Special Session 1: Oscillations and Synchronization in Neuronal Networks

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Rhythmogenesis in bursting motifs

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We show that the regulation of bursting activity in cells forming networks with mixed, inhibitory and excitatory fast chemical synapses is a crucial skill for controlling rhythmic movements in motifs, which are the building blocks of central pattern generators governing various motor behaviors. We have found that an order or bifurcation parameter controlling the network is the ratio of the burst durations of the cells, so that the designated pace makers identified by either intrinsic properties of the cell staying close to the tonic spiking threshold, or by the architecture of the network under consideration, is able to synchronize other strongly uncorrelated or desynchronized neurons on the network, thereby determining the network's paces and rhythms. We analyze different topologies and synaptic configurations of motifs to determine the mechanisms for universality and synergetics of bursting patterns observed in distinct networks. We also discuss multistability of rhythms and causes for intertransitions.

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Synchrony and phaselocking between neural clusters

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Phase resetting curves (PRC) characterize the change in cycle period of an oscillator due to a perturbation. Under the assumptions that the oscillator relaxes back to the limit cycle between perturbations and that the perturbations received in a circuit are similar to those used to generate the PRC, the PRC of the individual components of the circuit can be used to predict the collective activity of the network. These methods have successfully been applied to the generation of phase-locked clusters in all to all networks by examining the stability of synchrony within clusters and the stability and existence of the splay mode between clusters. The simplest example of the splay mode is two clusters in antiphase. The slope of the PRC at a phase of zero is the key determinant of synchronization properties, but surprisingly, a robust antiphase mode between two clusters can sometimes enforce synchronization within a cluster even if synchrony with a stand-alone cluster is not stable. Simulations with Wang and Buzsaki model neurons confirm that the PRCs contain all the information required to predict network activity in the parameter ranges studied.

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Neuronal mechanisms of synchronized 10 Hz oscillations in visual cortices

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Field oscillation at around 10 Hz in the visual cortices is known as the alpha rhythm. Its physiological mechanisms are not well understood. In vitro studies have implicated pyramidal neurons in both infragranular and supragranular layers as pacemakers. To what degree these observations generalize to the intact brain in behaving animals remains unknown. We analyzed laminar profiles of field potentials and multi-unit activity (MUA) recorded with linear array multielectrodes from visual areas V2, V4 and inferotemporal (IT) cortex of two awake behaving macaque monkeys. Current source density (CSD) analysis was combined with CSD-MUA coherence to identify intracortical alpha current generators and their potential for pacemaking. Coherence and Granger causality analyses were used to study the interaction among different alpha current generators. In V2 and V4, alpha current generators were found in all layers, with the infragranular layers acting as pacemakers. In contrast, in IT, alpha current generators were found only in supragranular and infragranular layers, with supragranular generators acting as pacemakers. We compare these findings with prior in vitro work, and discuss their interpretation in the context of columnar circuitry.

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Dynamical properties of a simple feed forward network

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Synchrony-breaking Hopf bifurcations in a small three node feed forward network lead generically to periodic solutions whose amplitudes in the third node have a surprising $1/6$ power growth rate. Moreover, when this network is tuned near such a Hopf bifurcation, it can act as an efficient frequency filter / amplifier. I will describe the general theory, recent experiments of McCullen and Mullin on coupled electrical circuits that confirm this structure, numerical simulations of LieJune Shiau that suggest interesting theoretical questions, and recent analytic work with Yanyan Zhang.

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Effective computation of phase resetting curves (PRC) using a parametrization method

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For a generic limit cycle γ of a planar vector field X, there exists a neighborhood of γ, Ω, foliated by sections transversal to γ and isochronous with respect to the flow of X. These sections are known to be the solutions of any vector field Y transversal to and conjugated with X; that is, $[Y, X] = \mu X$, with μ being a scalar function. In fact, the time-variables of both X and Y constitute a system of coordinates on Ω.

In this work, we use a parametrization method to obtain an analytical expression for the isochrons in these coordinates in a neighborhood of the limit cycle. These expressions turn out to be useful to obtain the so-called *phase resetting curves* (PRC). PRC curves are useful for the study of synchronization of coupled oscillators and a basic tool in experimental biology (circadian rhythms, synaptic and electric coupling of neurons,...). We establish the relationship between the PRCs and Y and, from this link, we are able to compute PRCs, not only on γ (as usual in the literature) but also in an open subset in Ω, giving rise to what we call *phase resetting surfaces*.

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Mixed mode oscillations in three time scale systems

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Mixed-mode oscillations (MMOs) are solutions combining small oscillations (Hopf type) and large oscillations (relaxation type) in one time series. In the context of neuronal dynamics MMOs correspond to time series including spiking and subthreshold oscillations and may be related to delayed firing or irregular firing We discuss two examples of three time scale systems, both motivated by neuronal models, in which MMOs arise.

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Noise-sensitive amplitude and phase dynamics in the context of multiple time scales

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Na Yu and Yue Xian Li

This talk covers a few biological models where the noise-sensitivity is due to the intrinsic multiple time scales, sometimes hidden in the dynamics. We focus on oscillations sustained by stochastic effects in otherwise quiescent systems. The fact that these oscillations have a strongly deterministic behavior, even though they are purely noise-induced, obscures their stochastic sensitivity. The types of phenomenon include amplification through coherence resonance, as well as synchronization and localized oscillations. We show how different stochastic multiple scales analyses illustrate the mechanism responsible for the phenomenon and the conditions for its appearance.

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Oscillatory bursting in chay neuronal model

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The Chay neuronal model, which consists of the fast and slow subsystems, is chosen to explore the dynamical behavior and the types of neuronal bursting under different dynamical parameters. According to the number of the Hopf bifurcation points on the upper branch of the bifurcation curve of the fast subsystem, which is associated with stable limit cycles corresponding to spiking states, different types of bursting and their respective dynamical behavior are surveyed by means of fast-slow dynamical bifurcation analysis. Two different types of bursting, that is, fold/Hopfbursting viafold/foldhysteresis loop andfold/foldpoint-point hysteresis loop bursting, are associated with two Hopf bifurcation points on the upper branch of the bifurcation curve. With only one Hopf bifurcation point on the upper branch of the bifurcation curve, there are three types of burstingincludingfold/homoclinicbursting via fold/homoclinic hysteresis loop, circle/homoclinic bursting viacircle /homoclinic hysteresis loop and Hopf/homoclinic bursting viafold/homoclinic hysteresis loop. Thefold/foldpoint-point hysteresis loop bursting appears if there is no Hopf bifurcation point on the upper branch of the bifurcation curve.

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Noise-induced bursting

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We consider a phenomenological model of a square-wave bursting neuron in the regime of tonic spiking but close to the transition to bursting. Under small random perturbations, the model generates irregular bursting. We study the statistical properties of the emergent bursting patterns. For this, we derive a Poincare map for the randomly perturbed system. The analysis of the first return map yields the distributions of the number of spikes within one burst and the interspike time intervals and reveals their dependence on the small and control parameters present in the model.

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Analytic tools for studying the role of noise in bursting pancreatic beta-cells

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Insulin secreting pancreatic beta-cells are electrically coupled in the islets of Langerhans, where they show bursting electrical activity. On the other hand, isolated beta-cells usually show spiking, very fast, or very slow bursting behavior. It has been suggested that the burst period is shortened due to stochastic effects on the single cell level, which are less important when averaged over many coupled cells. This can be modeled by using different noise strengths for single versus coupled cells. We present analytic tools based on collective coordinates and a stochastic Melnikov method, which allow us to follow the saddle-node/homoclinic bifurcations controlling standard square wave bursting, as the noise intensity is varied. The results are used for investigating the mechanism underlying slow oscillations in single cells, by applying to so-called "phantom" and "glycolytic" bursting. We find that electrical events are unlikely to account for slow bursting, while bursting driven by metabolic oscillations is stable to stochastic fluctuations, which suggests that metabolism is underlying pulsatile insulin secretion.

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Prediction of phase-locking in hybrid circuits based on phase response curves

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Phase-locking between oscillatory neurons occurs in a variety of neuronal systems and is known to underlie motor pattern generation, cognition, and neuronal disorders such as epilepsy. Whether and how neuronal oscillators will phase-lock depends on cellular phase response properties and the nature and strength of synaptic connections. Here, we use hybrid circuits constructed by coupling an intrinsically bursting biological neuron to a bursting model neuron via inhibitory or excitatory synapses of various strengths. We use the open-loop phase response curves of both neurons to predict existence, stability, and timing of phase-locked modes and compare the predictions to the actual behavior of the hybrid circuits. If the biological variability of phase response curves is taken into account, our method accurately

predicts both phase-locking and network phase relationships in most mutually excitatory and inhibitory networks.

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Transitions between bursting and spiking in conditional pacemaker networks with excitatory synaptic coupling

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Evandro Manica and Georgi Medvedev

In past work, we have used fast-slow decompositions and bifurcation analysis to study transitions between bursting and spiking dynamics in a pair of model conditional pacemaker neurons from a respiratory network in the mammalian brainstem (Best et al., 2005). In this talk, I will discuss the reduction of the coupled network to a map, which allows for a more thorough analytical study of the network. Results include conditions that specify transition conditions away from the singular limit and conditions that establish the instability of the spike synchronized state. Additional topics may include extensions to a larger network and the inclusion of heterogeneity.

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Kalman filter control of spatiotemporal cortical dynamics

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Recent advances in Kalman filtering to estimate system state and parameters in nonlinear systems has offered the potential to apply such approaches to spatiotemporal nonlinear systems. We here adapt the nonlinear method of unscented Kalman filtering to observe the state and estimate parameters in a computational spatiotemporal excitable system that serves as a model of cerebral cortex. We demonstrate the ability to track spiral wave dynamics, and to use an observer system to calculate control signals delivered through applied electrical fields. We demonstrate how this strategy can control the frequency of such a system, or quench the wave patterns, while minimizing the energy required for such results. These findings are readily testable in experimental applications, and have the potential to be applied to the treatment of human disease.

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Spike and burst synchronization of coupled neurons

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There are two basic types of firing patterns of a neuron: spiking and bursting, and bursting is the most important firing pattern in neural system. The modern neurophysiological experiments show evidence that synchronous oscillations of neural activities in the brain play an important role in information processing and coding. In order to understand neural information processing in the brain, we study two typical firing synchronization of coupled neurons, spike and burst synchronization. Firstly, the phase of a neuron is defined by the method associated with the Poincare section, and it is shown that the spike synchronization is equivalent to the phase synchronization for coupled neurons. Secondly, considering the slow variable being the key point for bursting process in the neuronal system, the similarity function of the slow variables of neurons is proposed to judge the burst synchronization. It is also found that the burst synchronization can be achieved more easily than the spike synchronization, whatever the firing patterns of the neurons are.

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Regular bursting solutions arising from synaptically coupled chaotic neurons

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In this talk, we discuss the change of collective behavior of synaptically coupled bursting systems as the strength of coupling increases or decrease. The individual cells present chaotic bursting behavior when uncoupled. But as the strength increases past a certain value, the behavior of two cells becomes synchronized regular bursting motions. Various transient patterns can be observed numerically and analyzed by a geometric method. It shows that regular oscillations can emerge from connecting intrinsically chaotic oscillators with synapses.

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A neurobiological model of the human sleep/wake cycle

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Michael Rempe and Janet Best

We propose a detailed, biologically based model for the human sleep/wake cycle. The model is based on Saper's flip/flop switch model of sleep/wake regulation which proposes that sleep-promoting neurons within the ventral lateral preoptic nucleus and wake-promoting neurons in the monoaminergic cell groups inhibit each other resulting in stable wakefulness and sleep. Input from orexin neurons to the monoaminergic cell groups help to stabilize the flip/flop switch; in particular, a loss of orexin may lead to unwanted switching between sleepiness and wakefulness associated with narcolepsy. Saper has also proposed a flip/flop switch for REM/NREM rhythms, which we have incorporated into our model. The model includes interactions between the circadian and homeostatic processes and accounts for certain features of sleep deprivation, as well as, ultradian rhythms.

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Dynamics in neuronal networks with delay

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Spatial coherence resonance in neuronal networks with delay that is locally modeled by Hodgkin-Huxley (HH) neurons is studied in this paper. We focus on the ability of delay to spatial patterns and coherence resonance. We show that spatial coherence can persist when the delay appears. As the delay increases, optimal noise intensity also increases correspondingly. However, as the diffusive topology of the medium is relaxed via the introduction of shortcut links introducing small-world properties, the ability of additive Gaussian noise to evoke ordered excitatory waves deteriorates rather spectacularly, leading to the decoherence of the spatial dynamics.

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Transition in complex calcium bursting induced by IP3 degradation

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In this short note, complex intracellular Ca^{2+} oscillations are systematically investigated in a mathematical model based on the mechanism of Ca^{2+}-induced Ca^{2+} release (CICR), taking account of the Ca^{2+}-stimulated degradation of inositol 1,4,5-trisphosphate (IP_3) by a 3-kinase. Periodic, quasi-periodic and chaotic bursting oscillations exist in a wide range of parameter values and occurs alternatively as the parameters change slightly. The transition among them can be observed by the evidence in their interspike interval and Lyapunov exponent. The results reveal the role of agonist-stimulated of IP_3 degradation as a possible source for complex patterns in Ca^{2+} signaling

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