GEV and NGEV) were determined with respect to finger tip position. Based on this, a synergy index was defined as the ratio GEV/NGEV, reflecting the flexibility/stability aspect of synergies (Latash, Scholz & Schöner, 2007). For the RM analysis, joint angles were randomly permuted across pointing trials; the resulting increase in finger tip variability (real vs. surrogate data) was used to define a generalized correlation (Müller & Sternad, 2003). Younger adults showed higher synergy indices and higher generalized correlation than older adults, in particular towards the end of the movement. In contrast, no effect of target schedule was present.

Our results complement previous findings on adult age differences in the organization of multi-DOF movements, with older adults making less flexible use of motor abundance than younger adults.