BP 15: Focus session: Collective Dynamics in Neural Networks

Time: Wednesday 9:30–13:00 Location: H11

Invited Talk BP 15.1 Wed 9:30 H11

Statistical physics of correlated neuronal variability — •Moritz Helias — INM-6, Forschungszentrum Juelich, Germany — Condensed matter theory, RWTH Aachen University, Germany

Neuronal networks can be considered as many particle systems with interesting physical properties: They operate far from thermodynamic equilibrium and show correlated states of collective activity [1].

We here discuss recent progress in understanding the structure of these correlated states by methods from statistical physics and disordered systems [2,3,4].

Our analysis shows that the heterogeneity of the network connectivity enables critical dynamics that unfolds in a low-dimensional subspace. The structure of correlations predicted by this theory is found in line with massively parallel recordings from motor cortex [2]. We then demonstrate that networks in such regimes possess optimal capacity to memorize past input sequences [3]. We find that they operate in a hitherto unreported regime that combines instability on short time scales with asymptotically non-chaotic dynamics. As an outlook, we demonstrate how methods from field theory [4] help us understand the interplay of non-linearities and fluctuations that is vital to neuronal network dynamics.

1. Dahmen, Bos, Helias (2016) Phys. Rev. X 6, 031024; 2. Dahmen, Grün, Diesmann, Helias (2018) arXiv:1711.10930; 3. Goedeke, Helias (2018) Phys. Rev. X 8, 041029; 4. Kühn, Helias (2018) J Phys A 51, 37

BP 15.2 Wed 10:00 H11

Precise Synaptic Balance in a Homolog of Olfactory Cortex — Peter Rupprecht[1,2] and •Rainer Friedrich[1,2] — [1]Friedrich Miescher Institute for Biomedical Research, Basel, Switzerland — [2]University of Basel, Basel, Switzerland

In the classical balanced state, uncorrelated excitatory and inhibitory inputs result in irregular spiking that is inefficient for specific computations. More recently, theoretical studies have shown that correlating excitatory and inhibitory inputs on a short timescale (tight balance) and in a multi-dimensional coding space (detailed balance) can neutralize these drawbacks of balanced networks.

We used whole-cell voltage-clamp recordings in the intact zebrafish brain to directly analyze synaptic inputs to neurons in a distributed olfactory memory network. We found that large excitatory and inhibitory recurrent inputs establish a transient balanced state during odor stimulation. Using 20 Hz upstream oscillations as a reference clock to align excitatory and inhibitory inputs in time, we found a tight balance, with inhibition tracking excitation by a 3 ms delay. Finally, by studying the odor-specificity of excitatory and inhibitory inputs, we found inhibition and excitation to be co-tuned, as a signature of a detailed, high-dimensional balance in stimulus space. This precise synaptic balance implies specific and non-random connectivity among neurons, despite the absence of an obvious topography in olfactory cortex. We propose that this network is the substrate for a pattern classification process that is fast, as in classical balanced networks, but also stable in many coding directions.

BP 15.3 Wed 10:15 H11

Long-Range Collective Dynamics in the Balanced State — •Moritz Layer, Lukas Deutz, David Dahmen, and Moritz Helias — Forschungszentrum Juelich, INM-6, Wilhelm-Johnen-Strasse, 52428 Juelich, Germany

Experimental findings suggest, that cortical networks operate in a balanced state, in which strong recurrent inhibition suppresses single cell input correlations. The balanced state, however, only restricts the average correlations in the network, the distribution of correlations between individual inputs is not constrained. We here investigate this distribution and establish a functional relation between the distance to criticality and the spatial dependence of the statistics of correlations. Therefore, we develop a mean-field theory that goes beyond self-averaging quantities by taking advantage of the symmetry of the disorder-averaged effective connectivity matrix. We demonstrate that spatially organized, balanced networks can show rich pairwise correlation structures, extending far beyond the range of direct connections. Strikingly, the range of these correlations depends on the distance of the network dynamics to a critical point. This relation between the operational regime of the network and the range of correlations is a potential dynamical mechanism that controls the spatial range on which neurons cooperatively perform computations. In the future we will compare our results with data from multi channel recordings to infer new constraints on realistic network models.

BP 15.4 Wed 10:30 H11

Effects of cellular excitatory-inhibitory composition on neuronal dynamics — •Oleg Vinogradov[1,2], Nirit Sukenik[3], Elisha Moses[3], and Anna Levina[1,2] — [1]University of Tübingen — [2]MPI for Biological Cybernetics — [3]Weizmann Institute of Science

Excitation/Inhibition balance is essential for stable neuronal dynamics. It is considered to be strongly related to the relative counts of excitatory and inhibitory neurons. However, it is not clear if the relative counts indeed change the excitation/inhibition balance on a synaptic level and affect the neuronal dynamics. To investigate these effects, we recorded Ca-activity of hippocampal cultures with various numbers of inhibitory neurons. In experiments, all cultures developed network bursting. The cultures with various fractions of inhibitory neurons showed stable average inter-burst intervals. The variance of inter-burst intervals, however, grew with the number of inhibitory neurons. We reproduced the results of experiments in a model network of leaky integrate-and-fire neurons with different numbers of inhibitory neurons, but balanced strength of excitation and inhibition, and adaptation. The model showed that the stable mean and increasing variance of inter-burst intervals can be achieved by the synaptic balance between excitation and inhibition that regulates effects of adaptation. We also show that an equivalent mean-field model of excitatory and inhibitory rate-neurons with adaptation can account for these effects in terms of simple attractor dynamics. Overall, our results suggest that hippocampal cultures with various cellular compositions tend to maintain the balance.

BP 15.5 Wed 10:45 H11

Functional Renormalization Group for Stochastic Rate Neurons — •Tobias Kühn[1], Jonas Stapmanns[1,2], David Dahmen[1], Carsten Honerkamp[2], and Moritz Helias[1,3] — [1]Institute of Neuroscience and Medicine (INM-6), Forschungszentrum Juelich, Germany — [2]Institute for Theoretical Solid State Physics, RWTH Aachen, Germany — [3]Department of Physics, Faculty 1, RWTH Aachen, Germany

It is often suggested that the cortex operates close to a critical point at which linear response theory fails since the neural dynamics is dominated by large fluctuations on all length scales. The functional Renormalization Group (fRG) is not stained with this flaw because in principle it treats statistics of arbitrary order in an unbiased and self-consistent way. We apply fRG to a self-interacting, stochastic, quadratic rate neuron and show how this method incorporates corrections to the mean dynamics and time-dependent statistics due to fluctuations in the presence of nonlinear neuronal gain. To obtain a simplified treatment of the frequency-dependence of all observables, we adapt the Blaizot Méndez-Galain Wschebor (BMW) scheme to the vertex expansion, which yields good predictions.

We expect that the insights into fRG-techniques gained within our study will help to tackle challenges occurring in the description of phenomena in spatially extended networks, notably the calculation of critical exponents and the coarse-graining of microscopic models.

15 minutes break.

BP 15.6 Wed 11:15 H11

Resonant chaos in random networks of adapting neurons — Samuel Muscinelli[1], Wulfram Gerstner[1], and •Tilo Schwalger[2,3] — [1]Brain Mind Institute, École polytechnique fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland — [2]Institut für Mathematik, Technische Universität Berlin, 10623 Berlin — [3]Bernstein Center for Computational Neuroscience, 10115 Berlin

The dynamical response of cortical neurons to inputs is governed by several history-dependent mechanisms. One prominent example are slow negative feedback mechanisms that lead to spike frequency adaptation – a widely observed feature of neurons. Despite the importance of adaptation, it is theoretically poorly understood how such neuronal properties shape the collective activity of recurrent networks.

Here, we study the dynamics of a random recurrent network of multi-dimensional rate neurons admitting adaptation. Using dynamical mean-field theory and an iteratative map for the self-consistent second-order statistics of neural activity, we show how local adaptation and recurrent feedback from the network give rise to two distinct types of chaotic behavior, resonant and non-resonant chaos. The type of chaos as well as the resonance frequency can be predicted by the single neuron susceptibility. Interestingly, the emerging correlation time of the network activity cannot be increased by slow adaptation. We also find that suppression of chaos is maximized by input frequencies close to the resonant one. More generally, our work sheds light on the complex interplay between local neuron properties and recurrent network connectivity beyond adaptation.

BP 15.7 Wed 11:30 H11

Growing Critical: Self-Organized Criticality in a Developing Neural System — •Sven Goedeke[1], Felipe Yaroslav Kalle Kossio[1], Benjamin van den Akker[2], Borja Ibarz[3], and Raoul-Martin Memmesheimer[1,2] — [1]Neural Network Dynamics and Computation, University of Bonn, Germany — [2]Department of Neuroinformatics, Radboud University Nijmegen, Netherlands — [3]Nonlinear Dynamics and Chaos Group, Universidad Rey Juan Carlos, Madrid, Spain

Experiments in various neural systems found avalanches: bursts of activity with characteristics typical for critical dynamics. A possible explanation for their occurrence is an underlying network that self-organizes into a critical state. We propose a simple spiking model for developing neural networks, showing how these may “grow into” criticality [1]. Avalanches generated by our model correspond to clusters of widely applied Hawkes processes. We analytically derive the cluster size and duration distributions and find that they agree with those of experimentally observed neuronal avalanches.

[1] Kalle Kossio, F. Y., Goedeke, S., van den Akker, B., Ibarz, B., and Memmesheimer, R. M. (2018). Growing Critical: Self-Organized Criticality in a Developing Neural System. Phys. Rev. Lett. 121(5), 058301.

BP 15.8 Wed 11:45 H11

Homeostatic plasticity and external input shape neural network dynamics — •Johannes Zierenberg[1,2], Jens Wilting[1], and Viola Priesemann[1,2] — [1]Max-Planck-Institut für Dynamik und Selbstorganisation, Göttingen — [2]Bernstein Center for Computational Neuroscience, Göttingen

In vitro and in vivo spiking activity clearly differ. Whereas networks *in vitro* develop strong bursts separated by periods of silence, *in vivo* cortical networks show continuous activity. This is puzzling as both networks presumably share similar single-neuron dynamics and plasticity rules. We propose that the defining difference between *in vitro* and *in vivo* dynamics is the strength of external input. *In vitro*, networks are virtually isolated, whereas *in vivo* every brain area receives continuous input. We analyze a model of spiking neurons in which the input strength, mediated by spike rate homeostasis, determines the characteristics of the dynamical state. Our analytical and numerical results on various network topologies show that under increasing input, homeostatic plasticity generates distinct dynamic states, from bursting, to close-to-critical, reverberating and irregular states. This implies that the dynamic state of neural networks can readily adapt to the input strengths. Our results match experimental spike recordings: *in vitro* bursts are consistent with a state generated by very low network input ($< 0.1\%$), whereas *in vivo* activity suggests that on the order of 1% recorded spikes are input-driven, resulting in reverberating dynamics. This implies that one could impose *in vivo*-like activity in *in vitro* preparations by exposition to weak long-term stimulation.

BP 15.9 Wed 12:00 H11

Critical dynamics in models and experimental data — •Anna Levina — Tübingen University — BCCN Tübingen

Understanding the complex dynamics of the human brain is one of the most exciting challenges in modern science. Novel experimental methods allow acquiring unprecedented amounts of high-quality data. However, making sense of all these data requires an integrative theoretical approach to foster a deeper understanding of brain activity. Here I will discuss the critical dynamics approach that provides an explanation for a plethora of empirical results regarding scale-free spatiotemporal dynamics observed through a multitude of experimental methodologies across different spatial and temporal scales. The hypothesis that the brain operates close to the critical state is supported by the theoretical evidence suggesting multiple aspects of information processing to be optimized at the second order phase transition. I will give an overview of the experimental evidence and theoretical modeling of criticality in neuronal systems. Using an example of an efficient coding network, I will demonstrate how optimization of the network for particular function might result in a critical-like dynamics. Considering the problem from the other side, I present evidence that approaching critical state can improve the general computational capabilities in the developing cortical and hippocampal cultures.

BP 15.10 Wed 12:30 H11

Critical avalanches in a spatially structured model of cortical On-Off dynamics — •Roxana Zeraati[1,2], Tatiana Engel[3], and Anna Levina[1,2] — [1]University of Tübingen — [2]MPI for Biological Cybernetics — [3]Cold Spring Harbor Laboratory

Spontaneous cortical activity unfolds across different spatial scales. On a local scale of individual columns, activity spontaneously transitions between episodes of vigorous (On) and faint (Off) spiking, synchronously across cortical layers. On a wider spatial scale of interacting columns, activity propagates as neural avalanches, with sizes distributed as an approximate power-law with exponential cutoff, suggesting that brain operates close to a critical point. We investigate how local On-Off dynamics can coexist with critical avalanches. To this end, we developed a branching network model capable of capturing both of these dynamics. Each unit in the model represents a cortical column, that spontaneously transitions between On and Off episodes and has spatially structured connections to other columns. We found that models with local connectivity do not exhibit critical dynamics in the limit of a large system size. While for a critical network, it is expected that the cut-off of the avalanche-size distribution scales with the system size, in models with nearest-neighbor connectivity, it stays constant above a characteristic size. We demonstrate that the scaling can be recovered by increasing the radius of connections or by rewiring a small fraction of local connections to long-range random connections. Our results highlight the possible role of long-range connections in defining the operating regime of the brain dynamics.

BP 15.11 Wed 12:45 H11

Inferring network wiring from recorded activity — •Nataliya Kraynyukova and Tatjana Tchumatchenko — Max-Planck-Institute for Brain Research, Frankfurt am Main, Germany

The cortical circuits are able to perform a variety of nonlinear computations. One of the most ubiquitous representations of neural activity observed throughout sensory modalities is a tuning curve. In the visual cortex the tuning curves have been often shown to be contrast invariant. Contrast invariance means that after normalizing by the peak value tuning curves recorded at different contrast values will have a universal shape. We show that if the activity of a neural rate network is contrast invariant, then network connectivity and input profiles have a specific, mathematical relation to activity tuning curves. This simple theoretical observation provides constraints on the possible network connectivities and we show how it serves to infer connectomes.