# CNS*10 WORKSHOP (July 29th) on

# Computational models for movement control and adaptation during BMI operation

*Organizer: Miriam Zacksenhouse, Technion*

The development of Brain-Machine Interfaces (BMIs) has been motivated by insights about neural encoding in the motor cortex, and in particular the evidence that cortical motor neurons encode the direction of movement. However, it is evident that cortical motor neurons encode multiple signals and that encoding may change with task. Of particular interest are the changes that may occur following changes in the motor environment, and, specifically, when switching to operate a BMI. Computation motor control models may facilitate the investigation of these changes and their potential interpretation and decoding. This workshop is targeted at bringing together researchers investigating neural encoding and decoding in the motor cortex, and in particular those working on BMIs, with researchers developing computational motor control models, to further explore neural changes during BMI operation and their potential interpretation within the context of computational motor control. It is expected that such a workshop would both motivate further development of computational motor control models and facilitate the development of BMIs.

**PART A: BMI operation: Interpreting and shaping the neural activity**

1. *Ferdinando Mussa Ivaldi – Northwestern University*:
Designing dynamical behaviors with a bidirectional BMI

2. *Stephen Helms Tillery – Arizona State University*:
Somatosensory cortical activity during haptic exploration.

3. *Andrew Tate – Duke University:*
Lower-limb BMI: a pathway to restore locomotion and balance in paralysis

4. *Wei Wu – Florida State Uni*versity:
A Family of Information-Geometric Metrics for a Statistical Analysis of Spike Trains

**PART B: Neural response and adaptation to BMIs**

5. *Jose Carmena – University of California, Berkeley*:
Neural adaptations to a brain-machine interface

6. *Steve Chase – University of Pittsburgh*:
Differentiating global and local adaptation responses to visuomotor perturbations of a brain-computer interface

7. *Justin Sanchez – University of Florida*:
Symbiotic Brain-Machine Interfaces

8. *Maurice Smith – Harvard University*:
Credit assignment and motion state representations for motor learning in humans

9. *Miriam Zacksenhouse – Technion, Israel*:
Optimal control framework successfully explains changes in neural modulations during BMI experiments

**CNS*10 WORKSHOP on**

# Computational models for movement control and adaptation during operation of Brain-Machine Interfaces (BMIs)

| JULY 29 | PRESENTATION |
|---|---|
| 9:00-9:05 | Opening remarks,<br>*Miriam Zacksenhouse, Technion, Israel* |
| **PART A** | **BMI operation: Interpreting and shaping the neural activity** |
| 9:05-9:50 | ***Ferdinando Mussa-Ivaldi*** – *Northwestern University*:<br>Designing dynamical behaviors with a bidirectional Brain Machine Interface |
| 9:50 – 10:35 | ***Stephen Helms Tillery*** – *Arizona State University*:<br>Somatosensory cortical activity during haptic exploration |
| 10:35 – 10:50 | Coffee Break |
| 10:50 – 11:35 | ***Andrew Tate*** – *Duke University:*<br>Lower-limb BMI: a pathway to restore locomotion and balance in paralysis |
| 11:35 – 12:20 | ***Wei Wu*** – *Florida State Uni*versity:<br>A family of Information-geometric metrics for a statistical analysis of spike trains |
| 12:20 – 14:00 | LUNCH |
| **PART B** | **Neural response and adaptation to BMIs** |
| 14:00 – 14:45 | ***Jose Carmena*** – *University of California, Berkeley*:<br>Neural adaptations to a Brain-Machine Interface |
| 14:45 – 15:30 | ***Steve Chase*** – *University of Pittsburgh*:<br>Differentiating global and local adaptation responses to visuo-motor perturbations of a Brain-Computer Interface |
| 15:30 – 15:45 | Coffee Break |
| 15:45 – 16:30 | ***Justin Sanchez*** – *University of Florida*:<br>Symbiotic Brain-Machine Interfaces |
| 16:30–17:15 | ***Maurice Smith*** – *Harvard University*:<br>Credit assignment and motion state representations for motor learning in humans |
| 17:15 – 18:00 | ***Miriam Zacksenhouse*** – *Technion, Israel*:<br>Optimal control framework successfully explains changes in neural modulations during BMI experiments |
| 18:00–18:30 | **DISCUSSION** |

# Designing dynamical behaviors with a bidirectional BMI

*Ferdinando A. Mussa-Ivaldi*
*Northwestern Univ*

Several studies of motor control and learning have led to describing the action of the neuromotor control system in terms of fields of forces acting on the limbs. The resulting motor behavior is the product of the interaction of this field with the limb and environment dynamics. Here, I will discuss the problem of generating pre-specified force field acting on a controlled mechanical system by tuning the two sides of a bidirectional BMI. One side, the "sensory interface" encodes the state of the controlled system as a pattern of electrical stimuli to be delivered by a microelectrode array. The other side, the "motor interface" maps the activities recorded over another array into a force vector acting upon the controlled device. Dynamic Shaping (DS) is the calibration procedure that sets the parameters of the two interfaces to approximate a desired force field. I will present recent results of DS in simulations and in experiments with anesthetized rats.

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# Somatosensory cortical activity during haptic exploration.

*Stephen Helms Tillery*
*Arizona State Univ.*

Multiple somatic sensory modalities are modulated during hand movements and active exploration of haptic objects. Some of the signals which arise (exteroceptive signals) are crucial to forming tactile images of manipulated objects. Other signals (interoceptive signals) are modulated by self-movement. Traditionally these sets of signals were thought to be segregated by labeled lines which arose from tactile and proprioceptive receptor systems.

We now know this is not true, and that signals related to self-movement and haptic interaction are intermingled amongst the sensory systems. Here we describe a series of experiments in which we have devised a method to disentangle signals in S1 that arise from self-movement and from haptic manipulation. We recorded in primary somatosensory cortex (areas 1, 2, and 3b) as an animal performed a reach-to-grasp task in both virtual and physical space. By combining virtual (non-haptic) and physical (haptic) trials, we were able to identify subsets of neurons which encoded only haptic interactions, neurons which encoded only self-movement, and neurons which encoded a mix. We also found that signals arising from these two modalities appeared to combine linearly in the firing of S1 neurons. These findings are one step towards creating an encoded stimulus pattern for directly driving S1 neurons to provide sensory information about haptic interactions.

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# Lower-limb BMI: a pathway to restore locomotion and balance in paralysis

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Brain-Machine Interfaces (BMIs) are a highly promising strategy for restoring limb mobility to people with spinal cord injuries and loss of limbs. While initial progress has been made in BMIs that enact motor functions of upper extremities, BMIs for lower limbs are virtually unexplored. Moreover, the basic neural mechanisms that govern bipedal lower-limb function in primates are also poorly understood. Recently we conducted large-scale cortical recordings in bipedally standing and walking rhesus monkeys in which we obtained proof of concept demonstrations of cortical control of balance, locomotion and volitional movements involving lower extremities. Moreover, we have developed a BMI that extracted lower limb kinematics from cortical ensemble activity [1]. Furthermore, we have now started to incorporate in this BMI the contribution of cortical ensemble activity to balance, in particular in relation to anticipatory postural adjustments and compensatory postural reactions to positional perturbations. In these experiments, monkeys implanted with chronic multielectrode arrays in the primary motor cortex (M1) maintained upright posture on a platform that underwent translational shifts to perturb the balance. Platform shifts were either rhythmic, allowing the animal to anticipate the upcoming movement, or arrhythmic, so no definite anticipatory strategy could be adopted. Specific directional tuning was found in individual M1 cortical neurons. Shift velocity and EMG activity in the lower-limb muscles could be predicted with good signal-to-noise ratios from M1 ensemble activity. Moreover, we found differences in the baseline neural activity and neuronal modulations during anticipated versus unanticipated movements of the platform.

These findings, along with ongoing work studying voluntary stepping behavior, suggest that residual cortical activity following SCI or lower-limb loss could be used to drive a lower-limb neuroprosthetic or exoskeleton capable of functions comparable to normal lower-limb use. Cortically-driven BMI also presents unique challenges regarding the computational strategies used to control neuroprosthetics that restore posture and balance.

1. Fitzsimmons NA, Lebedev MA, Peikon ID and Nicolelis MA **Extracting kinematic parameters for monkey bipedal walking from cortical neuronal ensemble activity.** *Front Integr Neurosci* 2009, 3(3)

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## A Family of Information-Geometric Metrics for a Statistical Analysis of Spike Trains

*Wei Wu, Anuj Srivastava*
*Department of Statistics*
*Florida State University*

Understanding information represented in spike trains has been a fundamental problem in neural coding. Therefore, a metric for comparing spike trains is centrally important in characterizing the variability of neural firing activity. Various mathematical frameworks, such as the commonly-used Victor-Purpura metrics and van Rossum metric, have been developed to quantify differences between spike trains. Motivated by the Fisher-Rao metric used in information geometry, we introduce a parametrized family of metrics that takes into account different time warpings of spike trains. The parameter is similar to p in the standard Lp norm used in functional analysis. The metrics are based on optimal matching of spikes (and inter-spike intervals) across spike trains under a penalty term that restrains drastic temporal mapping. In particular, when p equals 1 or 2, this metric generalizes the Victor-Purpura metric D{interval}[q] and the van Rossum metric, respectively. Motivated by a long-term goal of a comprehensive statistical framework for analyzing spike train data, these new metrics further allow the notions of basic descriptive statistics such as means and variances for spike trains and shortest paths between two spike trains. Using some restrictive conditions, we derive analytical expressions for these quantities. Finally, we test the new method in measuring distances between spike trains on simulations as well as experimental recordings from primate motor cortex. It is found that all these methods achieve desirable classification performance in all cases.

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# Neural adaptations to a brain-machine interface

*Jose Carmena*
*Univ. of California, Berkeley*

Research in Brain-Machine Interfaces (BMIs) has led to demonstrations of rodents, non-human primates and humans controlling prosthetic devices in real-time through modulation of neural signals. In particular, cortical BMI studies have shown that improvements in performance require learning and are associated with a change in the directional tuning properties of units directly incorporated into the BMI (hereafter 'direct units').

However, little is known about modifications to neurons in the surrounding cortical network (hereafter 'indirect units') during neuroprosthetic control. Moreover, the time course and the reversibility of any such changes remain unclear. Using stable recording from large ensembles of units from primary motor cortex in two macaque monkeys, here we demonstrate that proficient neuroprosthetic control reversibly reshapes cortical networks through local effects. By monitoring large ensembles of both direct and indirect units during long-term neuroprosthetic control, we observed large-scale changes in the preferred direction and the depth of modulation of indirect units. Strikingly, proficient control was specifically associated with an apparent distance-dependent reduction in modulation depth. These observed changes were also rapidly reversible in a state-dependent manner. Thus, ensemble control of a neuroprosthetic device appears to triggers large-scale modification of cortical networks centered on units directly incorporated in the BMI.

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# Differentiating global and local adaptation responses to visuomotor perturbations of a brain-computer interface

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Visuomotor transformations are one of the canonical perturbations used to study motor learning and adaptation. One of the limiting factors in studying neural correlates of these perturbations, however, is that typically millions of neurons are involved in the adaptation process; when recording from a limited subset of the population, it is difficult to know exactly how meaningful a given neural change is to the subject's overall behavior. Brain-computer interfaces (BCIs) can address this problem. In a BCI, the neural activity of recorded neurons can be used to drive a cursor on a computer screen, providing a defined link between neural activity and behavior. By implementing visuomotor perturbations in this framework, it is possible to understand the behavioral relevance of particular neural changes. We trained monkeys to perform 2D center-out movements of a computer cursor under brain-control. We then applied a perturbation by decoding a subset of randomly chosen neurons incorrectly, by rotating their contribution to cursor movement by a consistent angle. While globally this perturbation mimics a visuomotor perturbation, only some of the cells in the population actually contribute to error.

Cortical neurons often exhibit changes in firing rates during motor learning. These firing rate changes have two potential sources: first, the behavior could change, as the subject attempts to produce a movement that counters the perturbation to achieve the desired output (re-aiming); second, the tuning curves of individual motor cortical cells could change through some kind of plastic mechanism that allows the subject to relearn the association between intent and action under the perturbation state (re-tuning). In this talk, we demonstrate a computational approach for differentiating local, re-tuning adaptation responses from global, re-aiming adaptation responses.

We find evidence for both adaptation mechanisms in the neural responses. The majority of the error reduction (~80%) can be attributed to re-aiming, while the remainder (~20%) can be attributed to re-tuning. Both of these compensations increase as the perturbation error increases. Furthermore, the re-tuning response can be broken down into changes in preferred direction and changes in modulation depth. While the preferred direction changes are evident in all of our perturbations, we only see changes in modulation depth when the number of cells in the perturbed population is small relative to the total population.

**Acknowledgements**
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# Symbiotic Brain-Machine Interfaces

*Justin C. Sanchez, Ph.D.*
*Departments of Pediatrics, Neuroscience, and Biomedical Engineering*
*University of Florida*

Symbiotic Brain-Machine Interface (S-BMI) design is paradigm that divides sensorimotor control and “intelligence” between the user and a Computational Agent (CA). By modeling of the perception-action-reward cycle (PARC), a co-adaptive computational architecture can be derived that allows both the artificial system and biologic system to *participate* in shared goal-directed behavior. This presentation will overview the experimental and computational approaches capable of translating a user’s intention into commands to control Brain-Machine Interfaces in the context of a rich real-time environment.

# State estimation and encoding successfully explain changes in neural modulations during BMI experiments

*Miriam Zacksenhouse, Dan Corfas, and Koren Beiser*
*Faculty of Mechanical Engineering,*
*Technion*

Experiments with Brain-Machine Interfaces (BMIs) provide a unique opportunity to investigate neural processing involved in performing novel motor tasks. The BMI is trained to imitate the transformation from the recorded neural activity to the movement of the controlled cursor. In the current experiments this is performed during an initial part of the session when the cursor is controlled via a hand held pole. Subsequently, the BMI is used to control the cursor directly using the recorded neural activity to predict the desired movement. To the extent that the BMI fails to predict the desired movement exactly it provides a novel motor environment.

BMI experiments with monkeys indicate that the extent of neural modulations increases abruptly upon starting to operate the BMI, especially after the monkeys stopped moving their hands (brain control without hand movements). This increase was NOT matched by a similar increase in task related modulations, so the nature of the enhanced modulations remains unknown. Furthermore, as training progressed and performance improved, the enhanced modulations subsided. We model these phenomena using the framework of optimal control and relate the enhanced neural modulations to the changes in the variance of the internally estimated signals.

The model includes four main parts: (i) State estimation based on both visual and properioceptive feedback, with different delays and noise variance. (Brain control without hand movements is simulated with infinitely high proprioceptive measurement noise). (ii) Neural encoding of the predicted state, including the predicted position, velocity, speed and target location; (iii) Controller that generates the control signal to the hand based on the estimated state. (iv) BMI that is trained during the simulated pole control, and used to control the cursor during simulated brain control. To reflect the increased variability in the movement, we increase the internal estimate of the process noise when switching to brain control. However, no other change is made.

The activity of the simulated neurons demonstrates the same phenomena observed in the data: the percent neural modulations is higher in brain control without hand movements than in pole control, while the percent task-related modulations does not increase. We demonstrate that this depends strongly on increasing the internal estimate of the process noise. Most importantly, the simulations suggest that the enhanced modulations may reflect the increase in the variances of the predicted velocity. Finally we discuss the potential encoding of other related signals.

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