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Poster Abstracts

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Resonant and anti-resonant response of conductance based neuron models

Lech S. Borkowski (Faculty of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznan, Poland)

I study the dynamics of Hodgkin-Huxley neurons stimulated by periodic and stochastic short current pulses. In the high frequency regime there is a multimodal transition [1] between the odd-only modes and the state with both odd and even modes. I present evidence that this phenomenon has been observed experimentally [2]. In the presence of noise this singularity appears as a stochastic coherence anti-resonance [3]. The coefficient of variation (CV) has a sharp maximum as a function of the noise intensity and the average output frequency has a minimum. The competition of different parity modes is reflected also in the structure of the resonances, where even and odd phase-locked states are separated by crossover regimes. Different ISI modes have different excitation thresholds. The dependence of the average frequency f on the stimulus amplitude is continuous or nearly continuous in the regimes of irregular response and at the resonance, where f is the square root function of the current amplitude near the threshold. I also study response of regular spiking cortical neurons and identify forms of resonant and anti-resonant behavior. These features depend stronly on the amplitude of the stimulus. In the inhibitory neuron the average output frequency, CV, and the duration of bursts are oscillatory functions of the stimulus amplitude.

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Quantifying neurotransmission through an entropy measure embedding spike train metrics

Romain Brasselet (CNRS-UPMC UMR7102, Univ Paris 6, Paris, France), Roland S. Johansson (Umea University, Sweden), Angelo Arleo (CNRS-UPMC UMR7102, Univ Paris 6, Paris, France)

We set forth a novel information theoretical measure [1] to quantify neurotransmission reliability while taking into full account the metrical properties of the event space. This parametric information analysis relies on a similarity measure to estimate, as spikes flow in, the metrical relations between neural responses. In order to assess the conditional entropy and the overall information transfer, this method does not require any a priori decoding algorithm to partition the space into equivalence classes (e.g. clusters of neural responses based on confusion matrices). To validate the proposed information theoretical approach, we study precise temporal decoding of human somatosensory signals (i.e. the responses of fingertip mechanoreceptors to tactile stimulation) recorded via microneurography experiments [3]. For this analysis, a similarity measure based on the Victor-Purpura spike train metrics [2] is employed. It is shown that the relative spike timing of the mechanoreceptors responses can convey enough information to perform optimal discrimination (defined as maximum metrical information and zero conditional entropy) of 81 distinct stimuli within 60 ms of the first afferent spike. The proposed information theoretical measure proves to be a suitable generalisation of Shannon Mutual Information in order to consider the metrics of temporal codes explicitly. It permits an assessment of neurotransmission reliability in the presence of large spike train spaces (e.g. neural population codes) with high temporal precision (e.g. 1 ms).

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Towards a new computational framework for studying networks of spatially-extended neurons

Quentin Caudron (Centre for Complexity Science, University of Warwick), Yulia Timofeeva (Department of Computer Science and Centre for Complexity Science) and Stephen Coombes (School of Mathematical Sciences, University of Nottingham)

The complex structure of dendritic trees combined with the connectivity of neural networks and properties of individual synapses are known to play a signicant role in neuronal computation. A brute-force numerical simulation is one of the approaches used for studying the dynamics of large networks of spatially-extended neurons. However, this can be computationally expensive and restricts any mathematical insight. We aim to apply a combination of mathematics and computation to develop an efficient framework for studying the dynamics of neural networks connected by both electrical and chemical synapses. We propose to use a Greens function approach for calculating the dynamics of the network for different types of stimuli and present here a fast algorithm for computing the response function on a dendritic tree of arbitrary geometry for any number of stimuli. This requires an efficient identication of all paths shorter than a pre-dened cutoff length between all combinations of stimuli and measurement points on a tree. This algorithm can be naturally generalised to a network of cells connected by gap-junctions. Preliminary results of a C++ implementation of the algorithm applied to an arbitrary tree show an accurate solution provided in 0.05 seconds, compared with the 80 seconds required for calculation by numerical simulation. One of the phenomena that will be studied using the proposed computational framework is the directional selectivity in the retina. Some preliminary results are shown for a chain of idealised cells and a moving stimulus that mimics a light signal applied to the retina in experiments.

Neuronal modeling of the SCN

Casey Diekman, Mino Belle, Hugh Piggins and Daniel Forger (Department of Mathematics, University of Michigan)

In mammals, the suprachiasmatic nucleus (SCN) acts as the central circadian pacemaker of the brain. I will describe recent progress in modeling the SCN as a neuronal system. Models study the interactions between: 1) ion channels in a single neuron to form complex electrical behaviors, 2) neurons within the SCN to form co-ordinated timekeeping signals and 3) the SCN itself and other brain regions. I will focus on how models are developed from biological data as well as their predictions.

Synchronisation of non-autonomous oscillators

Stephen Gin (Mathematics Institute, University of Warwick)

I will first introduce the oscillator which has a linearly attracting limit cycle - the simplest example of a normally hyperbolic invariant manifold. Subject to time dependent forcing, the oscillation is generally Non-Periodic. However we will see that for weak time dependent forcing, not necessarily periodic, the oscillation survives - in a sense that there is an attracting normally hyperbolic invariant cylinder in the time extended space. We will see, under this view, that under certain conditions the dynamics can be collapsed to an attracting normally hyperbolic trajectory. We will then look at the coupling of two, not necessarily identical, oscillators and see that the theory in the one oscillator case extends to this case. I will present sufficient conditions for them to synchronise - which will be defined in the non-autonomous setting. Finally, I will outline the routes that we can take to study synchronisation of many oscillators in a network.

Effects of synaptic filtering on the firing rate response of the exponential-integrate-and-fire neuron

Azadeh Khajeh Alijani (Mathematics Institute, University of Warwick) and Magnus JE Richardson (Warwick Systems Biology Centre, University of Warwick)

The exponential-integrate-and-fire (EIF) model is a reduced model of a conductance-based neuron model. The aim of our work is to extend the threshold integration method to the EIF neuron driven with filtered noise, assuming that the driving noise is fast and to derive linear correction to the firing rate response to both mean input and noise intensity oscillations.

One rule to grow them all: A general theory of neuronal branching and its practical application

Hermann Kuntz (University College London)

Understanding the principles governing axonal and dendritic branching is essential for unravelling the functionality of single neurons and the way in which they connect. Nevertheless, no formalism has yet been described which can capture the general features of neuronal branching. Here we propose such a formalism, which is derived from the expression of dendritic arborizations as locally optimized graphs. Inspired by Ramón y Cajal's laws of conservation of cytoplasm and conduction time in neural circuitry, we show that this graphical representation can be used to optimize these variables. This approach allows us to generate synthetic branching geometries which replicate morphological features of any tested neuron. We demonstrate that the structure of a neuronal tree is captured by its spatial extent and by a single parameter, a balancing factor weighing the costs of conservation of cytoplasm and conduction time. This balancing factor allows a neuron to adjust its preferred electrotonic compartmentalization. A general set of tools can be derived from these simulations for analyzing, manipulating and generating dendritic structure, including a tool to generate artificial members of any particular cell group and an approach for model-based supervised automatic morphological reconstruction from fluorescent image stacks. These approaches provide new insights into the constraints governing dendritic architectures. They also provide a novel framework for modelling and analyzing neuronal branching structures and for constructing realistic artificial neural networks.

Shape dependence of the neuronal response to alternating electrical fields

Naveed A Malik and Magnus JE Richardson (Warwick Systems Biology Centre, University of Warwick)

Neuronal interactions with electric fields depend on the biophysical properties of the neuronal membrane as well as the geometry of the cell relative to the field vector. Biophysically detailed modeling of these spatial effects is central to understanding neuron-to-neuron electrical (ephaptic) interactions as well as how externally applied electrical fields, such as radio-frequency radiation from wireless devices or therapeutic Deep Brain Stimulation (DBS), interact with neurons. Here we examine in detail the shape-dependent response properties of cells in oscillating electrical fields by solving Maxwells equations for a geometrically extended neuron of various radii-to-length ratios.

Early modeling [1] for compact (spherical) cells in alternating fields predicts a smaller effective membrane time constant for the field-cell system compared to direct current injection via whole-cell patch clamp. This result, predicting that cells should respond strongly to field oscillations in the kHz range, was verified later [2] in vitro for murine myeloma cells. However, recent experiments [3] on CA3 pyramidal cells (highly elongated neurons) in the hippocampus do not exhibit this high frequency response. Our modeling demonstrates that the radius-length ratio and orientation of the cell to the field are key determinants of the neuronal response to oscillating fields. This explains the experimentally observed absence of the high frequency response for pyramidal neurons when the applied field direction is oriented along their dendritic axis. Additionally, we developed biophysically detailed models of neuronal membranes with quasi-active electrical properties stemming from voltage-gated currents. These are known to lead to resonances at characteristic frequencies in the case of current injection via whole-cell patch clamp. Interestingly, in the field-cell system, the resonance was masked in compact, spherical neurons but recovered in elongated neurons.

These findings delineate the relationship between neuron shape, orientation and susceptibility to high frequency electric fields, with implications for DBS efficacy, ephaptic coupling in networks and the filtering properties of cortical tissue.

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Constructing functional human brain networks from MEG (Magnetoencephalography) data using the multiple trial mmn paradigm

R. M. Nicol, S. C. Chapman (Centre for Fusion, Space and Astrophysics, University of Warwick), E. Bullmore, M. G. Kitzbichler and P. Vertes (Brain Mapping Unit, University of Cambridge)

A complex networks approach to building functional brain networks is an emergent field of research. The brain possesses many features in common with complex networks such as the existence of highly connected regions or “hubs”, small world properties and strong modularity. This work uses magnetoencephalography (MEG) studies of the mmnm (mismatched negativity or “oddball”) paradigm to build functional directed graphs of brain activity. During this task, subjects are alternatively given standard and deviant (e.g. different frequency) auditory stimuli. Multi-channel MEG measurements are then used to build cross-correlation matrixes C_{ij} between channels i and j for consecutive time epochs following the different stimuli. The strongest correlations form the graph or network of the neural activity. Furthermore, as we are considering correlations at lag 1, the resultant graph is also directed as the correlation coefficient between i and j differs from that between j and i. By maintaining the number of nodes (channels) and edges (connections between channels) fixed, the resultant networks are compared to equivalent random and rest data networks. We study the variation of the networks with increasing number of edges and we find strong differences between the random networks and the brain networks in key graph parameters such as mean minimum path length, clustering coefficient and the size of the maximum spanning cluster. The brain networks display smaller path lengths, a small world property, and require a higher connection density in order to become fully connected. We compare our results across different subjects and for different deviant stimuli in the mmnm task.

Information-optimal neural coding in poisson neurons

A. Nikitin, N. G. Stocks, R. P. Morse and M. D. McDonnell (Department of Engineering, University of Warwick)

The firing rate of afferent neurons is limited. Also, the time available for decoding the message in the brain is limited. We obtain the optimal tuning function for a population of the Poisson neurons by maximizing the Shannon mutual information and investigate how optimal coding changes with the time available for decoding. We prove that the information-optimal tuning function is discrete. In other words, we prove that the optimal tuning function has a multi-step form and the number of steps depends on the decoding time. The number of discrete steps undergoes a hierarchy of phase transitions from mono-population coding, for small decoding time, toward multi-population coding with two, three more subpopulations for larger decoding times. We postulate that the presence of subpopulations with specific neural characteristics, such as the threshold to stimulus, could be a signature of an optimal coding strategy and we use the mammalian auditory system as an example.

A. Nikitin, N. G. Stocks, R. P. Morse and M. D. McDonnell, Phys. Rev. Lett. 103 (2009) 138101.

Dendritic spines can stabilise synaptic strength

Cian O'Donnell (Institute for Adaptive and Neural Computation, University of Edinburgh), Matthew F Nolan (Centre for Integrative Physiology, University of Edinburgh) and Mark CW van Rossum (Institute for Adaptive and Neural Computation, University of Edinburgh)

Although stable synaptic weights are important for long-term memory, it is not known how synapses retain their relative strengths over time. We've been working on a new model which might solve this problem. Most excitatory synapses in the brain are hosted on small structures called dendritic spines. Spine size is tightly correlated with synaptic strength. The function of this relationship is not known. Notably, dendritic spine size is one of several factors that regulate calcium signalling at the synapse. Because calcium signals trigger synaptic plasticity, this spine size scaling might result in a weight dependence in the synaptic plasticity rule. We explored the implications of different spine-size to calcium-influx relationships on a synaptic plasticity rule and find that different scalings result in either stable or unstable synaptic weight dynamics. We then built a biophysical model of a CA1 pyramidal neuron spine and synapse and found that it predicts these synapses to fall in to the 'stable' category. Finally, we explored each scenario's synaptic weight distributions and calculate synaptic lifetimes. These results support a new model where dendritic spines actively regulate synaptic plasticity rules as a function of synaptic strength in order to stabilise memory storage.

Dynamic properties of neural assemblies during reactivation of episodic memories in the hippocampus

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Recent advances in neural data acquisition have dramatically increased the magnitude of the data that can be recorded in neuroscience experiments. To address these issues, we implemented and adapted subspace projection statistical methods and data-mining techniques to directly address these specific data constraints, revealing the existence of putative reactivations of startling episodic memory traces (Lin, Osan et al PNAS 2005). We also showed that the use of these data analysis techniques facilitates the understanding and monitoring of the dynamics of these neural populations, reflecting the network-level ensemble representations (Osan et al, PLOS One 2007). Building upon previous research, we designed new experiments aimed to differentiate between somato-sensory and memory components of hippocampal representations in freely behaving mice, by varying the intensity of stimuli used to produce episodic event. We find that the recorded neural population can be classified into two categories: units that respond in an invariant fashion to the stimuli of all intensities and units that modulate their responses as a function of the magnitude of the stimuli.In line with our previous results we find that firing patterns with similar dynamics but reduced intensities emerge spontaneously in the hippocampal network during post-event time periods (putative reactivations). More importantly, our results suggest that the units from the first category, namely invariant-responding neurons, are active during the putative reactivation of the memory traces, while the modulated units have negligible reactivation levels during these events.

The nonlinear response of neurons to time-dependent inputs

Tilo Schwalger (Max Planck Institute for the Physics of Complex Systems, Dresden, Germany), Sven Goedecke (Georg August University, Göttingen, Germany) and Markus Diesmann (RIKEN Brain Science Institute, Wako-shi, Japan)

We consider a leaky integrate-and-fire neuron in the presence of an arbitrary time-dependent input current and synaptic background noise. Using the statistics of level crossings of smooth Gaussian processes and results from renewal theory we find approximations for the (time-dependent) firing rate of the neuron. In particular, the cases of strong input transients and continually varying stimuli are discussed. We find that the firing rate crucially depends on both the ensemble-average of the membrane potential and its temporal derivative. The theoretical results are applied to the propagation of short but strong pulse packets across cortical feed-forward networks (synfire chains).

Coordination of cortico-hippocampal network dynamics by theta oscillation

Anton Sirota (CIN, University of Tuebingen, Germany), Kenji Mizuseki, Sean Montgomery and Gyorgy Buzsaki (Rutgers University, USA)

Theta and gamma oscillations are believed to play an important role in coordinating the network dynamics in the cortical networks engaged in learning. Specifically, theta oscillation is coordinating the dynamics between various cortical networks, whereas gamma oscillations as associated with synchronization within these networks. We address this question by recording local field potentials (LFP) and multiple single units in different layers of neocortex, entorhinal cortex and hippocampus using extracellular recordings with silicon probes in rats during exploratory behavior and REM sleep. Using spectral and latent variable analyses of unit firing and LFP we reveal multiple gamma oscillators confined to different frequency bands and anatomical regions. These gamma oscillators are nested within hippocampal theta oscillation cycle. The emergence of theta-nested gamma oscillations is closely associated with neuronal firing in the populations of neurons in respective local or afferent networks.

Thus gamma-synchronization in local cortical networks is temporally integrated and segregated with respect to each other by theta rhythm.

Spike-based reinforcement learning in continuous state and action space

Eleni Vasilaki (Department of Computer Science, University of Sheffield), N. Fremaux, R. Urbanczik, W. Senn and W. Gerstner

Changes of synaptic connections between neurons are thought to be the physiological basis of learning. These changes can be gated by neuromodulators that encode the presence of reward. We study a family of reward-modulated synaptic learning rules for spiking neurons on a learning task in continuous space inspired by the Morris Water maze. The synaptic update rule modifies the release probability of synaptic transmission and depends on the timing of presynaptic spike arrival, postsynaptic action potentials, as well as the membrane potential of the postsynaptic neuron. The family of learning rules includes an optimal rule derived from policy gradient methods as well as reward modulated Hebbian learning. The synaptic update rule is implemented in a population of spiking neurons using a network architecture that combines feedforward input with lateral connections. Actions are represented by a population of hypothetical action cells with strong mexican-hat connectivity and are read out at theta frequency. We show that in this architecture, a standard policy gradient rule fails to solve the Morris watermaze task, whereas a variant with a Hebbian bias can learn the task within 20 trials, consistent with experiments. This result does not depend on implementation details such as the size of the neuronal populations. Our theoretical approach shows how learning new behaviors can be linked to reward-modulated plasticity at the level of single synapses and makes predictions about the voltage and spike-timing dependence of synaptic plasticity and the influence of neuromodulators such as dopamine. It is an important step towards connecting formal theories of reinforcement learning with neuronal and synaptic properties.

Auditory coding in the inner hair cell ribbon synapse

Daniela Woltmann (Warwick Systems Biology Centre, University of Warwick) and Nigel Stocks (Department of Engineering, University of Warwick)

In the mammalian auditory system, the cochlear inner hair cell (IHC) ribbon synapse constitutes the primary coding synapse for auditory signals ([1]). The most prominent difference between IHC ribbon synapses and conventional synapses is a presynaptic structure known as synaptic ribbon, the function of which is still largely unknown ([2]). Further characteristics include: the change from action potentials to graded receptor potentials (RPs) and the loss of the sodium current with the onset of hearing ([3]); the ability to sustain tonic release of vesicles over long time intervals ([4]) and synchronous, ribbon-dependent multi-vesicular release ([5]). Over the years a number of auditory models have been developed that try to capture the stimulus response of the IHC ribbon synapse. Arguably, the most well known and widely used model is the Meddis model ([6]), together with a later modication known as the Sumner model ([7]). Although these phenomenological models are successful in simulating some of the synaptic responses observed experimentally, they fail to replicate all the response characteristics ([8]). Here, some of these auditory models will be reviewed, together with suggestions for modifications or improvements.

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