17th Annual GCC Theoretical and Computational Neuroscience Annual Conference

Jan 31, 2020

BioScience Research Collaborative
6500 Main St.
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Gulf Coast Consortia

QUANTITATIVE BIOMEDICAL SCIENCES

The Gulf Coast Consortia (GCC), located in Houston, Texas, is a dynamic, multi-institution collaboration of basic and translational scientists, researchers, clinicians and students in the quantitative biomedical sciences, who benefit from joint training programs, topic-focused research consortia, shared facilities and equipment, and exchange of scientific knowledge. Working together, GCC member institutions provide a cutting-edge collaborative training environment and research infrastructure beyond the capability of any single institution. GCC training programs currently focus on Biomedical Informatics, Computational Cancer Biology, Molecular Biophysics, Neuroengineering, Pharmacological Sciences, Precision Environmental Health Sciences and Antimicrobial Resistance. GCC research consortia gather interested faculty around research foci within the quantitative biomedical sciences, and currently include Antimicrobial Resistance, Nanox, Mental Health, Innovative Drug Discovery and Development, Translational Pain Research, Theoretical and Computational Neuroscience, Single Cell Omics, Regenerative Medicine, Translational Imaging and Cellular and Molecular Biophysics. Current members include Baylor College of Medicine, Rice University, University of Houston, The University of Texas Health Science Center at Houston, The University of Texas Medical Branch at Galveston, The University of Texas M. D. Anderson Cancer Center, and the Institute of Biosciences and Technology of Texas A&M Health Science Center.

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17th Annual GCC Theoretical and Computational Neuroscience
January 31, 2019

Agenda

8:30	Poster Set-up and Light Breakfast
8:50	Welcome
9:00	*The Stabilized Supralinear Network Model of Cortical Circuitry: The Importance of Being Loosely Balanced* Ken Miller, Columbia University
9:45	*Physiological Signatures of Memory* Tom McHugh, Riken
10:30	Break
11:00	*Systematic, Normative Biases in Rare-event Inference with Few Observations* Tahra Eissa, University of Colorado, Boulder
11:20	Flash Talks
11:35	Poster Session and Lunch
1:00	*Inferring the Visual World from the Retinal Images is Actually Nontrivial* Alex Huk, University of Texas, Austin
1:45	*Efficient and Flexible Internal Representations to Link Sensation and Action* Ann Hermundstad, Janelia Research Campus, HHMI
2:30	Coffee/Networking Break
3:00	*A Directed Form of Synaptic Plasticity Underlies Hippocampal Representations* Jeff Magee, Baylor College of Medicine
4:00	Keynote/Keck Seminar: *Movements, Decisions, and Wholistic Behavior* Anne Churchland, Cold Spring Harbor
5:00	Poster Awards and Closing Remarks
	Reception Following

Anne Churchland, PhD
Associate Professor
Movements, Decisions, and Wholistic Behavior

Anne K. Churchland received her Ph.D. in neuroscience from the University of California, San Francisco, advised by Dr. Stephen Lisberger. She then did a postdoctoral fellowship with Dr. Michael Shadlen at the University of Washington in the Physiology and Biophysics Department. Her postdoctoral work focused on mechanisms of decision making in nonhuman primates and included both experimental and theoretical work. The latter was funded by a Pathways to Independence (K99) Award from the National Eye Institute. In 2010, she became an assistant professor at Cold Spring Harbor Laboratory. In starting her own laboratory, Professor Churchland began studying decision making using rodent models to take advantage of emerging tools for circuit dissection which are readily available in rodents. Since then, her laboratory has been a major player in bringing behavioral paradigms to rodents that have been successful in elucidating neural mechanisms in primates. These include perceptual decision making and multisensory integration.

Since joining Cold Spring Harbor Laboratory, Professor Churchland has been the recipient of awards from the McKnight Foundation, the Pew Charitable Trusts, the Klingenstein-Simons Foundation, the John Merck Fund and the Chapman Foundation. She received the Janett Rosenberg Trubatch career development award from the Society for Neuroscience (2012) as well as the Louise Hanson Marshall Special recognition award (2017). She is a co-founder of the International Brain Laboratory, a collaboration of 21 experimental and theoretical neuroscientists. She has played an organizational role in many conferences including the Computational and Systems Neuroscience conference (cosyne) and the Canonical Computations in Brains and Machines conference. She maintains a website (anneslist.net) to promote women in systems and computational neuroscience.

Abstract: When experts are immersed in a task, do their brains prioritize task-related activity? Most efforts to understand neural activity during well-learned tasks focus on cognitive computations and task-related movements. We wondered whether task-performing animals explore a broader movement landscape, and how this impacts neural activity. We characterized movements using video and measured neural activity using widefield and two-photon imaging. Cortex-wide activity was dominated by movements, especially uninstructed movements not required for the task. This held true throughout task-learning and for extracellular Neuropixels recordings that included subcortical areas. Our observations argue that animals execute expert decisions while performing richly varied, uninstructed movements that profoundly shape neural activity.

Tahra Eissa, PhD
Research Associate
Applied Math

Systematic, Normative Biases in Rare-event Inference with Few Observations

Tahra Eissa received her BS in bioengineering from Cornell University. She then completed a PhD in neurobiology from the University of Chicago under the advisement of Dr. Wim van Drongelen. Currently, Dr. Eissa is a research associate at the University of Colorado Boulder, working in collaboration with Dr. Zachary Kilpatrick (UCB), Dr. Kresimir Josic (UH), and Dr. Josh Gold (UPenn), studying decision making in dynamic environments.

Abstract: When choosing between different options we frequently rely on information of non-uniform frequency and quality. In contrast to most experimental studies, when faced with two a priori equally likely options, evidence favoring one may be rare, but of high quality, while evidence favoring the other may be abundant, but less convincing. How do human observers make decisions in these situations? Here, we show that, when presented with such asymmetric evidence, responses of ideal observers exhibit strong biases, especially when evidence is limited. Likewise, behavioral data shows that responses of human subjects reflect these trends. Thus, we can yield new quantitative insights into rare-event inference, which is relevant to both real-world problems (like predicting stock-market crashes) and common laboratory tasks (like inferring rare state changes in dynamic environments).

Ann Hermundstad, PhD
Group Leader
Computation & Theory Research Core
Efficient and Flexible Internal Representations to Link Sensation and Action

Ann Hermundstad is a Group Leader in the Computation & Theory research core at Janelia Research Campus. She studies how the brain creates and uses adaptive sensorimotor representations to generate flexible behavior. Her lab uses a combination of theory, modeling, and data analysis to explore how neural circuits can do this efficiently and flexibly, and works in close collaboration with experimentalists to test these ideas in behaving animals. Ann received her PhD in Physics from UC Santa Barbara. Before starting her lab at Janelia in 2016, she did a postdoc in theoretical neuroscience with Vijay Balasubramanian, initially at École Normale Supérieure in Paris and later at UPenn in Philadelphia.

Abstract: To achieve desirable behavioral goals in the face of uncertainty and change, the brain is thought to flexibly link sensation and action through abstract internal representations that preserve information about statistical relationships in the environment and expected outcomes of actions. In this talk, I'll highlight two related (but currently distinct) efforts to understand how such internal representations are built, modified, and used to guide flexible behavior. In the first part of the talk, I will discuss our ongoing theoretical work to understand how efficient sensory coding supports and constrains internal representations, depending on behavioral demands. Specifically, we connect ideas from efficient coding and Bayesian inference to ask how sensory systems should efficiently allocate limited resources when the goal is to optimally infer latent states of the environment, rather than reconstruct incoming stimuli. We use these ideas to explore dynamic tradeoffs between the efficiency and speed of sensory adaptation schemes, and the downstream computations that these schemes might support. In the second part of the talk, I will discuss our ongoing experimental and computational work to understand how internal representations support and constrain flexible behavior. Here, we use ideas from reinforcement learning to understand algorithms by which animals learn to modify their behavior based on past experience. We explore these ideas in Drosophila melanogaster, where it is possible to monitor and perturb neural activity during operant learning and thereby tether the components of these algorithms to the internal representations carried in specific neural substrates. Our long-term goal is to bridge these two directions to understand how the brain efficiently and flexibly links sensation and action.

Alex Huk, PhD
Raymond Dickson Centennial Professor (II),
Neuroscience & Psychology
Director, Center for Perceptual Systems
Faculty Director, Polymathic Scholars Honors Program

Inferring the visual world from the retinal images is actually nontrivial

Alex Huk is the Raymond Dickson Centennial Professor of Neuroscience and Psychology, and Director of the Center for Perceptual Systems, at The University of Texas at Austin. He received his PhD from Stanford and did postdoctoral research at the University of Washington (Seattle). In Austin since 2004, his lab's work spans a range of topics covering visual processing, perceptual decisions, and working memory. Many of these projects reflect long-term collaborations with Jonathan Pillow and Larry Cormack.

Abstract: Sensory signals give rise to patterns of neural activity, which the brain uses to infer properties of the environment. For the visual system, considerable work has focused on the representation of frontoparallel stimulus features and binocular disparities. However, inferring the properties of the physical environment from retinal stimulation is a distinct and more challenging computational problem— and this is what the brain must actually accomplish to support perception and action. In this talk I describe a computational model that incorporates projective geometry, mapping the three-dimensional (3D) environment onto the two retinae. This mapping fundamentally shapes the tuning of cortical neurons and corresponding aspects of perception-- and can then explain the strikingly non-canonical tuning present in existing electrophysiological data and distinctive patterns of perceptual errors evident in human behavior. Decoding the world from cortical activity is strongly affected by the geometry that links the environment to the sensory epithelium.

Jeffrey C. Magee, PhD
Professor
Neuroscience

A Directed Form of Synaptic Plasticity Underlies Hippocampal Representations

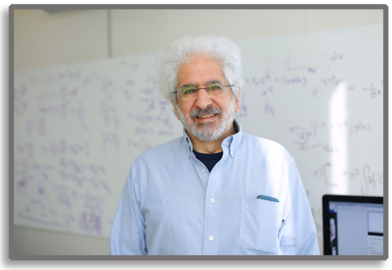
Overall the primary interest of the lab is in producing a biophysically based understanding of cortical circuit function. The lab has a long-standing interest in active input processing in neuronal dendrites and its role in learning and memory. We use a variety of electrical (whole-cell, juxtacellular, silicon probe) and optical (two-photon) recording and optogenetic manipulation techniques both in behaving animals and in brain slices. Magee received his PhD from Tulane University in physiology for work on ion channels and synaptic transmission in 1992. He next worked as a postdoctoral fellow in Dan Johnston's lab at Baylor College of Medicine where they began studies on the active properties of dendrites and dendritic integration. He subsequently started his own lab at LSU Medical School in New Orleans in 1997 where he continued to work on the integrative properties of neuronal dendrites and their role in neuronal information processing and storage. He next joined the newly formed Janelia Farm Research Campus of HHMI in 2006 where he expanded his research into the role of active dendritic integration and its regulation by various neuronal microcircuit elements in determining the fundamental feature selectivity of cortical neurons. At this point most work in the laboratory was in behaving animals. Finally, Magee has recently (2018) moved his lab back to Baylor College of Medicine where they are attempting to determine the mechanisms of experience-dependent shaping of network representations in the hippocampus and barrel cortex. They are also trying to understand the behavioral impact of this representation learning.

Abstract: According to standard models of synaptic plasticity, correlated activity between connected neurons drives changes in synaptic strengths to store associative memories. Here we tested this hypothesis in vivo by manipulating the activity of hippocampal place cells and measuring the resulting changes in spatial selectivity. We found that the spatial tuning of place cells was rapidly altered via bidirectional synaptic plasticity. To determine the rules shaping this plasticity, we evaluated two models – a standard model that depended on synchronous pre- and post-synaptic activity, and an alternative model that depended instead on the initial synaptic strength of each input at the time of activation. While both models accounted equally well for the data, they predicted opposite outcomes of a perturbation experiment, which ruled out the standard correlation-dependent model. Finally, network modeling suggested that this form of bidirectional synaptic plasticity enables population activity, rather than pairwise neuronal correlations, to drive plasticity in response to changes in the environment.

Thomas McHugh, PhD
Team Leader
Circuit and Behavioral Physiology
Physiological Signatures of Memory

Thomas McHugh majored in molecular and cellular biology at the University of California, Berkeley, before moving to the Massachusetts Institute of Technology (MIT) where he finished a PhD in biology. At MIT, he studied genetics and the physiology of spatial memory with Matt Wilson and Susumu Tonegawa, and continued to study the circuits of hippocampal memory as part of his postdoctoral studies. In 2009, he moved to what is now known as the RIKEN Center for Brain Science to start his own laboratory. His Laboratory for Circuit and Behavioral Physiology at RIKEN takes a multidisciplinary approach to understanding how memories are formed, stored and recalled in the mammalian brain, and how damage from factors such as stress and disease impair these functions.

Abstract: The hippocampus plays a critical role in memory and its dysfunction can lead to disorders ranging from epilepsy to dementia. Behavioral studies have shown that it is crucial for the formation of new episodic and contextual memories, as well as their consolidation, but how dynamic changes in its well-characterized neuronal activity map on to these functions and the theories explaining them has remained difficult to address. In rodents, genetic techniques allow specific access to discrete populations of neurons, both within the hippocampus and in areas projecting to it, permitting the manipulation of neuronal transmission and plasticity on a variety of timescales. In this talk I will introduce how we combine these tools with behavior and in vivo recording to gain a greater understanding of how information is processed in the structure. I will highlight some of the lab's recent efforts, including experiments designed to understand the links between place cell activity and the encoding of memory, as well as work focused on the identification of a dynamic physiological signature of memory age.



Ken MIller, PhD
Professor
Neuroscience

The Stabilized Supralinear Network Model of Cortical Circuitry: The Importance of Being Loosely Balanced

Ken Miller received an M.S. in Physics and Ph.D. in Neuroscience from Stanford University, working with Dr. Michael Stryker at UCSF. He did a brief postdoc at UCSF and then a postdoc at Caltech. He became Assistant Professor in the Dept. of Physiology at UCSF in 1993, advancing to Associate Professor and Full Professor. In 2004 he moved to Columbia University to co-found and co-direct, with Larry Abbott, the Center for Theoretical Neuroscience. He is also Professor of Neuroscience and co-director of the Neurobiology and Behavior Program at Columbia. In 2018 he was awarded the Swartz Prize for Theoretical and Computational Neuroscience from the Society for Neuroscience.

Abstract: Cortical neurons have expansive, supralinear input/output functions over their entire dynamic range. We start with this simple fact; the assumption that feedback inhibition is strong enough to keep the network stable despite the destabilizijng nature of expansive input/output functions; and simple assumptions on connectivity, i.e. that connectivity strength and/or probability decrease with cortical distance and with decrease in signal correlations. These ingredients suffice to explain a wide variety of nonlinear cortical behaviors. These include sublinear summation of responses to multiple stimuli, which becomes more linear for weak stimuli; summation field sizes (optimal stimulus sizes) that shrink with contrast, in real space and, as we predicted, in feature space, as well as the related fact that a high-contrast surround can facilitate response to a weak center stimulus but suppress response to stronger center stimuli; the suppression of correlated neuronal variability by a stimulus and its tuning and timing; and multiple ways in which attention modulates neural responses. These outcomes result from the fact that, given supralinear input/output functions and stabilization by feedback inhibition, the dynamics leads recurrent input to cancel or "balance" external input, so that most of the external input a cell receives is cancelled and the net input after cancellation grows sublinearly as a function of the external input. This occurs robustly, without need for fine tuning of parameters. The balance is "loose", meaning that the net input after cancellation is comparable in size to the factors that cancel. A classic "balanced network" model considered tight balancing, meaning that the factors that cancel were very large compared to the net input. At least in its simplest implementation, tight balance allows only linear response. We argue that cortex operates in a loosely balanced regime, which naturally explains the wide variety of nonlinear behaviors described above.

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Poster #1

Synaptic Plasticity in Balanced Networks

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The dynamics of local cortical networks is irregular, but correlated. While dynamic balance is a plausible mechanism that generates such stochastic activity both in asynchronous, and correlated regimes, it remains unclear how such balance is achieved and maintained in actual neural networks. In particular, it is not fully understood how plasticity induced changes in the network affect balance, and in turn, how correlated, balanced activity impacts learning.

How will the dynamics in balanced network change under different plasticity rules in the asynchronous or correlated state? How does the presence of correlations in the recurrent network impact learning? When and how do correlations change the evolution of weights, their eventual magnitude, and structure across the network?

To address these questions, we develop a general theory of plasticity in balanced networks. We show that, in general, balance is attained and maintained under plasticity induced weight changes both in the asynchronous and correlated state. We find that correlations in the input mildly, but significantly affect the evolution of synaptic weights. More importantly, under certain plasticity rules, we find an emergence of correlations between weights and rates. Under these rules, synaptic weights converge to a stable manifold in weight space with their final configuration dependent on the initial state of the network. Thus, the network can retain a memory of its initial state even under learning.

Poster #2

Inferring Sympathetic Nervous System Activity from Skin Conductance Signal: A Sparse System Identification Approach

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Sweat secretions in the epidermis due to sympathetic nervous system (SNS) activity result in skin conductance (SC) variations. The comparatively high-frequency component of an SC signal, known as the phasic component, reflects SNS activity. The low-frequency component, called the tonic component, is thought to be related to thermoregulation and general arousal.

Decomposing an SC signal into its constituent components to extract encoded neural information related to emotional arousal is a challenge. Moreover, identifying unknown system model parameters related to the constituent components of an SC recording is also difficult. Some of the challenges include non-convexity of the optimization formulation when identifying the system parameters for the phasic component, identifying the correct sparsity level for the neural impulsive driver, the presence of noise contamination and identifying the smoothness level for the tonic component.

We propose three novel methods to infer SNS activity from SC addressing non-convexity in the optimization formulation, robustness to noise with multi-channel measurements, and tonic component separation. In the first method, we solve the system parameter estimation problem using Hartley modulating function based continuous-time system identification so that the optimization formulation for estimating the parameters becomes convex. In the second one, we propose a physiological model for multi-channel SC recordings relating them to SNS activation events. Using a multi-rate approach, we formulate an optimization problem to identify the number, timings, and amplitudes of SNS activity and the unknown model parameters from multi-channel SC data to account for the noise in the signal. In the third method, we model the phasic component using a second-order differential equation representing the diffusion and evaporation mechanism of sweat, and model the tonic component with several cubic B-spline functions. As an input to the model, we consider a sparse impulsive neural signal. We formulate an optimization problem with physiological priors on system parameters, a sparsity prior on the neural stimuli, and an energy penalty on the weights of the cubic B-spline functions. In all these methods, we place sparsity constraints on SNS activity and physiologically plausible constraints on the system parameters.

By analyzing both simulated and experimental data, we show that our framework can successfully separate phasic and tonic components to infer SNS activity and estimate unknown system parameters. We also demonstrate our ability to automatically identify a reasonable sparsity level for sparse neural stimuli and smoothness parameters for the tonic component using generalized-cross-validation. Accurate decomposition of SC could potentially improve cognitive-stress-related state estimation in mental disorders.

This work was supported in part by NSF grant 1755780 - CRII: CPS: Wearable-Machine Interface Architectures. Rose T. Faghih served as the senior author.

Poster #3

Pinging the Network: Dynamics of Correlated Variability in Visual Cortex Induced by Optogenetic Stimulation

Andrei AR[1], Akil A[2], Kharas N[1], Pojoga S[1], Janz R[1], Josic K[2], Dragoi V[1]

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Cortical neurons produce highly variable responses to repeated presentations of identical stimuli. This variability is correlated between neurons within a local population (commonly called ‘correlated variability’), and provides a simple, dynamic measure of the functional connectivity within a network. Correlated variability has been demonstrated to change as function of arousal, attention, learning, and even under different task rules. Many theoretical studies have proposed that correlated variability can be both beneficial and detrimental to stimulus encoding. However, how such changes in correlation structure can be mechanistically implemented in local networks is unknown. Furthermore, to directly study the impact of correlation structure on stimulus encoding requires the ability to causally modulate correlations independent of other task parameters, and no such method currently exists.

Previously, we have shown that during the presence of a low contrast visual stimulus, optogenetic activation of excitatory V1 neurons in awake, behaving non-human primates leads to an overall decrease in correlated variability (Andrei et al. 2019). In this study we investigate whether optogenetic activation of excitatory neurons *in the absence* a visual stimulus alters the correlation structure of the network. We also extend our analysis to examine time periods both *during* and *after* the optogenetic stimulation. We report two surprising results. First we demonstrate that in the time period immediately following optogenetic stimulation (several hundred milliseconds), when firing rates have returned to baseline, there is a robust drop in correlations across the population. Is the drop in correlations immediately present, or does it develop across trials, which would indicate plastic changes within the network? Surprisingly, we found that during the optogenetic stimulation, early trials show increases in correlated variability, while late trials were decreased compared to baseline and control trials.

Our study provides the first demonstration of a causal method by which to modulate correlated variability without affecting firing rates. Additionally, we showed that population correlations during laser stimulation drop over the course of minutes/hours. Lastly, a balanced network model with homeostatic synaptic plasticity replicates both experimental findings.

SUPPORT FROM NIH U01NS094368-03

Poster #4

Real-Time Seizure State Tracking Using Two Channels: A Mixed-Filter Approach

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Accurate and cost-effective seizure severity tracking is an important step towards limiting the negative effects of seizures in epileptic patients. Electroencephalography (EEG) is employed in this research due to its reliable acquisition, high temporal resolution, portability, and relatively low cost. In this research, seizure state detection was performed using a mixed-filter approach to reduce the number of channels. We first found two optimized EEG features (one binary, one continuous) using wrapper feature selection. This feature selection process reduces the number of required EEG channels to two, making the process more practical and cost effective. These continuous and binary observations were used in a state-space framework which allows us to model the continuous hidden seizure severity state. Expectation maximization was employed offline on the training and validation data-sets to estimate unknown parameters. The estimated model parameters were used for real-time seizure state tracking. A classifier was then used to binarize the continuous seizure state in order to compare our results to past research.

Our results on the experimental data (CHB-MIT EEG database) validate the effectiveness of our proposed method, leading to an average accuracy, sensitivity, and false positive rate of 85.8%, 91.5%, and 14.3%, respectively. These results have similar performance characteristics as compared to previous studies who analyzed the same dataset. These previous studies employed all channels, complex features and machine learning algorithms, larger window sizes, and only offered binary seizure information. The above results have shown that it is indeed possible to perform real-time seizure detection using EEG with a limited number of channels to track the continuous seizure state, which provides us information about the timing and severity of the seizure. This type of seizure state modeling could be used in further implementations of adaptive closed-loop Vagus nerve stimulation applications. Further research may see benefits from focusing improvements in several key aspects: channel count restrictions, type of features to include, and global seizure state acquisition. First, it may be a beneficial to locate all affected channels during the training stage, rather than a maximum of two, which would increase the number of necessary electrodes, but would likely be able to achieve a higher performance. Secondly, the method described in this research uses a single continuous and single binary feature, but steps had to be taken to avoid overfitting to the continuous feature as the algorithm seemed to favor the continuous feature over the binary feature. Future algorithm design could instead take as inputs two or more continuous features, in addition to the sole binary feature. Finally, if future applications do not require any form of channel restriction (i.e. due to a reduced cost in EEG headsets), the above algorithm could use a Kalman filter to find a global seizure state based on channel-specific seizure estimations. While this negates the goal of channel restriction since information from all EEG channels would be necessary, the ability to predict in real-time would be maintained and, by using all channels, it is expected to achieve higher performance.

Poster #4

The work was supported in part by NSF grant 1755780 CRII: CPS: Wearable-Machine Interface Architectures– NRI: Collaborative Research: Multimodal Brain Computer Interface for Human-Robot Interaction, and NIH grant 1R01NS092894-01 – Towards an Autonomous Brain Machine Interface: Integrating Sensorimotor Reward Modulation and Reinforcement Learning. Rose T. Faghih served as the senior author.

Poster #5

Time-Dependent Decision Urgency in Dynamic Reward and Evidence Quality Conditions

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Making accurate and rewarding choices requires adaptive evidence accumulation and decision strategies that respect the potentially-dynamic environment. A foraging animal must decide to continue exploiting their current territory or to risk exploring new areas for potentially better alternatives. To make these decisions effectively, they must consider unexpected environmental changes (e.g., in food availability). Work on understanding how subjects behave in such dynamic contexts has mostly focused on tasks where the strength of observed evidence changes between trials.

To better understand how time-dependent decision criteria influences subjects, we extend Bayesian strategies to "dynamic-context" environments, where the reward or evidence quality changes within-trial according to a discrete-state Markov process. Using dynamic programming we find optimal decision thresholds for observers that maximize their reward rate. This results in time-varying thresholds that depend strongly on task parameters: thresholds can collapse as in the "urgency-gating model", exhibit non-monotonic behavior when context change times are known in advance, or jump discretely when context changes in a Markovian fashion. Using these thresholds, we leverage efficient solution methods for dynamic drift-diffusion models to find response time statistics of the observer. Our results can aid in experimental design and give insight for interpreting data from dynamically-changing tasks.

Poster #6

Modularity Allows Classification of Human Brain Networks During Music and Speech Perception

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Therapeutic music engagement has been shown to enhance traditional medical treatments for neurological disease and trauma by increasing recovery gains and improving cognitive health. However, further research is needed to quantify the impact of music on the brain. Here, we investigated the extent to which modularity could be used to differentiate and predict whole-brain network structure while healthy subjects actively listened to a variety of auditory pieces that varied in cultural familiarity and emotivity. Modularity measures the degree to which functional activity within a module of brain regions is more highly correlated than activity between modules.

We acquired fMRI data of 25 healthy subjects at the MRI core of Houston Methodist Hospital (Philips Ingenia 3.0T scanner, 2.4s repetition time, 130 volumes) using a block design of six alternating 24s-intervals of silence and auditory stimulus. Subjects listened to a favorite song, unemotional speech (newscast by Walter Cronkite), emotional speech (Charlie Chaplin in The Great Dictator), culturally familiar music (instrumental piano by J.S. Bach), culturally unfamiliar music (Gagaku classical Japanese opera), and unfamiliar foreign speech (click language of the South African Xhosa tribe). We performed whole-brain network analysis and determined modularity using Newman's algorithm.

We categorized subjects based on their modularity during their favorite song. We found significant differences between these groups for how their brains adapted during the other auditory pieces. When comparing module composition, we found consistency in the network organization of brain regions associated with hearing, vision, and bodily sensation. However, there were group-wise differences in the module allegiance of brain regions involved in emotional processing and the default mode network across different auditory pieces.

The differences seen between the groups may provide insight into why the effect of auditory-based therapeutic interventions varies across individual patients. Furthermore, our analysis of the modular organization of brain regions begins to tackle the question of why listening to music is distinct from other auditory-based therapy enrichments, such as audiobooks, and help understand the mechanism of therapeutic action. Modularity as a quantifier of whole-brain activity paves the way for creating individualized predictions of response to music engagement and tailoring music therapy interventions.

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Poster #7

Towards a Unified Theory of Information Processing in Resource-constrained Brain Circuits

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One of the fundamental problems in the brain is inferring what's going on in the world given its sensory evidence. For example, how does the brain infer what a particular object is based on how it looks, smells, feels or tastes? Probabilistic graphical model is a promising approach to tackle such problems of finding the latent variable (e.g. what the object is), given the evidence of variables it is statistically related to (e.g. smell, taste etc.). One way of estimating the latent variables, given other observations, is by marginalizing all the latent variables that are not of interest. However, this would be computationally intense with an increasing number of latent variables. Message passing algorithms aim to find the posterior distribution of the hidden variable with a lesser cost, by sending information along the graph that represents what's statistically related to what. But even messages themselves are expensive. To that end, it would be computationally less expensive if only messages that carry unknown information are passed and the ones with known information are not. This had motivated the idea of 'predictive coding', which has now become a popular framework for understanding visual processing via message passing between lower and higher levels of cortical hierarchies. It is based on the assumption that there exists a hierarchical generative model that models the higher level `causes' that led to the lower level sensory observation. It posits that predictions are sent downstream from higher levels of the hierarchy, and the residual difference between the actual observation and the predictions are sent back upstream. These residuals aid in updating the internal generative model, so as to better fit the observation. However, a major drawback of predictive coding is that it doesn't actually account for the fact that sending predictions around could come with a huge cost. In this project we aim to account for some of the biologically plausible costs involved in performing brain inference, such as the power consumed in sending predictions and residual messages, and an accuracy-based cost that quantifies how close is the final estimate in comparison to the true distribution. By incorporating these costs, we design and analyze various scenarios that could help us understand when is it optimal to send predictions as compared to just having a feedforward strategy, and what kind of predictions are helpful. In order to make progress in this direction we started with a simplified system, with assumptions such as Gaussian and linearity to make it tractable. Although these assumptions are too strong to exactly model the brain function, it acts as a good starting point for building intuitions on modeling neural response properties from first principles. As a direct consequence of which we would be able to predict how neurons respond to novel inputs, and would thereby lead to a good theory of brain function. Understanding how neurons process information in resource-constrained settings also has potential applications in medicine and engineering, for example, in building smart devices that have to perform in high noise settings with minimum power consumption.

Poster #8

Meso-scale Functional Connectomics for the Characterization of the Cortical Wiring Diagram

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The last decade has seen a surge in artificial neural network performance on tasks ranging from object recognition to competitive games, in many cases surpassing human level performance. Despite these accomplishments, artificial neural networks are prone to adversarial attack and do not generalize well across tasks. In contrast, over millions of years, the mammalian brain has evolved a capacity for generalization and robustness that is thought to be implemented in the structure and function of its neural networks. We hypothesize that a thorough characterization of the wiring rules of the mammalian brain could inform and constrain neural network architectures to improve their performance. The task of determining the structure and function of neurons in the brain (functional connectome) is challenging because there are limited methods to assess synaptic connectivity while maintaining neural functional properties at scale. A recent collaborative initiative has yielded a $1mm^3$ electron microscopy (EM) dataset of mouse visual cortex (the largest functional dense reconstruction to date) spanning V1 and 3 higher visual areas that has been co-registered to 2-photon functional imaging of the same neurons.

In conjunction with collaborators, we have developed a number of tools to extract meaningful relationships from this data. Specifically, even with state-of-the-art EM segmentation algorithms, the final connectome (a collection of 3D neuronal meshes and their synapses) contains incorrect splits and merges that require additional processing to correct. Therefore, proofreading tools for both stitching neuron segments together and separating incorrect mesh merges was a necessary preprocessing step for obtaining clean connectome data. Then, using heuristic algorithms we can extract locations of soma centers, label unique subcellular compartments, and extract skeletons from meshes for morphological analysis. Additionally, we have developed tools to be able to assign functional properties such as orientation tuning or spatial receptive fields to the same neurons identified in both the functional data and EM segmentation. This pipeline therefore can yield an expansive wiring circuit overlayed with the response properties of the individual components.

In this ongoing project, we will investigate the brain's organization using a number of analysis methods: comparing graphical models generated from neural responses to the anatomical model, exploring spatial and functional wiring clusters or motifs, and observing the effects of neuron morphology on functional and wiring properties. We can then evaluate neural network architectures constrained on any organizational knowledge gained from our analysis not only for overall performance on different tasks but also for strength against adversarial attacks, with the goal of achieving higher generality and robustness.

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Poster #9

Beta and Low Gamma Oscillation Dynamics in Primary Motor Cortex of 6-OHDA hemi-Parkinson's Rat during Voluntary Movement Initiation

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The reduction in the number of dopamine (DA) cells in subthalamic nucleus (STN) is the pathological signature of the patients with Parkinson's Disease. With the loss of DA regulation, abnormally high power of electrophysiological oscillations, from 20 to 45 Hz near beta and low gamma band, in primary motor cortex (M1) is observed and is believed to be the reason of bradykinesia in DA patients. Studies using 6-hydroxydopamine (6-OHDA) rat model showed the frequency and power modulation of the abnormal oscillation during movement. However, constrained environment, for instance, treadmill for forced movement, did not demonstrate the voluntary aspect or allow to target the transition between behavioral statuses of 6-OHDA-lesioned rats. And the temporal dynamics of the abnormal rhythm during behavior and how it is different from healthy rat's M1 signal oscillation is still not understood.

Here, we used simultaneous video tracking and electrocorticography (ECoG) recording of M1 in both hemispheres of 6-OHDA-induced hemiParkinsonian rats during free moving on customized tracks. Behavioral performance degradation of rats from early lesion stage to late lesion stage was showed with the change of defined movement initiation (MI) events. Based on the findings, we suggest that there are components in different frequency bands in the abnormal oscillation in M1 of 6-OHDA lesioned rats and they have different likelihoods to happen during the initiation of a behavior. The potential multiple types of rhythm inside M1 could help us understand the dynamics of lack of regulation of DA cells in STN.

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Poster #10

Non-Markovian Sequence Learning and Recall with Hebbian Based Learning Rules

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Sequence learning and representation is essential for many aspects of behavior. However, the ability to learn and recall complete sequences with biophysically realistic networks and learning rules is non-trivial. In particular, encoding non-Markovian input sequences (sequences where transitions depend on prior states, e.g. 1-2-1-3) is a challenge for many types of networks. We propose here a biophysically realistic, three-stage network that is capable of learning complex non-Markovian sequences, recalling them in their entirety upon only partial reactivation. While this model is not explicitly based on particular brain regions in particular animals, one may compare it to other multi-stage brain networks which can learn non-Markovian sequences (e.g. the auditory processing system in songbird[1], wherein neurons have been shown to encode history dependent, non-Markovian transitions[2]).

The model consists of three distinct stages – 1. A columnar network consisting of populations of rate based model neurons which receive sequential external inputs, 2. A fixed liquid state machine (LSM) which receives inputs from the columnar network, thereby maintaining a history dependent representation of the main network, 3. A sparse network which receives inputs from the LSM, so as to create easily separable and unique patterns that represent the history in the network up to and including time t. These sparse patterns then learn to feed back into the columnar network, allowing the main network to indirectly encode history dependent information. Learning within the columnar network is performed via Hebbian activated "eligibility traces", which hold a history of synaptic activity before being converted into changes in synaptic strength upon a change in stimulus. Learning between the sparse pattern network and the columnar network is performed via a simple Hebbian rule.

During training, a particular sequence of inputs is presented to the columnar network. Elements may be repeated such that the presented sequence is non-Markovian (e.g. 1-2-1-3). As this sequence is presented, neurons within a particular column learn to modify their recurrent weights as to represent the duration of a particular element in the sequence. The sparse, history dependent patterns then learn to connect to subsequent columns implicated in the sequence, thereby encoding order. After training, presentation of only the first element (e.g. 1) in that sequence is sufficient for the network to recall its entire representation of the trained sequence (e.g. 1-2-1-3). This capability demonstrates the efficacy of the model as a framework for non-Markovian sequence learning and memory.

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Poster #12

Dendritic Ca^{2+} Imaging of a Looming Sensitive Neuron Shows Segregation of Excitation by Contrast Polarity

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Visually-guided collision avoidance and escape is critical to the survival of many animals, and a wide range of species from insects to mammals possess dedicated neurons for the detection of impending collisions. Of the neural circuits dedicated to collision avoidance, one of the best understood is in grasshoppers, which have a single neuron per eye called the lobula giant movement detector (LGMD) that responds preferentially to objects approaching the animal on a collision course or their two-dimensional simulations called looming stimuli. The LGMD has three distinct dendritic fields: A, B, and C. Field A receives retinotopic excitatory inputs through nicotinic acetylcholine receptors (nAChR). Fields B and C have long been believed to receive synaptic inputs limited to non-retinotopic, GABAergic feedforward inhibition. Here, we reveal an additional novel excitation impinging onto dendritic field C. Calcium enters field C of the LGMD through excitatory nAChR with larger responses for white looming stimuli (luminance increment) than for black looming stimuli (luminance decrement). This polarity preference is the opposite of the previously described excitation onto field A. As with excitatory inputs onto field A, excitation onto field C is enhanced by muscarinic receptors. Although many neurons have synaptic inputs impinging onto separate dendritic fields, the computational roles of this input segregation are still largely undescribed. Therefore, describing this novel excitatory pathway and its functional consequences will help us understand how visual systems implement collision avoidance and the computational roles of segregating synaptic inputs onto separate dendritic fields.

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Poster #11

Neural Circuits and Pupil Readouts of Motivated Shifts in Attentional Effort

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Background: Attending to a speaker in a noisy environment, such as a cocktail party, can be a pleasantly immersive experience for individuals with normal hearing and cognitive function. However, for individuals with hearing loss or cognitive impairment, this auditory attentional effort, also called 'listening effort', is their primary complaint, and can be a severe source of stress and fatigue. Pupillometry (measuring the size of the pupil of the eye) has proven extremely useful as a physiological readout of AE. However, we have very little understanding of what the pupil actually indicates about activity in the brain during attentional tasks, including about the neural circuits underlying AE.

Objective: In previous work, we extensively characterized the physiological correlates in the auditory system of several pupil metrics during a simpler auditory behavior. The combined results lead us to the following three hypotheses regarding neural circuit mechanisms and pupil readouts of AE: 1) pupil metrics of AE on fast and slow timescales, track release of norepinephrine and acetylcholine in auditory cortex, respectively; and 2) efficacious AE (motivated, high d') is associated with improved extraction of task-relevant acoustic information by the auditory cortex. In addition, human fMRI work consistently finds that frontal cortex structures known to combine task performance and motivation contribute to AE. Therefore, we hypothesize 3) that stimulus representation-enhancing sensory-frontal interactions are also tracked by the pupil.

Methods: To test these hypotheses, we have developed a behavioral approach to motivated AE in mice. We analyze behavior, physiology, and pupil data using drift diffusion modeling (DDM) and a new approach we call real-time signal detection theory (RT-SDT). Mice report detection of temporal coherence in a cloud of tones by licking for sugar reward. We parametrically vary the difficulty on each trial and manipulate AE by changing reward volume in blocks of trials.

Results: Here, we report behavioral and physiological signatures of flexible effort allocation in >30 mice. First, increased attentional effort in high reward blocks manifested as improved detection of the weak signals. Specifically, in high-reward blocks, mice increased their sensitivity (d') to detect coherence in noise, particularly for the weak-coherence targets. Second, mice exhibited at least 5 attentional effort shifts within a single session, which were tightly time-locked to the switches in reward context (e.g. within a small # of trials). Third, contrary to the trivial prediction that higher rewards increase general arousal, we found that mice actually *decreased* their arousal in high reward blocks, apparent in the baseline pupil diameter. This indicates that the brain stabilizes in a moderate-arousal state that is more optimal for detecting weak signals. Fourth, the feedback-related pupil response reflected multiple learning signals across blocks, including correctness, reward context, and prediction errors, which might be used to flexibly regulate attentional effort.

Conclusion: In sum, we find that mice adapt their allocation of cognitive resources to changes in the environment. In ongoing work, we are electrically recording from neurons in the auditory cortex and two-photon imaging interactions with neuromodulatory systems or frontal cortex, while doing pupillometry during our task, and applying the above-mentioned computational frameworks. Our results will reveal the contributions of neuromodulatory and frontal cortex inputs to auditory cortex to motivated shifts in temporal coherence detection and will directly relate

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multiple pupillometry metrics and statistical modeling approaches to these circuit mechanisms in a computationally robust way.

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Poster #13

Biased Response Distributions For Short Observation Sequences Of Rare Events

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When choosing between different options we frequently rely on information of non-uniform frequency and quality. In contrast to most experimental studies, when faced with two *a priori* equally likely options, evidence favoring one may be rare, but of high quality, while evidence favoring the other may be abundant, but less convincing. How do human observers make decisions in these situations? Here, we show that when presented with such asymmetric evidence, responses of ideal observers exhibit strong biases, especially when evidence is limited. Preliminary behavioral data shows that responses of human subjects reflect these trends.

We consider a task in which subjects observe a sequence of red/blue balls drawn with replacement from one of two jars. Subjects must infer which of the two a priori equally probable jars the balls were drawn from. When both jars have a small fraction of red balls and only a few balls are drawn, an ideal observer exhibits a strong bias towards the jar with fewer red balls, even on trials when balls come from the high-fraction jar. This bias occurs because observations that point to the high-fraction jar (in this case, red balls) are rare, and are not often seen in short sequences. This response bias disappears with long observation sequences or in tasks where red ball fractions sum to one.

To see whether and how humans deviate from ideal observers, we are recruiting a large number of subjects on Amazon's crowdsourcing website, Mechanical Turk. Preliminary data suggests humans implement a near-Bayesian strategy in identifying the true jar, including the same bias toward the low-fraction jar in asymmetric tasks. Thus, our study yields new quantitative insights into rare-event inference, which is relevant to both real-world problems (like predicting stock-market crashes) and common laboratory tasks (like inferring rare state changes in dynamic environments).

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Poster #14

Approximate marginalization of graphical models with third-order interactions using Graph Neural Networks

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Statistical inferences are widely used in neuroscience including modeling neuronal coding mechanism, predicting animal's behavior given neural measurements, and vice versa. A fundamental step to perform statistical inference is to compute the parameter posteriors, which is equivalent to computing the marginal distributions over observable variables. To this end, graphical model is a common method used to describe conditional dependencies and reduce computational complexity. We would like to *perform inference on graphical models with higher-order interactions* for neuroscientific interest. For example, the Gaussian Scale Mixture model for divisive normalization in cortex can be naturally expressed as a third-order interaction model.

Message-passing algorithms like belief propagation are commonly used to compute marginal distributions, but it usually fails on loopy graphical models. Previous studies show that models with merely pairwise interactions like variants of Ising model are not sufficient to explain some neural dynamics, while specific organizations of higher order interactions are still elusive. Among higher order interactions, the third-order one is of interest to us since one component could act like an on-off or positive-negative switch that controls the correlation dependence of the other two and thus remains interpretable. In this work we train *Graph Neural Networks* (GNNs) to learn a *message-passing function* that is capable of performing approximate inference on graphical models with loops and third-order interactions.

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Poster #15

Closed-loop Physiological Signal Processing in Stress Management and Energy Regulation

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The brain can be considered as a control system with a strong impact on all human functions, including health and performance. Inspired by recent advances in wearable technologies, we employ virtual sensing to infer brain activity. Specifically, the objective here is to use wearable-machine interface (WMI) architectures for controlling biomedical systems. The WMI architecture encompasses collecting physiological data using wearable devices, inferring neural stimuli underlying pulsatile signals, estimating an unobserved state based on the underlying stimuli, designing the control, and closing the loop in real-time. In this work, our research focus is on: (1) regulating one's cognitive stress, and (2) regulating an energy levels in hypercortisolism.

Distress, or a substantial amount of stress, may decrease brain functionality and cause neurological disorders. On the other hand, very low cognitive arousal may affect one's concentration and awareness. The human body responds to cognitive stress in multiple ways through its autonomic nervous system. One of the most important responses is changes in sweat gland secretions. Our goal here is to maintain a person's stress levels within a desired range. To do so, by monitoring skin conductance variations (as a validated stress indicator), we relate it to one's cognitive stress-related state. Then, using Bayesian filtering approach, we estimate a hidden cognitive stress-related state. Finally, we employ control strategies to regulate stress and close the loop. In particular, we design two classes of controllers for our WMI architectures: (1) an inhibitory controller for reducing arousal and (2) an excitatory controller for increasing arousal. One of the main advantages of the proposed structure is its expandability. The knowledge-based fuzzy approach can be modified to cover different types of stress tasks as well. Music could eventually be used as a non-invasive means of actuation for managing stress.

The other area is energy regulation in hypercortisolism. Cortisol, one of the most important glucocorticoid hormones, is released in a pulsatile manner. An abnormal cortisol secretion pattern can be critical, and usually results in irregular daily energy variations. Hypercortisolism, a pathological secretion of excess cortisol, widely causes sleep disorders and daytime fatigue. To regulate energy levels in patients with hypercortisolism, we first employ a state-space model to infer a hidden cognitive energy-related state from one's cortisol secretion patterns. We estimate this hidden energy state using Bayesian filtering. Finally, we design a fuzzy control structure and simulate corresponding cortisol drug dynamics to regulate cortisol secretion and thereby regulate energy. In order to verify the performance of our proposed architecture, we consider one open-loop (i.e. a healthy subject) and two closed-loop scenarios (i.e. Cushing's patients- patients with excessive levels of cortisol- with and without circadian rhythm in their profiles). To regulate the cortisol levels to follow a circadian rhythm, we simulate the effect of medications (e.g. Mifepristone for elevating cortisol and Ketoconazole for clearing cortisol). Future work would include incorporating other possible medications and designing the control algorithms with the capability to choose from them. This system design could potentially be

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included in an automated cortisol infusion pump to enable efficient energy regulation with minimal side-effects in the real world.

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Poster #16

Low-dimensional Geometry of Receptive Fields Constrains Correlations

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Schneidman et al. demonstrate in their seminal paper “Weak pairwise correlations imply strongly correlated network states in a neural population” (Nature, 2006) that pairwise correlations capture most of the information-theoretic content of network states in vertebrate retina. They show that a second-order maximum-entropy model accounts for more than 90% of information beyond the firing rates of the population. Similar methods have been used to show that low-order correlations can accurately predict global network states in the retina of a variety of vertebrates, as well as in mouse hippocampus. We suggest that there is an elementary explanation for these results: the observed information-theoretic properties of the neuronal activity are heavily influenced by the geometry of the underlying receptive fields that induce the pairwise correlations.

To test our hypothesis, we investigate model neuronal populations of independent Poisson processes. Each model neuron has a receptive field in a d-dimensional space but no network interactions with the other neurons; thus, the receptive fields alone induce a pattern of pairwise correlations. Using these populations, we study the information content of the neural code as a function of the dimension of the stimulus space. We find the original result of Schneidman et al. is reproduced in these model populations as long as the stimulus space dimension d is relatively small and the receptive fields are *convex* subsets of the stimulus space. Moreover, as d increases, this information content is no longer well-explained by the pairwise correlations.

We find there is a simple mathematical explanation of our results: Helly's theorem restricts the possible intersection patterns of convex receptive fields, which naturally translates into the result that higher-order correlations can be mostly explained by the pairwise correlations for neurons with convex receptive fields. Helly's theorem has analogues in any dimension d, but for brevity we state it here for $d = 2$:

Helly's Theorem. If every three-fold intersection of a collection of two-dimensional convex sets is nonempty, then all possible higher-order intersections of these convex sets is nonempty as well.

In our model, the correlation between neurons is determined by the intersections of convex receptive fields, so this theorem implies that higher-order correlations are determined by the correlations of order $d + 1$. In the $d = 2$ case, as in the retina, the constraints of geometry make it unlikely that mutual pairwise intersections among three receptive fields hold without the three-fold intersection, and thus we expect the higher-order correlations to be mostly determined by the pairwise correlations. Moreover, this will fail to hold in higher dimensions, suggesting that information-theoretic analysis of neural codes may shed light on the dimension of the stimulus space represented by the neuronal population under consideration.

Poster #17

Inverse Rational Control with Partially Observable Continuous Nonlinear Dynamics

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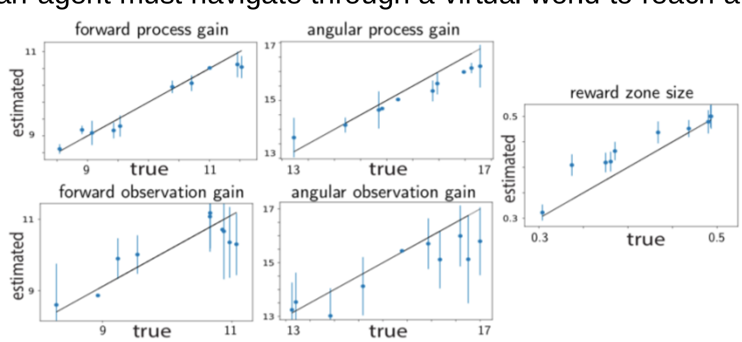
Summary A fundamental question in neuroscience is how the brain processes sequences of ambiguous sensory information to plan and generate actions. This is naturally formulated as a control or reinforcement learning problem under partial observations, where an animal must estimate relevant latent variables in the world from its evidence, anticipate possible future states, and choose actions that optimize expected reward. This problem can be solved by control theory which allows us to find the optimal actions for a given system dynamics and objective function. However, animals often appear to behave suboptimally. Where does this discrepancy come from? We hypothesize that animals have their own internal model of the world which may not be always correct, but they still behave rationally, choosing actions with highest expected subjective reward according to their internal model. Inverse Rational Control (IRC) [1] has been proposed to learn which internal model best explains an agent's behaviors. This method finds the parameters of a class of Partially Observable Markov Decision Processes (POMDPs) that have the maximum likelihood of explaining experimental observations. In [1], the authors focus on a foraging task in discrete belief and actions spaces. Here we extend IRC to more difficult problems where the state space and actions both take continuous values. This allows us to estimate animals' internal models in more naturalistic, complex neuroscience tasks. In order to address continuous state, action and parameter spaces, we use a deep reinforcement learning method called Deep Deterministic Policy Gradient (DDPG) [2] to optimize the policy. In order to maintain interpretability of deep learning based approach, we provide the model parameters as explicit additional inputs to the actor- critic networks of DDPG, so the network learns to generalize over the entire model parameter space. We then induce a likelihood over these parameterized tasks and use gradient ascent to find the model parameters that maximize the likelihood for the measured trajectories of sensory observations and action. Our proposed method is able to recover the true model of simulated agents within theoretical error bounds given by limited data. This approach provides a foundation for interpreting the behavioral and neural dynamics of animal brains.

Results We demonstrate the success of our proposed framework by a simulation study where we know the ground truth. In our task, an agent must navigate through a virtual world to reach a flashing target. The agent can control its forward and angular velocity, and the reward is given if the agent is sufficiently close to the target location. Each target is visible only briefly and sensory inputs provide noisy observations of self-motion, so the agent is uncertain about the current position of its target as well as its current velocity. We parameterize



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the agent's model of the environment by the gains on its control inputs and sensory observations. Our simulation results show that we successfully recover all of these parameters using our method.

Poster #18

Learning from Brains How to Regularize Machines

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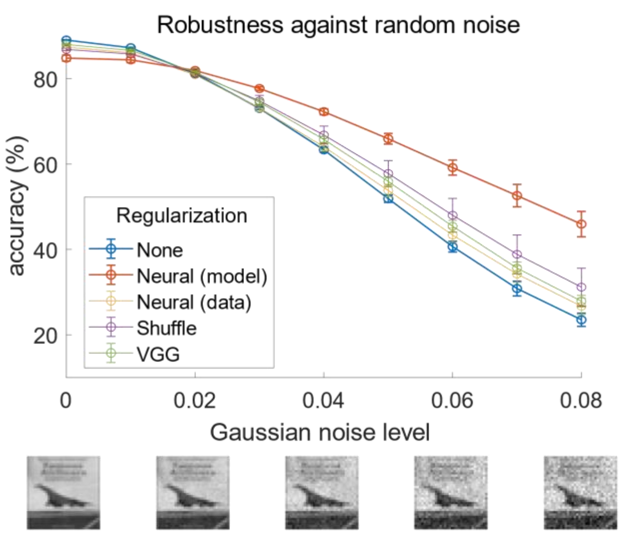
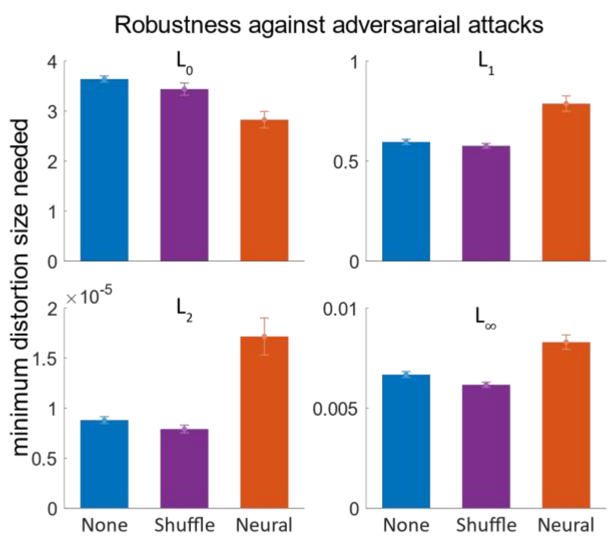
Despite impressive performance on numerous visual tasks, Convolutional Neural Networks (CNNs) — unlike brains — are often highly sensitive to small perturbations of their input, *e.g.* adversarial noise leading to erroneous decisions. We propose to regularize CNNs using large-scale neuroscience data to learn more robust neural features in terms of representational similarity. We presented natural images to mice and measured the responses of thousands of neurons from cortical visual areas. Next, we denoised the notoriously variable neural activity using strong predictive models trained on this large corpus of responses from the mouse visual system and calculated the representational similarity for millions of pairs of images from the model's predictions. We then used the neural representation similarity to regularize CNNs trained on image classification by penalizing intermediate representations that deviated from neural ones. This preserved performance of baseline models when classifying images under standard benchmarks, while maintaining substantially higher performance compared to baseline or control models when classifying noisy images. Unlike data augmentation by adding noise during training, the neural regularization induces robustness that generalizes to other types of noise. Moreover, the models regularized with cortical representations also improved model robustness in terms of adversarial attacks. This demonstrates that regularizing with neural data can be an effective tool to create an inductive bias towards more robust inference.





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Acknowledgements
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Poster #19

Superficial vs. Deep Neural Oscillations in Human Prefrontal Cortex

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Introduction

Neural oscillations in the prefrontal cortex are linked to higher order cognitive processes such as abstract thinking and cognitive control. It is currently unknown how information is transferred across the laminar structure of the PFC. We used a rare opportunity for simultaneous recording of electrocorticography (ECoG) and a Utah microelectrode array (UMA) to record superficial vs. deep LFP in the dorsolateral PFC (dlPFC).

Methods

A single patient with medically refractory epilepsy had a subdural ECoG grid and a UMA placed underneath for simultaneous recording of superficial and deep LFP in the dlPFC. They performed 3 sessions of the multi-source interference task (MSIT), which combined 'spatial' and 'distractor' conflict. We computed the phase-locking value (PLV) of the superficial and deep LFP (4-150 Hz) to determine if phase coherence is a mechanism for information transfer across depths.

Results

We observed significant phase locking ($p < 0.05$) between superficial LFP and deep LFP at lower frequencies (< 50 Hz), regardless of conflict type. When both spatial and distractor conflict were present in the MSIT task, phase locking maximized in the theta/alpha band (7-14 Hz) at about 300 ms post-stimulus. Post-stimulus spectral power showed a strong depth x frequency interaction ($p < 0.001$, $\eta^2 = 0.507$). Theta and alpha power were similar on the surface, but there was a greater disparity for deep LFP in the dlPFC ($p < 0.001$, $\eta^2 = 0.09$). Deep LFP was not phase locked to ECoG channels that were farther away from the UMA.

Conclusions

Low frequency phase locking could be a key mechanism promoting communication through coherence across cortical layers in the dlPFC. There may also exist a degree of frequency specialization, where theta oscillations are more prevalent deeper in the cortex.

Poster #20

Dissection of the Ionic Currents of Plateau-genic and regular Firing Neurons Indicates Unique Expression and Properties of Voltage-gated and Ca^{2+}-gated K^{+} Channels

Curtis L. Neveu, John H. Byrne

The computations employed by a neural network are mediated by specific configurations of ion channels within neurons and synaptic connections between neurons. Many questions remain as to what extent specific ion channels differ among neurons with different firing properties. For example, some neurons when activated express a plateau of activity that greatly outlasts the stimulation, whereas others do not. Some neurons are selectively activated by a network depending on the context (e.g., the presence or absence of food), while other neurons are activated in all contexts. I took advantage of the relatively simple neuronal circuit mediating feeding motor programs in *Aplysia californica,* to analyze the biophysical properties of three behaviorally important neurons: a selectively active plateau-genic neuron (SP), a non-selectively active plateau-genic (XP), and a selectively active regular spiking (i.e., non-plateau-genic) neuron (SX). Therefore, these experiments allows a comparison between plateau-genic vs regular spiking neurons and selectively active vs non-selectively active neurons. We found that transiently activated A-type K^{+} has a steeper voltage dependency of activation and inactivation and higher current density in the SP neuron, whereas the inactivation of A-type K^{+} is slower in the SX neuron compared to other neurons. The more persistent delayed K^{+} has a greater current density and lower inactivation in the XP neuron compared to the SP neuron. The Ca^{2+} activated K^{+} was not expressed in the XP neuron and had a similar current density in the SP and SX neurons. These results were surprising in that many properties of these channels were similar in neurons with vastly different firing properties (e.g., the voltage dependency of A-type K^{+} is similar in the plateau-genic XP neuron and the regular spiking SX neuron), whereas other properties were dramatically different in neurons with similar firing properties (e.g., the voltage dependency of A-type K^{+} is different between the plateau-genic SP and XP neurons). Conductance-based computational models will help explain how the different firing properties emerge from the unique configuration of these ion channel properties and provide insights into how these properties affect the computations of the network. Repetuar

Poster #21

Probabilistic Feedback Updates Priors in Sequential Decisions with Accumulated Evidence

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To make the best decisions organisms must flexibly accumulate information, accounting for what is relevant and ignoring what is not. Many decision-making studies focus on sequences of independent trials in which the evidence gathered to make a choice, as well as the resulting actions and feedback are irrelevant to future decisions. Two-alternative forced choice tasks (2AFC) are often used to characterize strategies subjects use to make decisions. Normative theories have been developed for such tasks when rewards provide the sole evidence (e.g., two-armed bandit tasks). Less is known about how observers should integrate probabilistic rewards interspersed with noisy evidence to inform their decisions in future, correlated trials. To understand decision-making under more natural conditions, we propose and analyze models of ideal observers who accumulate evidence to freely make choices across a sequence of correlated trials and receive noisy feedback. We describe the behavior of an ideal observer and ask how actual subjects' decision-making strategies could deviate from optimality.

We extend drift-diffusion models to obtain the normative form of evidence accumulation in a series of 2AFC trials with the correct choice evolving as a two-state Markov process. We analyze 3 different feedback cases: no trial-to-trial feedback, probabilistic trial-to-trial feedback, and probabilistic reward as feedback. Ideal observers integrate noisy evidence within a trial until reaching a decision threshold and bias their initial belief depending on the evidence accumulated and feedback received on previous trials.
Ideal observers optimize their reward rate across trials by adjusting their sequence of decision thresholds to deliberate longer on early decisions and respond more quickly in later trials. We show how conflicts between feedback and accumulated evidence are resolved, and under which conditions one of them dominates. Our findings are consistent with experimentally observed response trends.

Acknowledgement
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Poster #22

Hierarchical Latent Dictionary Models for Mental Workload Classification

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Human-computer interfaces (HCI) have been extensively researched due to their myriad applications. Rapid advancements in technology have led to human computer interactions in various fields, ranging from wearable health monitoring systems to online and virtual classrooms. As such, it is important to improve this interface so that the interaction between the human and the machine is seamless. Several factors affect the performance of this interface; chief among them being the mental workload or cognitive stress of the user during interactions (especially during brain-machine interactions). Here we present a novel method to detect and classify the mental workload of the user during several memory-related tasks. Data from the neuroimaging technique known as Functional Near Infrared Spectroscopy (fNIRS) is analyzed using a Hierarchical Latent Dictionary Method (HLDM) to extract correlations that provide information on how the connections among different regions of the brain evolve.

When neurons in the brain are processing information, there is an increase in the overall blood flow to that area leading to a higher ratio of oxygenated hemoglobin to deoxygenated hemoglobin. fNIRS detects these changes in oxygenated and deoxygenated hemoglobin ratio using spectroscopy. Oxygenated and deoxygenated hemoglobin absorb the light that is incident upon them at different levels. A source-detector pair is used to measure the amount of oxygenated and deoxygenated hemoglobin, which indirectly points to which regions of the brain are active. Modified Beer Lambert Law is then used to quantify hemoglobin concentration changes based on the variations in absorption. On this data, we apply the HLDM which defines the observations as a result of a few latent factors. These latent factors are modeled as the influence of neural signals, represented as Gaussian processes. Thus, extracting the correlations between channels incorporates the influence of neural signals and time-evolving connections between different regions of the brain. These covariance matrices are then used as inputs to several machine learning algorithms to classify between different levels of difficulty in the memory tasks.

HLDM is applied to an n-back experiment, where the participant is presented with a series of stimuli and must determine whether the current stimulus is the same as the n_{th} previous one. We successfully obtain the time evolving functional connectivity for different difficulty levels. The lowest level of difficulty, the 1-back task, had few areas of the brain that were similarly correlated when compared with the connectivity map from the highest difficulty level, the 3-back task, which had major portions of the prefrontal cortex similarly correlated indicating increased neuronal participation. This shows that processing during the 1-back task requires fewer neuronal correlation, whereas processing during the 3-back task requires almost all of the pre-frontal cortex region of the brain. The covariance maps are thus instrumental in differentiating between different amounts of mental workload. We then utilize machine learning algorithms such as support vector machines, decision trees, and k-nearest neighbors to obtain good classification accuracies between different n-back tasks demonstrating the viability of the HLDM for building next-generation HCIs. Future avenues of work include applying HLDM on other existing neuroimaging data such as functional magnetic resonance imaging,

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magnetoencephalography, and electroencephalography in order to derive the functional connectivity.

The work was supported in part by NSF grant 1755780 CRII: CPS: Wearable-Machine Interface Architectures. Rose T. Faghih served as the senior author.

Poster #23

Population-level Analysis of Motor Pattern Selection During Feeding in *Aplysia*

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Rhythmic behaviors are often mediated by specialized circuits termed central pattern generators (CPGs). Substantial progress has been made toward understanding the cellular and synaptic processes that underlie the genesis of rhythmic neural activity. However, broader aspects of CPG function, such as tracking and characterizing the neural state of the CPG as it initiates, selects, and terminates patterned neural activity, are not well understood. Here, we describe methods for examining the extent to which both single-neuron and population-level activities can predict the initiation, selection, and termination of specific patterns of neural activity. Using voltage-sensitive dye imaging, we simultaneously monitored activity in ~100 cells in the buccal ganglia of *Aplysia*, which contain a CPG that mediates rhythmic feeding movements. This CPG generates buccal motor patterns (BMPs) corresponding to several types of feeding behaviors, such as ingestion (iBMPs) and rejection (rBMPs). We monitored and classified spontaneously generated BMPs using simultaneous recordings from buccal nerves. We used principal component analysis (PCA) to represent the activities of the ~100 cells in a low-dimensional space, and linear discriminant analysis (LDA) to find points in time at which neurons become predictive (Briggman et al., 2005). Preliminary results indicate that three principal components (PCs) are sufficient to capture distinguishing features of iBMPs and rBMPs. To examine the possibility that these features might be influenced by differences in the duration of the different patterns (Nargeot et al. 2002), we normalized the timescale, and repeated the analysis. We found that iBMPs and rBMPs are distinguishable (pattern selection) even when the patterns are compared on a normalized timescale. Lastly, we ranked neurons by how well they predicted pattern type, based on their weights across the first three PCs and the weights of the PCs across predictive linear discriminant functions. We found that the neurons that best predicted pattern type on the raw timescale, also were the best predictors on the normalized timescale. These results outline a generalizable approach that will be useful for making population-level predictions regarding the initiation, selection, and termination of patterned activity in neural circuits.

Funding:
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Poster #24

Optimality Test for Neural Networks Engaged in Fine Estimation with Nuisance Variables

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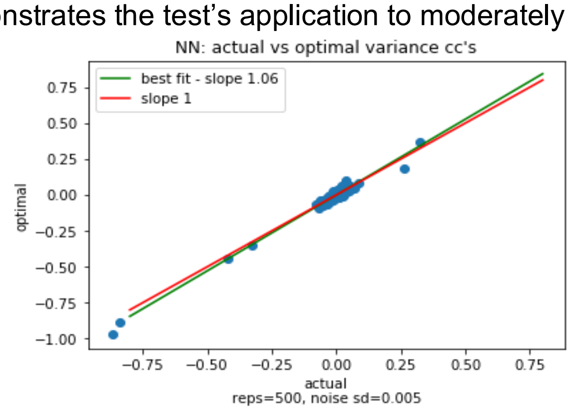
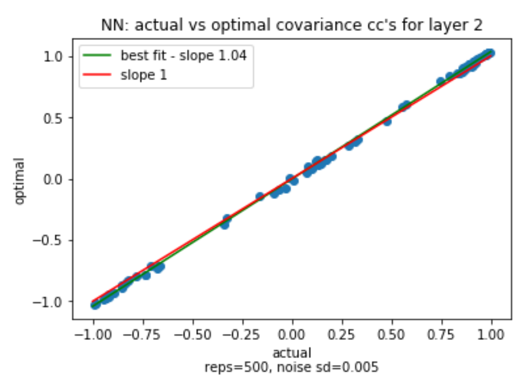
The brain must infer properties of the world even though its evidence is confounded by the presence of nuisance variables. The entanglement of the relevant and irrelevant variables causes sensory information to be hidden in the higher-order neural response statistics, embodying a nonlinear code. The presence of a nonlinear neural code is an unsurprising conclusion; after all, if a linear code were always sufficient, then our brains would not need nearly as much mass. However, the question that remains is how well does the brain use the resulting nonlinear information? Recent results (Yang, Pitkow 2018) provide a test that quantifies the brain's efficiency of using the information contained in neural response statistics, such as the mean or variance. The purpose of the present work is to apply this test to neural networks engaged in a moderately complex task. Neural networks are a good candidate for the test because of their power as a universal approximator. Thus, a neural network can reasonably extract higher-order informative statistics given enough resources. Treating a trained neural network as an artificial brain allows us to evaluate the utility of the efficiency test on a general computational network, and may be useful in diagnosing suboptimality in decoders.

The task is pose estimation, identifying the orientation of a sphere with varying texture as it moves along an arbitrary axis of rotation. A neural network was trained on images of the sphere rotating through a range of angles on the axis, and tested on images of the sphere rotating through a narrower range on the same axis. This produces a fine estimation task. Using the optimality test, we are able to compare the neural network's choice correlations to the optimal choice correlations predicted to arise when the decoder efficiently uses information contained in the input statistics such as pixel-pixel covariance.

Quantitatively, the test measures the choice correlation, namely the Pearson correlation $C_k := Corr(r_k, \hat{s})$, between the response r_k of neuron *k* and the behavioral estimate $\hat{s}$ of a stimulus *s*, to the corresponding correlation predicted from optimal decoding, $C_k^{\text{opt}} := \sqrt{\frac{J_k}{J}}$.

The network's performance is evaluated on training and test data; the training data covers a range of angles 0–15° while the test data covers 12–13°. We find that each layer of our trained network passes the optimality test for the mean, variance, and covariance of pixel data. This demonstrates the test's application to moderately complex tasks.





Poster #25

Neurophysiological Trait Effects Associated with Long Term Practice of Meditation

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Introduction: The scientific interest on meditation have grown drastically over the last few decades. Studies have shown structural changes in the brain as a result of long term meditation practice such as cortical thickness increase, factional anisotropy, axial and radial diffusivity, grey matter volume and density [1]. It has also demonstrated functional and clinical outcome such as reduced stress, depression and anxiety, better management of pain etc [2]. However, the effects of type of meditation on EEG is still not yet understood. Therefore in this study, we compare changes in spectral and functional connectivity features in 3 different styles of meditation traditions - Hatha Yoga (HY), Isha Yoga (ISY), Vipasana (VIP) practices w.r.t. age matched controls who do not practice meditation during breath awareness condition.

Methods: EEG was collected from 16 subjects who are long term meditators, trained in 3 separate meditation tradition along with 16 age matched controls new to meditation. The data used in the study was obtained from a previously published study [3]. Here we compare the EEG during breath awareness condition wherein the participants were asked to focus on their breath. EEG data was cleaned to remove low frequency drift, eye and muscular artifacts along with sudden non stereotypical bursts. The spectral band power features as shown in Figure 1 was computed for 1 second windows. Connectivity measure in different bands was estimated across sensors using debiased weighted phase locking value. Spectral features were compared against age matched controls as well as between conditions (meditation vs breath awareness). Statistical testing was done using non parametric bootstrapping (2000 iterations) and multiple comparison correction for channels was done using clustering technique.

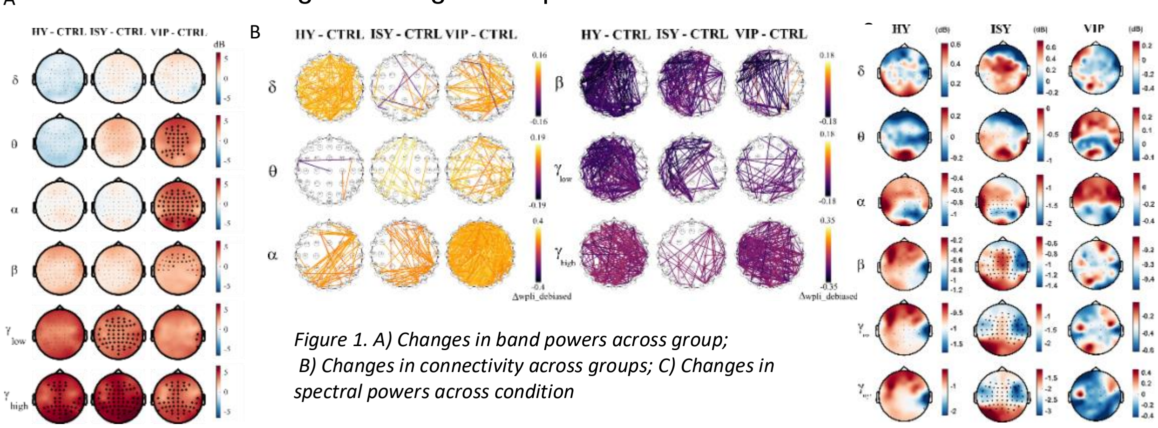

Figure 1. A) Changes in band powers across group; B) Changes in connectivity across groups; C) Changes in spectral powers across condition

Results: High gamma power (60-110Hz) increased in all 3 meditator group compared to controls. Low gamma power (30-45Hz) increased significantly in ISY alone. Alpha and beta power increased significantly only in VIP meditator group. Similar trend was seen in others practices even though not significant at $p < 0.05$. Power in higher frequency is significantly reduced during ISY (conscious non doing). Alpha power show trends of opposite behavior in anterior-posterior regions in VIP. Localization in occipital theta showing similar increase is observed in all 3 types. Connectivity is significantly different in slower vs faster bands across groups.

Conclusions: Distribution of power from higher frequencies to lower frequencies is generally observed with aging and in neuropsychiatric diseases. The findings here suggest the potential of meditation to slow down this trend. Comparing the changes in gamma power, alpha and gamma synchrony, we see that they follow trends opposite to majority of neurological diseases and could

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be signs of enhanced mental health.

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Poster #26

Functional Connectivity Graph Estimation from Nonsimultaneous Recordings

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Neuronal functional connectivity is the statistical dependence structure of neurons' activities. Functional connectivity is typically inferred from data recordings in the framework of *conditional dependence graphical models*, where nodes represent neurons, and an edge connects two nodes if and only if the two neurons' activities share covariability conditionally on the activities of all other cells and input sources. Estimating functional connectivity helps us understand how neurons interact with one another while they process information under different stimuli and other experimental conditions. These networks let us study the functions of neuronal circuits, and the causes of their dysfunction characterizing brain disorders. Functional connectivity estimation becomes a compelling statistical problem when based on *calcium imaging* data. Calcium imaging is a powerful technology that lets us record the activity of tens of thousands of neurons from the same brain. However, typically only smaller subsets of neurons are recorded at once to guarantee good temporal resolution of the recordings. If these subsets of the neuronal population are recorded *nonsimultaneously*, the joint activities of several pairs of neurons remain unobserved. For these pairs even the simplest metric of covariability, the sample covariance, is unavailable. In the Gaussian graphical model setting, the unavailability of parts of the covariance matrix translates into the unidentifiability of the precision matrix, which specifies the graph, unless additional assumptions are made. We call this challenging situation the *graph quilting problem*. We demonstrate that, under mild conditions, it is possible to correctly identify not only the functional connections of the observed pairs of neurons, but also a superset of the connections among the neurons that are never observed jointly. We propose an l_1 regularized graph estimator based on partially observed sample covariances and establish its rates of convergence in high-dimensions. We perform an extensive simulation study and apply the methods to estimate the functional connectivity graph of ten thousand neurons in *mouse visual cortex* recorded via calcium imaging technology.

Funding: NSF NeuroNex-1707400, NSF DMS-1554821, Rice Academy Postdoctoral Fellows, and Dan L. Duncan Foundation.

Poster #27

Bayesian Filtering Methods for Tracking Arousal and Energy

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The human body is a complex system with multiple internally-regulated state variables. The states include energy, hydration, emotion etc. While the states themselves are largely unobservable, they nonetheless give rise to measurable electrical and chemical phenomena – phenomena that can be conveniently measured with the aid of sensors. Here, we present state-space approaches to track an unobserved emotional arousal state and a metabolic energy state from skin conductance and heart rate, and blood cortisol measurements respectively. The state-space methods enable the design of appropriate control signals to stabilize the internal state variables of interest when they lie outside desirable ranges.

While sweat helps maintain body temperature, tiny bursts of sweat are also released in response to psychologically-arousing stimuli. Consequently, the conductivity of the skin provides an index into the emotional state of the brain. The fast-varying phasic component of a skin conductance signal consists of a sequence of individual skin conductance responses (SCRs). The greater the arousal, the higher the rate at which SCRs occur. We model the brain's arousal state as following a random walk and probabilistically relate it to the binary SCR occurrences. We use Bayesian filtering within an expectation-maximization (EM) framework for tracking emotional arousal and determining model parameters.

An increase in arousal also gives rise to an increase in heart rate and greater force of contraction. We develop a second model in which heartbeat occurrences expressed as a string of binary numbers are also used for arousal estimation. Heartbeats and SCRs are thus considered as two binary sequences that encode arousal information in the rate at which the 1's occur. Heartbeat inter-arrival times are modeled using a history-dependent inverse Gaussian (HDIG) distribution. Arousal is assumed to affect the HDIG mean and a similar EM framework is used for state estimation and model parameter recovery.

Cortisol is the body's main glucocorticoid and is responsible for raising blood glucose levels in response to external stress. These external stressors can be psychological (e.g. exam stress) or physical (e.g. temperature changes) in form. Cortisol thus plays a significant role in energy homeostasis. Cortisol secretion is pulsatile in nature and between 15-22 pulses are secreted in a healthy adult each day. We develop a third state-space model relating an unobserved energy state to the cortisol pulse occurrences and the upper and lower blood cortisol envelopes. We again use the EM framework for estimation.

Results on experimental data for estimating arousal based on skin conductance show an agreement with different experimental conditions. Estimates are high during cognitive stressors and low during periods of relaxation. Arousal estimates on skin conductance and heart rate show that task unfamiliarity appears to be a significant source of mental stress. Finally, results on simulated blood cortisol data show rhythmic 24 h energy variations in healthy subjects and almost random variations in patients with Cushing's disease (a type of disorder with excess cortisol secretion), shedding light on why they may experience daytime fatigue and nighttime

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insomnia. State-space approaches are thus able to successfully estimate unobserved variables within the human body and are promising unsupervised methods for closed-loop therapy.

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Poster #28

Constraints on Place-field Arrangements and Capacity in Place Cells with Grid Cell Inputs

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A hippocampal place cell exhibits multiple firing fields within and across environments. What factors determine the configuration of these fields, and could they be set down in arbitrary locations? We conceptualize place cells as performing evidence combination across many inputs and selecting a threshold to fire. Thus, mathematically they are perceptrons, except that they act on geometrically organized inputs in the form of multiscale periodic grid-cell drive, and external cues. We analytically count which field arrangements a place cell can realize with structured grid inputs, to show that many more place-field arrangements are realizable with grid-like than one-hot coded inputs. However, the arrangements have a rigid structure, defining an underlying response scaffold. We show that the ``separating capacity" or spatial range over which all potential field arrangements are realizable equals the rank of the grid-like input matrix, which in turn equals the sum of distinct grid periods, a small fraction of the unique grid-cell coding range. Learning different grid-to-place weights beyond this small range will alter previous arrangements, which could explain the volatility of the place code. However, compared to random inputs over the same range, grid-structured inputs generate larger margins, conferring relative robustness to place fields when grid input weights are fixed. Finally, the realizable arrangements are determined by the input geometry, thus the model predicts that place fields should lie in constrained arrangements in relation to their grid inputs and within and across environments.

This work was supported by the Simons Foundation through the Simons Collaboration on the Global Brain, the ONR, the Howard Hughes Medical Institute through the Faculty Scholars Program to IRF, and the Alfred P. Sloan Research Fellowship FG-2017-9554 to TT.

Poster #29

Delayed Differential Equation from Replica-mean-field Limit of Exponential Firing Model

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Relating the spiking activity of neuronal circuits to their finite network structure is hindered by the presence of high-order correlations. To address this limitation in intensity-based neural models, it was recently proposed to consider limit networks made of infinitely many replicas with the same basic neural structure. These so-called replica-mean-field (RMF) networks are in fact simplified and tractable versions of neural networks that retain important features of their finite structures. Tellingly, the stationary state of an RMF network is entirely characterized by the mean neuronal firing rates, which solves a set of self-consistent mean-field equations. Unfortunately, solving such equations remains computationally challenging for networks that include both excitation and inhibition. Here, we overcome this computational challenge for point-process-based neural networks with exponential stochastic intensities. In the RMF limits, the stationary firing rates can be determined by solving a set of delayed differential equations (DDEs) under certain regularity conditions. Interestingly, and by contrast with the classical treatment of delayed equations, solving these equations hinges on finding global self-consistent solutions to each DDE, with no reference to any initial conditions. To our knowledge, there are no known methods for such problems. We propose an original iterative scheme inspired from the resolvent formalism to compute the stationary firing rates. In the parametric region where this scheme converges, the results are supported by numerical simulations.

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