Part I

CONFÉRENCIERS INVITÉS
INVITED SPEAKERS

Nonlinear Dynamics with Spatio-Temporal Spikes and Possible Information Coding

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Abstract.

Excitable dynamics of a neuron generates dynamical phenomena with various attractors, which include deterministic chaos and multistability [1, 2]. A neural network composed of neurons with such excitable dynamics also produces much more interesting and richer nonlinear dynamics with spatio–temporal structure of spikes [3, 4].

In this talk, I consider nonlinear dynamics with spatio–temporal spikes and possible information coding. In particular, a possibility of spatio–temporal coding based upon inter–event intervals is explored from the viewpoint of nonlinear time series analysis [5], where the event can be a single spike, more robust synchronous firing and so on. Effects of noise on such spatio–temporal coding are also discussed.

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A neural model of hippocampal-parietal interactions in spatial memory

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Abstract.

In this talk, a new computational model of the neural mechanisms in the parietal and temporal lobes that support spatial navigation, imagery, and episodic recall will be presented. Long-term allocentric representations of scenes are stored in the hippocampus and associated with object and texture information in the surrounding medial temporal lobe. Viewpoint-dependent representations are generated in the parietal part of the model to enable construction of an imagined retinotopic scene and generation of appropriate body movements. Bidirectional interactions between the hippocampal and parietal modules allows translation between allocentric and egocentric representations, with dynamical interactions between recalled episodic memories and viewer-centered mental images. Damage to the parietal part of the model produces symptoms of hemispatial neglect, including neglect in mental imagery that rotates with the imagined perspective of the observer, as in the famous Milan Square experiment with parietally lesioned patients reported by Bisiach and Luzatti (1978).

Joint work with Neil Burgess (UCL).

Bifurcation interactions as a source of multistability in systems with delays

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Abstract.

It is well known that the standard codimension two bifurcation interactions: Hopf-Hopf, Hopf-Steady State and Takens-Bodganov, can give rise to multistability between steady states and/or limit cycles. Although these bifurcations are often viewed as "rare" in the context of ordinary differential equations, we will show that they can arise quite easily in delay differential equations, even if there is only one state variable. We will illustrate our ideas with models of systems with delayed feedback and of neural oscillators with delayed coupling.

A Phase Resetting Analysis Shows How Delayed Feedback Gives Rise to Multistability

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Abstract.
In a loop circuit of oscillators, there are several sources of multistability associated with delayed feedback. In circuits composed of spontaneously firing neurons, the effective feedback time is itself variable depending upon the phasic firing pattern of each circuit element relative to the others. For example, in a circuit with three neurons (identified as neurons 1, 2 and 3) connected in a unidirectional ring or loop, the firing pattern could be 1-3-2 or 1-2-3. If the circuit is initially unconnected, it will require either one or two cycles (in which each neuron fires) after the circuit is closed in order for each neuron to have received a perturbation, depending upon the firing order. The effective delay is variable integer multiple of the entrained cycle period and dependent upon initial conditions even though all circuit parameters are constant. Not only is the firing order variable, but also the precise timing of firing intervals within a given firing order, so that the entrained cycle period associated with a given integer multiple is also variable. Numerous combinations of these two variables (entrained period and an integer multiplier of that period) may result in a firing pattern that satisfies the periodicity constraint. A third variable which could contribute to multistable patterns is the m:n entrainment ratio of the component neurons; however this discussion will be restricted to 1:1 entrainment. In addition to satisfying the periodicity constraint, stability constraints must be satisfied in order for a given firing pattern to be observable. Open loop phase response curves generated using simulated intrinsic bursts of action potentials in the presynaptic neuron have been successfully used to predict all 1:1 entrainment modes observed in closed loops (or rings) of oscillators as well as their stability and their basins of attraction.

Redistribution of synaptic efficacy and stable pattern learning in neural networks

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Abstract.
ART (Adaptive Resonance Theory) neural networks for fast, stable learning and prediction have been applied in a variety of areas, including airplane design and manufacturing, automatic target recognition, financial forecasting, machine tool monitoring, digital circuit design, chemical analysis, and robot vision. In traditional ART networks, localist, or winner-take-all (WTA), competitive activation supports stable coding by limiting learned changes to memory traces that project to or from the one active category node. However, this maximally compressed activation pattern may cause category proliferation when noisy inputs are trained with fast learning. In contrast, multilayer perceptrons (MLPs) feature distributed McCulloch-Pitts activation, which promotes noise tolerance and code compression, but which is prone to catastrophic forgetting. Distributed ART (dART) models seek to combine the best of these two worlds: distributed activation enhances noise tolerance and code compression while new system dynamics retain the stable fast learning capabilities of WTA ART systems. The dART network automatically apportions learned changes according to the degree of activation of each coding node, which permits fast as well as slow learning without catastrophic forgetting. A parallel distributed match-reset-search process also helps stabilize memory.

The critical new element that allows dART to solve the catastrophic forgetting problem is the dynamic weight, which replaces the traditional neural network path weight. This quantity equals the rectified difference between coding node activation and an adaptive threshold, combining short-term memory (STM) with long-term memory (LTM) in the basic unit of memory. Thresholds increase monotonically during learning according to a principle of atrophy due to disuse. However, in the code selection paths, monotonic change at the synaptic level manifests itself as bidirectional change at the dynamic level, where the result of adaptation resembles long-term potentiation (LTP) for single-pulse or low-frequency test inputs but can resemble long-term depression (LTD) for higher frequencies. This dynamic is traced to dual computational properties of frequency-dependent and frequency-independent components of the coding signal. Seemingly paradoxical, the disappearance of LTP enhancement for high-frequency test inputs is similar to the phenomenon

of redistribution of synaptic efficacy, as observed by Markram and Tsodyks (1996) in the neocortex. Analysis of the dART learning system indicates how these dynamics are related to the computational components needed to support stable coding in a real-time neural network.

Dendritic integration in neocortical pyramidal neurons in vivo

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Abstract.
Neocortical pyramidal neurons in vivo are subject to an intense synaptic background activity but little is known of how this activity affects cellular responsiveness, or what function it may serve. These issues were examined in morphologically-reconstructed neocortical pyramidal neurons. Synaptic background activity was simulated based on intracellular recordings during active states in cat parietal cortex in vivo. Measurements of membrane parameters before and after application of TTX in the same cells allowed us to estimate the conditions of release (conductance, frequency, random nature) at excitatory and inhibitory synapses corresponding to active states in vivo. We found that this activity has a considerable impact on the integrative properties of pyramidal cells: although the total conductance was approx. 5-fold larger, the initiation and propagation of dendritic action potentials was favored. Remarkably, the efficacy of synaptic inputs became approximately independent of their location in the dendrites. There was also a general enhancement of the responsiveness, caused by mechanisms similar to stochastic resonance. At the network level, the presence of background activity allowed populations of pyramidal neurons to instantaneously detect inputs that are small compared to the classical detection threshold. Contrary to the intuitive idea that neurons might encounter difficulties to process information in highly fluctuating states, we find here that cortical neurons perform a finer detection and process events that would normally be undetectable. The intense network activity therefore seem to set pyramidal neurons into a particular state of responsiveness, which may be related to arousal or attentional mechanisms.

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Sensorimotor Coordination: Behavior and Brain Analysis

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Abstract.

In the first part we report results from analyzing fluctuations in timing errors when human subjects attempt to coordinate movement with external rhythmic signals. We demonstrated that timing errors are characterized by a $1/f\alpha$ type of long memory process. The value of the exponent α differentiates two different types of coordination state: synchronization and syncopation. More interestingly, we found some evidence that α can be changed when subjects use different coordination strategies. Together with our understanding of the generation mechanism for long memory processes, these results suggest that the correlated timing errors are of higher cortical origin and likely the outcome of distributed neural processes acting on multiple time scales. In the second part we report results from analyzing a set of full-head (66 channels, CTF Inc.) magnetoencephalography (MEG) data recorded when 5 subjects performed rhythmic right-finger movements either syncopating or synchronizing with a visual metronome at 1Hz. Oscillatory neurmagnetic activities in the alpha (8-14Hz), beta (15-20Hz) and gamma (35-40Hz) ranges were shown to correlate with different aspects of the task.

Mathematical models of eye movement control in reading

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Abstract.

When we read a text, movements of our eyes are driven by two processes: lexical access and programming of saccades (fast eye movements that take the eyes from one word to the next). Stochasticity plays an important role in both sub-processes [1]. A crucial assumption for mathematical models of eye movement control is that of the coupling between eye movements and shifts of attention [2]: How are lexical access and programming of eye movements coordinated? While current theoretical models are based on the assumption that lexical access completely governs eye movement control in reading [1], the alternative notion that low-level oculomotor properties might explain most of the experimentally observed fixation patterns may still be a viable alternative [3]. We use a minimal model of eye movement control [4] to investigate the influence of physiological properties of the oculomotor system on the dynamics of eye movements and its interaction with lexical processes.

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Joint work with André Longtin (University of Ottawa) and Reinhold Kliegl (University of Potsdam)

Multistability and Clustering in Networks of Pulse-Coupled Integrate-and-fire Neurons with Delays

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Abstract.
In the recent years, many theoretical studies focused on the dynamics of globally coupled neural networks, and derived conditions for which those systems display collective phenomena like oscillations and synchronization. Many of these works, however, dealt only with instantaneous interactions between the elements, ignoring the fact that in most biological systems, transmission delays are substantial and may lead to a very different dynamical behaviour. One particularly interesting phenomenon, tightly connected to the existence of delays, is multistability: depending on its initial conditions, a network may converge to different (stable) attractors. In systems of many neuronal oscillators, there exists a multistability that leads to phase clustering of a variable number of subpopulations where the elements in each subpopulation are synchronously active, while the different subpopulations are active at different times. This behaviour can be understood qualitatively by a rigorous analysis of a minimal system of two coupled neuronal oscillators. While for inhibitory couplings, clustering is stable with respect to noise, for excitatory couplings, clusters emerge and decay spontaneously if the noise level is non-zero. It appears that multistable clustering is not only an interesting dynamical property of delay-coupled neuronal oscillators, but it may also implement a robust form of short-term memory. Due to the delays, the infinite dimensionality of the phase-space leads to a very high storage capacity superior e.g. to the Hopfield-type of networks. As an example, this mechanism may help to segment a natural scene in the early stages of our visual system: while neurons representing similar levels of grey are grouped together, populations of neurons representing different patches of varying intensity are activated alternately. It is shown that it is possible to activate almost arbitrary combinations of neurons, and to represent a huge number of populations in such a network. Typically, the maximum number N of populations which may be alternatively active, is anti-proportional to the delay τ, $N = const./\tau$. The limitations to this type of short-term memory, which depend on the delay distribution and the noise level, are discussed.

Joint work with K. Pawelzik and T. Geisel.

Information transmission by populations of spiking neurons

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Abstract.
I consider a single homogeneous population of spiking neurons coupled by synaptic interactions with delays. An integral equation for the population activity allows me to discuss the following phenomena from a unified point of view
- stability of the asynchronous firing state as a function of the noise level and the axonal delay.
- the signal transmission properties as a function of input frequency and noise level.
- the response to a step current input as a function of the noise level.
To adress these phenomena I linearize the population equations about the self-consistent asynchronous firing state. No weak coupling expansion is necessary. The spiking neuron model I use (spike response mdel) is a generalization of the integrate-and-fire model and can be adapted to approximate the dynamics of Hodgkin-Huxley neurons.

Stimulation of Biological Oscillators at a Fixed Delay Leads to Complex Rhythms

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Abstract.
Time delays enter naturally into physiological feedback systems as a consequence of time lags induced by processing information and activating an appropriate response. In this talk I summarize dynamics arising as a consequence of time delays introduced in a wide range of different settings ranging from simple mathematical models of feedback systems to experiments in neural and cardiac systems. A stimulus delivered at a fixed delay to a biological oscillator can provide a critical test of the hypothesis that the resetting of a biological oscillator depends only on the phase of the stimulus in the cycle (i.e. the relaxation time of the nonlinear oscillator to the attractor is short compared to the time delay). However, experimental studies demonstrate complex effects in which the same stimulus at the same delay gives rise to different effects on subsequent applications. In the cardiac setting, this can lead to complex bursting rhythms similar to some paroxysmal tachycardias.

Designing multistable hybrid analog-digital circuits that draw inspiration from cortical feedback

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Abstract.

The richness and complexity of cortical circuits seems to be an inexhaustible source of inspiration for thinking about high-level biological computation. Despite the lack of any coherent picture, even some simple cortical models bear interesting properties that have no equivalent in traditional electronic circuit design. For example, the multistability that is expressed by cortical circuits is very different from the multistability in digital circuits such as the flip-flop. That is, visual perceptions and neural responses to stimulation both exhibit multistability with analog properties, very unlike purely digital multistability.

We have designed an electronic circuit that is based on simple artificial neurons with graded, rectified neurons. As models, they were first used more than 40 years ago by Hartline and Ratliff and have recently become popular again, in attempts of modeling the abundant feedback excitation in cortical circuits. Our circuit design is not based on assembling traditional analog and digital building blocks. To the contrary, using a single design technique based on current mirrors, we demonstrate that in response to external stimulation, our circuit exhibits both digital-like multistability and analog amplification.

The rather long history of simple networks of rectified linear neurons might suggest that their theoretical understanding is more or less complete. However, whilst working on the stability properties of our circuit, we discovered a simple novel characterization of the possible stable steady states. This characterization is general enough to hold for any attractor network with symmetric connections. It says that the stability of a steady state only depends on the synaptic connections between active neurons. And, most importantly, if a set of active neurons is stable, then any subset of that set is stable as well and can be retrieved as a memory by suitable stimulation.

The recognition that stable steady states form partially ordered sets lead us to the following question: given a family of partially ordered sets, how is it possible to construct a synaptic weight matrix that represents these sets as stable steady states? We give some preliminary results about a method based on mutual inhibition. Any two neurons that never are in the same set

are connected by mutual inhibition. We point out the similarities with the Willshaw model.

Anti-phase, In-phase, and Bursting in Coupled Neural Oscillators

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Abstract.
It was shown that a diffusive coupling of two limit cycle oscillators near the homoclinic connection leads to dephasing of two oscillators in the weak coupling limit. To study the effect of finite coupling on the phase relations between two oscillators, we numerically investigate the phase diagram in two-dimensional parameter space, the coupling strength and the frequency mismatch parameter. There appears a region of resonant torus state, where the anti-phase rather than the in-phase solutions is stable.

As the coupling strength is increased beyond this region, the resonant torus structure is destroyed. At the point of bifurcation, it is broken as an unstable state approaches transversally toward the stable anti-phase solution on the surface of torus, while in the most conventional case the collision occur tangentially between the stable and unstable solutions on the torus. Although the structure of the torus has broken, the remnant stable and unstable manifolds of the anti-phase solution, the in-phase solution, and the non-oscillatory resting state are inter-connected to generate a new stable chaotic state. The chaotic state, visiting subsequently the anti-phase, in-phase, non-oscillatory state, and back to the oscillatory anti-phase, shows a bursting pattern, where the oscillatory anti-phase and in-phase oscillatory states separated by the long interval of non-oscillatory state. It is generated through self-organization among the unstable states, which is to be compared with the conventional one introduced by an additional slow modulating variable.

Neural Coding: On Time (Without Derailing Spiketrains)

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Abstract.
Time and timing plays a fundamental role for any sensory and motor system. I will first review some of my older work on storing temporal sequences in neural systems and on neural computation based on the precise timing of action potentials. In this part of the talk, I will argue that Lyapunov functions and functionals are of utmost importance for understanding the dynamics of large interconnected networks. I will then shift gears and ask the question whether "time" plays only the role of an independent variable or whether temporal relations could also be stored in a neural system in such a way that they can be used for nontrivial computations in the time domain, computations that might be highly relevant for sensory processing and (motor) planning.

Classification of Bursters: Why Bother?

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Abstract.
A neuron is said to exhibit bursting dynamics when its behavior alternates between spiking and rest. There could be many types of bursting patterns. The history of formal classification of bursting starts from the seminal paper by Rinzel (1987), who contrasted the bifurcation mechanism of the "square-wave", "parabolic", and "elliptic" bursters. We use geometric bifurcation theory to extend the existing classification of bursters, including many new types. We discuss how the type of burster defines its neuro-computational properties, and we show that different bursters can interact, synchronize, and process information differently.

This talk is based on the review/tutorial paper "Neural Excitability, Spiking, and Bursting". Int. J. of Bif. and Chaos (2000), 10:1171–1266.

http://www.nsi.edu/users/izhikevich/publications/nesb.htm

A spiking neuron model of binocular rivalry

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Abstract.

Recent recordings from single neurons in the cortex of monkeys experiencing binocular rivalry suggest that this phenomenon involves competition between alternative stimulus representations in binocular neurons at higher levels in the visual cortex (e.g. V4 and MT), rather than reciprocal inhibition between monocular neurons at lower levels (V1). We present a biologically plausible network of Hodgkin-Huxley type neurons that reproduces both the distribution of dominance durations seen in humans and primates and the lack of correlation between lengths of successive dominance durations. We then present a simplified population rate model that reproduces the following experimentally observed phenomena: (i) variation of stimulus strength to one eye influences only the mean dominance duration of the contralateral eye, not the mean dominance duration of the ipsilateral eye, (ii) increasing both stimuli strengths in parallel decreases the mean dominance durations. Explicit expressions for the dependence of these dominance durations on input strengths are derived, and we also derive an expression for the distribution of dominance durations that should be a better fit to experimental data than the ubiquitous gamma distribution.

Towards a Computational Theory for Wetware

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Abstract.
In contrast to computations in the computer, computations in wetware are based on transient events such as spikes. Consequently abstract computational models such as the Turing Machine, which require reliable storage of bits for longer periods of time, are less suitable for analyzing computations in wetware. We describe an alternative computational theory that provides a framework for analyzing computations based on transient events, such as trajectories of dynamical systems or spike trains. We also present some new ideas regarding learning for such systems.

Delayed recurrent neural lopps: Multistability and neural coding

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Abstract.

At an anatomical level the nervous system has a recurrently looped structure. An important, intrinsic property of these recurrent loops is the presence of time delays. The time delays arise because neurons are spatially separated and axonal conduction times are finite. Mathematical and experimental studies of pulse-coupled, time-delayed recurrent loops demonstrate the presence of multistability. The fact that the co-existing attractors differ with respect to their spiking patterns ties in well with current notions of the importance of spike time reliability and temporal pattern coding in the nervous system. A question that has received surprisingly little attention concerns how, given the presence of finite time delays and temporal pattern coding, is it possible for the nervous system to operate quickly. For example, psychophysical measurements demonstrate that the nervous system is able to acquire, transmit, decode, and act upon the ever changing information that it receives on time scales ($\sim 70 - 200$ msec) that are only slightly longer than the average interspike intervals of cortical neurons ($\leq 10-30$ msec) and neural time delays ($\sim 1-200$ msec).

Here I examine the possibilities for neural coding in terms of the statistical properties of dynamical systems with retarded variables. Attention is drawn to the property of statistical periodicity. Statistical periodicity is a statistical property of densities which arises in the description of retarded dynamical systems, including those exhibit multistability. For a population of neurons which exhibits statistical periodicity, information is not encoded by the periodicity of the densities, but rather by the spatio-temporal distribution of neural activity. Numerical simulations are used to demonstrate that statistical periodicity would be a very rapid, high storage capacity neuronal coding mechanism.

The above observations suggest that temporal pattern encoding, multistability, and statistical periodicity can be different perspectives of the properties of dynamical systems with retarded variables. Some observations on the human EEG which support this notion are briefly discussed.

Delay induced sustained and transient oscillations in neuron models

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Abstract.
Motivated by experiments on mechanoreceptors, we have examined the behavior of a neuronal model with a delayed self-interaction. This presentation willl first go over the description of the stationary dynamics of such systems, with special emphasis on multistability and sustained oscillations. Then, it examines how the interplay between the delay and coexisting stable equilibria can lead to transient oscillations, whose characteristics are analyzed. Finally, implications for the dynamics of neuronal networks as well as comparison with experimental data are considered.

Dynamics in Vision: Cortical Networks, Perceptual Oscillations & Migraine Auras

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Abstract.
Excitatory neocortical neurons contain membrane currents that produce a form of slow hyperpolarization known as spike frequency adaptation. A simplified dynamical description of cortical neurons comprising just four nonlinear differential equations can account for the effects of these currents in excitatory neurons. However, most cortical inhibitory neurons lack these currents. Simulations of excitatory-inhibitory cortical networks reveal that the presence of these currents can lead to bursting and oscillations under appropriate circumstances. Visual examples include the Marroquin illusion, binocular rivalry, and bursting during migraine auras.

Stable phase-locking induced by synaptic delays in networks of neurons

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Abstract.
We describe patterns which can be stored through very simple and small networks of neurons with delayed feedback: equilibria, synchronized and phased-locked periodic orbits, standing waves and their coexistence and connecting orbits. The long-term goal is to use these patterns to generate a wide range of nonlinear dynamics by coupling small networks through various connection topologies.

Part II

COMMUNICATIONS BRÈVES
CONTRIBUTED TALKS

Complex cooperative behavior of frustrated coupled oscillator system

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Abstract.

In many fields such as economics and neuroscience, there is currently much interest in the statistical physics of non-equilibrium frustrated and disordered many-body systems. Even relatively simple microscopic dynamics has been shown to lead to complex cooperative behavior. Here, we elucidated complex cooperative behavior of an oscillator associative memory model (which is one kind of non-equilibrium frustrated and disordered many-body system) in the memory retrieval phase and the spurious memory phase, respectively.

In the memory retrieval phase, almost all oscillators are mutually locked, and retrieves the stored phase patterns. Here, with a novel method based on the Sakaguchi-Kuramoto theory and the self-consistent signal to noise analysis, we elucidated the property of the mutual entrainment in the memory retrieval phase, especially, the acceleration (deceleration) effect in which the ORT (*Onsager reaction term*) plays a key role. The ORT, which describes the effective self-interaction, is of great importance in obtaining a physical understanding of frustrated random systems, because the presence of such an effective self-interaction is one of the characteristics that distinguish frustrated and non-frustrated systems. However, the role of the ORT is not yet well understood in non-equilibrium systems. Here, we considered two oscillator associative memory models, one with symmetric and one with asymmetric dilution of coupling. These two systems are ideal for evaluating the effect of the ORT, because, with the exception of the ORT, they have the same order parameter equations. We found that the two systems have identical macroscopic properties, except for the acceleration effect caused by the ORT. Therefore, comparing the two systems, we could extract the effect of the ORT only to the rotation speed of oscillators.

When the recalling process is unsuccessful, the systems are in the glass phase (spurious memory retrieval) instead of the the ferromagnetic phase (memory retrieval). In the glass phase, oscillators are mutually pulled via weak interaction. This weak interaction causes quasi-synchronization among oscillators which is refered as “the quasi-entrainment”. Here, we focused on the quasi-entrainment phenomenon in the glass phase. We also displayed the

distribution of local fields which takes the form like "volcano" in the glass phase. This phenomenon implies an outbreak of replica-symmetry breaking in the glass phase.

According to results obtained from analyses for its behavior in memory retrieval and spurious memory retrieval, it is possible to determine whether the recalling process is successful or not using information about the synchrony/asynchrony. There is one interesting physiological data related to our studies. Freeman and Sharda discovered chaotic behavior of olfactory systems in response to unknown odor. We expect that the chaotic behavior in response to unknown odor is related to asynchronous behavior of our systems in spurious memory states. Thus, we believe the present analysis may strongly influence debate on the functional role of synchrony in the brain.

Joint work with Masato Okada (ERATO Kawato Dynamic Brain Project).

Delayed neural networks

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Abstract.

Delay differential equations modeling artificial neural networks have been investigated. Linear stability analysis provides parameter values yielding asymptotic stability of the stationary solutions, as a function of the time delays: stability can be lost either through a Hopf bifurcation, or through a degenerate (higher-codimension) bifurcation. The role played by the eigenvalue distribution of the connection matrix, as well as the occurence of co-existing stable solutions will be discussed.

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Abstract.

In this work, a computational model of Multiple Sclerosis (MS) plaques affecting the axonal transmission is proposed and its simulation results are presented and discussed.

MS-plaques are "hallmarks" of the Multiple Sclerosis disease and are ubiquitous on various cerebral pathways of MS patients. These sclerotic plaques are the decay in the myelin sheathing of the myelinated axons from distinct regions within the CNS. From an engineering perspective, one can assume that these inflammatory processes are solely communication problems between different areas that need to "converse" through a given path. This approach abstracts all the unsolved medical aspects of MS, especially those concerning aetiology and therapy.

This work was started motivated by the need to understand the MS-plaque impairment mechanisms on a smaller scale of neural communication leading to the anomalous and complex communication behaviour when a cerebral pathway connecting two distinct cortical regions is affected by MS-plaques.

The model considers some of the biological features observed in the axon membrane, namely (1) the local dynamics of the internode interaction, and (2) the nature in which the axon sheathing is organised. Then, this was incorporated into artificial neural networks, which are composed of layers of threshold units $\neq$ artificial neurons. The model proposed here utilises a neural network arranged in distinct sub-nets (layers), representing two cortical areas connected by a number of myelinated axons. A set of synaptic parameters was produced by training the network on a non-linear input-output relation. The effects of the MS-plaques on the nerve fibres were obtained by varying the influence (i.e. resistance) of the insulation of the internodules of a subset of those axons (that are subject to the generated MS-plaques) within the pathway. Finally, conduction velocity changes, due to the MS-plaque effects, were observed using a varying time window in the target cortical area.

The simulations were organised in three distinct groups, starting with comparisons between the discrepancies of control and abnormal predicted values. The second group of simulations involves the same kind of comparison, as well as a varying time-window on the target cortical area for including or excluding delayed signals. The latter simulation presented here, different from the previous two, analyses the impact on the signal transmission delays. This simulation presents increases of their severity of internode damage. It was found that the number of affected axons was consistently the most influential factor causing transmission delays. This surpassed all the other investigated features, namely the number of internodes affected and the severity of individ-

ual attacks on internodes. In other words, transversal damage to the pathway is more devastating to neurocommunications than longitudinal destruction to the myelin, so that plaques layout can be a more relevant feature than their size.

Joint work with Philippe De Wilde.

On-off intermittency on the fingertip

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Abstract.
The act of balancing a pencil at the fingertip is often quoted as an example of the stabilization of an unstable equilibrium point by the addition of a time-delay. Once the pencil is sufficiently long it becomes easier to balance the pencil: as the pencil becomes longer its rate of movement becomes slowed relative to the reaction time of the nervous system for making corrective movements. Analysis of a simple model for this balancing task suggests that stochastic forcing of a critically bifurcation parameter (parametric noise) through a bifurcation point can occur. A 3-D motion analysis of a pencil balanced at the fingertip shows that a quantity proportional to the deviation angle of the balanced pencil from vertical undergoes an apparently random alteration between a quiescent state characterized by small deflections ("laminar" phases) and a bursting state characterized by relatively larger deflections. The laminar phases scale as $-3/2$ as predicted for dynamical systems which exhibit on-off intermittency (Heagy, et al, 1994; Platt, et al, 1993). The presence of on-off intermittency in postural tasks controlled by the nervous system may explain, for example, why unpredictable falls occur in the elderly.

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Correlation enhanced information transfer in electroreceptors

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Abstract.
Accurate detection of external stimuli is essential for survival of a species. Weakly electric fish use amplitude modulations of their self generated electric field to probe their environment. Using information theoretic measures that make no assumptions on the nature of the neural code, we show that correlations in the spike train can help in the detection of both low and high frequency time varying stimuli. Furthermore, we find that the loss of potential information incurred by decreasing the resolution on spike timing is lower for low stimulus cutoff frequencies than for high ones. This suggests that a rate code is used for the encoding of low frequency stimuli while spike timing is important for the encoding of high frequency stimuli.

Biased Competition Mechanisms for Visual Attention in a Multimodular Neurodynamical System

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Abstract.

Visual attention poses a mechanism for the selection of behaviorally relevant information from natural scenes which usually contain multiple objects. The limited processing capacity of the visual system does not allow the simultaneous analysis of many different object. Selective visual attention facilitates therefore the processing of that limited portion of the input associated with the relevant information and it suppresses the remaining irrelevant information. If attention is, for example, top-down guided to a certain spatial location in the visual field, like in the case of object recognition, information coming from the attended location will be facilitated whereas the information coming from the other unattended locations will be suppressed. On the other hand, if top-down bias the attention in such a way that only a specific feature (e.g. color) or a bundle of conjoined features (e.g. a given object) is important, like in the cases of visual search, then only the processing of the corresponding consistent input features in the visual field is augmented whereas the remaining irrelevant feature information is reduced. The aim of the present work is to formulate a neurodynamical model based on the "biased competition" hypothesis (Duncan, 1996) and structured in several network modules which can be related with the different areas of the dorsal and ventral path of the visual cortex (Ungerleider and Mishkin, 1982). Additionally, our model assumptions are consistent with the existing experimental single cell recordings (Reynolds et al., 1999) and recent functional magnetic resonance imaging (fMRI) studies (Kastner et al., 1999). The "biased competition" hypothesis proposes that multiple stimuli in the visual field activate populations of neurons that engage in competitive interactions. On the other hand, attending to a stimulus at a particular location or with a particular feature biases this competition in favor of neurons that respond to the features or location of the attended stimulus. This attentional effect is produced by generating signals within areas outside visual cortex which are then fed back to extrastriate areas, where they bias the competition such that when multiple stimuli appear in the visual field, the cells representing the attended stimulus "win", thereby suppressing cells representing distracting stimuli.

In this work, we formulate a neurodynamical system consisting of interconnected populations of cortical neurons distributed in different brain areas.

We show that object recognition and visual search can be explained in the theoretical framework of a biased competitive neurodynamics. The top-down bias can guide attention to concentrate at a given spatial location or at given features. The neural population dynamics are handled in the framework of the mean-field approximation, i.e. by the analytical description of the mean activity of a population of neurons. Consequently, the whole process can be expressed as a system of coupled differential equations. Additionally, we analyse the attentional enhancement of the spatial-resolution of the area containing the objects of interest. We propose and simulate two new psychophysical experiments where the effect of the attentional enhancement of spatial resolution can be demonstrated by predicting different reaction time profiles in visual search experiments where the target and the distractors are defined at different levels of resolution, i.e. in the context of the global-local paradigm. These experiments consist of a visual search task using hierarchical patterns and a counting task to discover how many prototypes of an a-priori given target are present in a complex scene. Our computational model assumes different modules for the analysis of global and local information which can be independently "damaged", and shows a neuropsychological dissociation in visual search paradigms and a model for visual neglect.

“Ghostbursters”: A novel bursting mechanism in pyramidal cells

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Abstract.
Pyramidal cells of the electrosensory lateral line lobe (ELL) of the weakly electric fish Apteronotus leptorhynchus have been shown to produce burst discharges with constant depolarizing stimuli (Turner and Maler, 1999; Lemon and Turner, 2000). We develop a six dimensional, two compartment, pyramidal cell model that matches ELL burst data. An accelerated “ping-pong” interplay between the soma and the dendrite is the process that drives the burst, and an abrupt halt of the interplay terminates the firing. We explore the relevant bifurcations of the model in order to classify the burst mechanism. The model undergoes a saddle node on an invariant circle bifurcation from quiescent to limit cycle firing as applied current increases (type I excitability). Neural models exhibiting this bifurcation show a strong dependence of oscillation period upon applied current. The accelerated “ping-pong” interaction increases the depolarization, hence reducing ISI length, during a burst. At “ping-pong” failure the depolarization is reduced and the period increases because the system approaches the “ghost” of the saddle node bifurcation. This increase in ISI is the termination of the burst. The model results challenge the implicit assumption that burst models must be classified by two bifurcations.

Joint work with André Longtin, Carlo Laing, and Len Maler (University of Ottawa).

Noise-Induced Phase Synchronization: An Analytic Approach

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Abstract.
The phenomenon of stochastic resonance (SR) can be reformulated in the framework of externally driven nonlinear oscillators. Amplitude and phase descriptions of the latter mentioned systems can be transferred to one of the paradigms for SR, the two state system. The phenomena of frequency and phase locking can thus be revisited in the context of SR which reveals itself through the fact that both effects can be enhanced by optimal noise.

We present the idea of noise-induced phase synchronization starting out from a simple model system which allows for an entirely analytic treatment. Bridging to the dynamics of neurons requires the inclusion of memory kernels (semi-Markovian processes).

Joint work with A. Neiman (Center for Neurodynamics, University of Missouri at St. Louis) and L. Schimansky-Geier (Institute of Physics, Humboldt-University at Berlin).

Approximate probability densities and transition rates for stochastic delay differential equations

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Abstract.

Approximate probability densities and transition rates for stochastic delay differential equations

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Stochastic delay differential equations (SDDE's) are now used increasingly often in modelling, notably in physiology. However, the analytical tools used to study non-delayed stochastic differential equations (SDE's) cannot usually be applied to SDDE's since they evolve in an infinite dimensional phase space. We developed a technique which allows these tools to be used on a SDDE when the delay is short [1]. In this method, a Taylor expansion in powers of the delay is performed on the SDDE. This leads to a non-delayed SDE, thus opening the door to the analytical tools which have been devised for these equations. This new technique, which has been shown to agree with numerical simulation results for a sufficiently small delay, can be applied to a wide variety of problems. Indeed, it can be used with any type of noise, white or coloured. Furthermore, it is easily generalised to multiply delayed as well as multivariate systems. A particularly interesting feature of this approach is that the Fokker-Planck equation associated with the original SDDE is non-delayed, whereby the delay appears only as a parameter.

In this talk, we apply this technique to the delayed quartic potential subjected to additive Gaussian white noise and study the noise-induced rate processes between the two wells [2]. Under an appropriate separation of time scales, a phenomenological rate law can be used to describe the statistical evolution of the system, even in the presence of a pathological asymptotic regime where the system diverges. For short delays, the approximate analytical transition rate is seen to agree with numerical simulation results.

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Joint work with Ivan L'Heureux, André Longtin (University of Ottawa)

Burst as a Source of Nonlinear Determinism in Interspike Interval Firing Patterns of Dopamine Neurons

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Abstract.
Dopamine (DA) neurons have two firing patterns, single-spike and burst, which interweave to produce irregular and complex interspike interval (ISI) patterns. Nonlinear dynamical analysis has shown the presence of a nonlinear deterministic structure in the ISI data. We examined the source of the nonlinear determinism in the ISI data obtained from the rat substantia nigra. We separated the bursts from the single-spikes in the ISI data, and estimated the dimensional complexity (D2) of each signal. The D2 refers to the number of degrees of freedom or complexity of a time series. The D2 values of the signals were compared with those of the surrogate data. We detected nonlinear deterministic structure in the burst time series, whereas no nonlinear determinism in the single spike time series was found. Interburst interval (IBI) data also had nonlinear determinism. These results indicate that the bursts may be a source of nonlinear determinism in the ISI data of DA neurons.

Asymptotic measures of noise sensitivity in systems with delays

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Abstract.

We discuss methods for analyzing the effect of noise on transitions in systems with delays. In particular, we consider systems in which the effect of small noise is amplified by the delay so that the dynamics are significantly altered. First, we outline a multiscale method for stochastic delay-differential equations. Here proximity to a critical delay results in noise amplification and an apparent shift in the transition to oscillations. We derive an evolution equation which extracts the effect of the noise from the oscillations. Second, we analyze a simplified model for an excitable dendritic spine, which exhibits bursting. Here transition to the active phase is analogous to a noise-sensitive delay bifurcation, and the exit from the active phase can be described using multiscale methods. The asymptotic analyses are used to quantitatively describe the noise sensitivity in the system. In both cases the asymptotic methods yield reduced, approximate models which give a clear indication of the influence of the noise and can be solved efficiently.

Joint work with Stever Baer (ASU), and Malgorzata Klosek (UW-Milwaukee).

Depth perception in weakly electric fish

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Abstract.
Weakly electric fish can accurately determine the location of objects in their surroundings using an active electric sense. Objects with electrical properties that differ from those of the ambient water produce distortions in the fishs self-generated electric field. On the body surface, these distortions form a 2D electric image and provide the sensory input required to accurately encode object location in 3D. We are using multiple approaches to investigate how object distance is encoded and processed in the early stages of the electrosensory pathways. In a comparative psychophysical study, we show that, despite the peculiar nature of the electrosense, cues that are used for electrosensory depth perception are very similar to those used for visual depth perception in humans. In the electrosensory pathways of the fish, the electric image is initially encoded by a population of pyramidal neurons in the electrosensory lateral line lobe (ELL). We investigate how the spatial response properties of this neural population impacts the encoding of the electrosensory cues necessary for depth perception. Our results suggest that different spatial response properties are required to optimally encode different sensory cues. The responses of these neurons are regulated by two distinct feedback pathways. Our future work will be aimed at determining the role of feedback in electrosensory depth perception in a dynamic environment.

Divisive and Subtractive Gain Control with Feedforward and Feedback

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Abstract.
Weakly electric fish are increasingly studied to shed light on key issues of neural coding. They generate a weak oscillatory electric field around their body. Amplitude modulations of this field, caused by environmental stimuli such as food or communication signals from other fish, are read by cutaneous P-type electroreceptors. The firing activity of these receptors is relayed to pyramidal cells. These cells are thought to perform, among other tasks, gain control. Such control maintains their output firing rate within certain bounds, so that the fish can properly discriminate a wide range of stimulus intensities; it may also highlight novel stimuli. Such control is achieved via delayed excitatory and inhibitory feedback pathways from higher brain structures to the pyramidal cells.

We present a mathematical model of the pyramidal cell firing activity in the presence of such feedback. It is based on recently obtained data from intracellular measurements. A simpler integrate-and-fire type model is also derived, which embodies the main features of the full model. Particular attention is paid to the stochastic nature of the synaptic input in each case. With a "static feedback", a form often assumed in studies of neural gain control, this noise is shown to produce a novel "divisive inhibition" regime for perithreshold stimuli. The analysis of the full model with dynamical feedback further reveals bifurcations to oscillatory activity involving the pyramidal cells and higher brain structures, as well as divisive gain control. In contrast, feedforward inhibition is shown to produce a blend of subtractive and divisive gain control.

Bistable Gradient Neural-like Networks

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Abstract.
We describe a neural-like homogeneous network consisting of bistable elements. Due to the absence of spurious states, this class of neural net allows new possibilities of learning, pattern recognition and computation, including the perfect recall of several memory patterns.

Joint work with V. Chinarov.

Chaotic neural control

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Abstract.

The issues of chaotic behaviors of the brain and possible role of chaos in information processing have been discussed at some length for at least 15 years (see [1,2] and references therein). Evidences have been given that chaos helps in cases such as (1) avoiding spurious memory, (2) providing novelty filters, and (3) searching memory. However, it is not yet clear why the brain should need chaos to perform its tasks. Here, we provide an indirect support for this need. We consider the problem of chaoticity from the point of view of acts of control. The control of body movement and orientation, as well as the control of chemical homeostasis within the body, should be performed by the neural system all the time. This control is performed by means of discrete pulses, so the procedure should be discrete (performed at discrete moments of time and the control impact also should take discrete values). We show that solving such problems may lead to chaotic behaviour and also require some irregularity from the controller for learning to perform such a control.

First, it is possible to show, by simple examples, that discrete control of unstable equilibrium (e.g. upright position of a body) leads to generating a chaotic attractor. Control in this case forms a feedback loop. If a control is performed by a neural network, then records of its activity also will show the signs of chaoticity or randomness. Therefore, one of the explanations of the brain chaoticity may be that it is related to the executions of the controls

Another and probably the more important connection between control and chaos may be related with learning to perform such a control. In contrast to usual learning tasks for which examples are available, for problems of our interests, there may neither be examples nor "obvious" policies (which action should be taken at a given state). A controller should learn from its own experience acquired through its trials and overall evaluation of performance in terms of achieving a final goal. This is the situation of reinforcement learning [3]. It implies exploration of possible states and actions during learning, and the usual source of such exploration is randomness in decision making. We conjecture that partially random policy may be replaced by a partially chaotic policy. Numerical experiments show that algorithms of reinforcement learning admit chaotic policies. Hence, the brain chaoticity may be a source of "initiative" and be a necessary element for adaptation in changing environment. The possibility of such a role of chaos was pointed out earlier by W. Freeman,

but our approach makes the conjecture more concrete and testable on models.

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Joint work with M.K. Ali.

Topographic Organization of Hebbian Neural Connections by Synchronous Wave Activity

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Abstract.

During the development of the brain, genetically encoded chemical markers provide the initial guidance for neural connections, which produces a diffuse distribution of synapses that only broadly overlaps the locations necessary for normal neural function. The onset of synaptic activity coincides with a rapid reorganization of the connections into a topographically precise neural network. In the visual pathway, for example, the unscrambling of initially imperfect connections in the optic nerve requires some form of visual input. Before the onset of vision, such input is likely provided by spontaneous, endogenous wave activity in the retina. Retinal waves and excited LGN domains define regions of correlated activity. Together with "coincidence-detecting mechanisms", which reinforce connections among coactive cells, these processes direct the organization of circuits in the brain and the refinement of the early connection scheme. However, the exact mechanism by which neural activity is translated into long-term structural changes in the neural connections remains obscure.

We study the entrainment of wave activity in coupled excitable media to explore the evolution of neural topographic organization in light of recent findings in neurobiology on the developing visual system. Our model is comprised of two excitable layers of FitzHugh-Nagumo neurons, with initially random unidirectional (synaptic) coupling between the layers and diffusive coupling within the layers. The two layers correspond to the retina and the LGN. Spontaneous retinal waves move very slowly, which suggests that they arise from slow extracellular diffusion of excitatory substances or the diffusion of messenger molecules through intercellular junctions. The activity of neighboring cells in the LGN relies on second messengers that diffuse through gap junctions. We find that this lateral diffusive coupling within the layers, together with spontaneous activity in the source layer, yields synchronization of wave activity between the layers. We explore how these synchronous patterns of activity serve to direct the topographic organization of the interlayer connections. The behavior found in this model resembles that observed in the developing visual system and, possibly, in other parts of the brain that involve

topographic projections between neural layers.

Joint work with Eugene Mihaliuk and Kenneth Showalter.

Part III

POSTERS

Self-adapting reactive autonomous agents

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Abstract.

Autonomous agents must perform many complex tasks in real-time. An intelligent autonomous agent must have the capability of both low-level reaction and high-level deliberation. This means that an autonomous agent must be able to pre-process incoming sensory information, decide what action to execute next, carry out that action and learning the consequences. Furthermore, the autonomous agents must operate successfully under changing environments.

This work describes a self-adapting control algorithm for reactive autonomous agents. The architecture of the autonomous agents integrates the reactive behavior with reinforcement learning. We show how these components perform on-line adaptation of the autonomous agents to various complex navigation situations by constructing an internal model of the environment.

In our approach to simulate autonomous agents we have developed a modular subsumption architecture acting as a hierarchical sensory-motor map. The subsumption architecture is a computational model based on a network of asynchronously computing elements. The computing elements communicate with each other by sending and receiving messages without implicit semantics. The meanings of the messages are given by the actions of both sender and receiver.

The subsumption architecture can be easily exploited by a neural network controller capable of introducing cooperation and coordination in a team of agents. The cooperation between agents was introduced by giving them the possibility to share the same memory. If the agents are starting to move from the same initial position but at different moments of time we can see how their performances are progressively improved: the first agent is teaching the second agent, the first and the second agents are teaching the third etc. The coordination of agents was introduced by using a neural network that controls the physical interaction between agents. In order to avoid the collisions between agents we have introduced a repulsive interaction. Also, an attractive interaction between agents was introduced. This attractive force is used to control the relative independence of the agents. In our simulations we have used attractive elastic forces with the elastic constants controlled by the neural network. This way the neural network can be used to control the global behavior of a team of agents. We have successfully tested this architecture for

simple group navigation and competitive goal problems. Other scenarios are also possible to implement by introducing a more sophisticated neural network controller.

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Joint work with M.K. Ali.

Coherence Resonance and Stochastic Resonance in a Three State System

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Abstract.

As a generalization of the two state models usually considered in research on stochastic resonance (SR) we present here results for a three state system. In the context of neuron dynamics the three states correspond to the quiescent, excited and refractory states. Unidirectional transitions between the states are governed by the standard, i.e. memoryless, master equation. In spite of the unrealistic Markovian assumption, which lies behind zero memory, the phenomenon of coherence resonance (CR) occurs when making the transition from the two state to the three state system.

An external harmonic stimulus acts on the system by modulating the transition rate from the quiescent to the firing state. The asymptotic evolution of probabilities can be solved analytically in the linear response regime. A peak in the spectral power amplification, one of the standard measure for SR, can be derived rigorously from this solution. The effect of CR is responsible for SR also being a *bona-fide* resonance.

Joint work with B. Lindner and L. Schimansky-Geier (Institute of Physics, Humboldt-University at Berlin).

Generalized Synchronization and Decoding Chaos in Spike Trains

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Abstract.

In this work we consider a pacemaker neuron driven by chaotic stimulus. While varying the strength level of the applied stimulus we examine the temporal spike patterns. When the amplitude of the driving stimulus is small enough the regular spiking of the pacemaker does not change much, and therefore the dynamics of the neuron has not much to do with the dynamics of the driving stimuli. As the amplitude of the stimulus becomes larger the dynamics of the neuron starts to be influenced and entrained by the stimulus, which is manifested by chaotic firings. Entrainment between the driving chaotic signal and the driven pacemaker appears as several different forms of chaotic synchronization: the weak generalized synchronization, the phase synchronization, and the strong generalized synchronization.

The entrainment provides the possibility of extracting from the spike train some amount of information contained in the chaotic stimulus. That amount in turn is attributed to a possible relation between the driving stimuli and the response firing patterns. One way of extracting the stimulus information from the neural spike patterns is first to reconstruct the response attractor from the inter-spike interval pattern of the neuron. Then the decoding corresponds to reconstructing the stimulus based on the existence of the mapping between the two attractors of the drive and the response system. The cross-predictability which measures the degree of predictability of the mapping is directly related to the inverse of the estimation error of the stimulus reconstruction. The quality of the reconstruction rises at the onset of the generalized synchronization as the predictability starts to increase. It becomes enhanced in the presence of the phase synchronization due to the phase ordering between the drive and the response. The reconstruction quality is further enhanced at the onset of the strong synchronization in which the amplitude ordering eventually occurs.

The results of the present work suggest a new scheme of the temporal coding that exploits the generalized synchronization between the time-varying stimulus and the irregular firing pattern of a pacemaker neuron. In the new scheme the generalized synchronization plays a role of an order that ensures the reliability of the neural code.

Joint work with Won Sup Kim (Chungbuk National University) and Hyungtae Kook (Kyungwon University).

Turning off by synchronisation in a working memory model

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Abstract.

We study a spiking neuron model that reproduces aspects of the activity seen in prefrontal cortex during working memory tasks in monkeys. The model consists of a large number of synaptically coupled excitatory and inhibitory Hodgkin–Huxley type neurons, with coupling strengths that decay with the distance between neurons. The state in which no neurons fire is stable, as is a "bump" state, in which there is a spatially localised patch of active neurons. The size of this bump is determined only by the structure of the coupling, not by e.g. the size of the transient external current input needed to move the network from the all–off state to a bump state. The location of the bump within the network is determined by the position of the transient external current input.

The structure of the coupling ensures that neurons within the bump fire asynchronously. Indeed, this asynchrony is essential to the existence of a bump, since causing all of the neurons involved in the bump to fire at the same time as the result of a transient external excitatory current input (that could be e.g. a copy of the motor command for the action that completes the working memory task) moves the network from a bump state back to the all–off state. This "turning off" mechanism is an alternative to an external inhibitory current input, which also moves the network into the all–off state.

Joint work with Boris S. Gutkin and Carson C. Chow.