CONFRONTING MEAN-FIELD THEORIES TO MEASUREMENTS: A PERSPECTIVE FROM NEUROSCIENCE

A BRAINSCALES WORKSHOP ORGANIZED BY
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AND CO-ORGANIZED BY
THE THEORETICAL NEUROSCIENCE DIVISION OF
THE HUMAN BRAIN PROJECT

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The aim of this two-days workshop is to analyze the successes and the failures of mean-field theories in accounting for measurements in neuroscience.

Mean-field theories in neuroscience are usually understood as ways to bridge spatial and temporal scales by lumping together the activities of many single neurons, and then explaining or predicting the spatio-temporal variations of mesoscopic or macroscopic quantities measurable with current technologies: EEG, MEG, fMRI, optical imaging, etc. . .

This is very much alike the situation in statistical physics where macroscopic quantities such as pressure, conductivity and so on are explained by the interactions between "microscopic" entities like atoms or molecules.

The situation in neuroscience is different however: the laws governing the microscopic dynamics in physics do not have the same structure as the laws governing neuronal dynamics; for example, interactions between neurons are not symmetric. Moreover, it is yet unclear what the relevant macroscopic quantities are in order to account for, say, visual perception. At the present stage of research, these quantities are considered to be what is measurable with currently available technologies, whereas better theories could reveal new types of phenomenological observables with a higher explanatory power.

Researchers in theoretical neuroscience have developed sophisticated mean-field theories ranging from phenomenological to first principle theories. Phenomenological theories such as neural fields aim to capture the essence of the phenomena at the macroscopic level by a set of equations without attempting to derive these equations from the microscopic dynamics of neurons. This is very much alike fluid mechanics theory where the Navier-Stokes equations have not been originally derived from the interactions of the fluids molecules.

First principle theories start from mathematical models of individual neurons, synapses, ion channels and of the way they are connected in large networks. Then, they attempt to derive macroscopic descriptions of these assemblies of neurons. Here, the adaptation of techniques coming from physics - statistical physics, path integrals, etc . . . - has been quite fruitful, although reaching their limits when attempting to describe e.g. neurons dynamics where synapses have spatio-temporal correlations. The theory of Large Deviations could be a way to go beyond these limits. It seems indeed to be a central tool in mean-field methods and is being used and further developed by a growing number of theoretical neuroscientists.

Many of these approaches attempt to thoroughly treat the stochastic aspects of neurons functioning. In some cases (e.g. when averaging the macroscopic behavior of a population of neurons over a random distribution of synapses) an unexpected result pops-up: the randomness that is occurring at the level of single neurons spreads up to the macroscopic level, leading to a new type of mean-field equations which are still far from being well understood.

This two-days workshop is meant to bring together researchers in neuroscience, theoreticians and experimentalists, in order to bridge the experiment/theory gap: we hope that theoreticians will be attracted by the idea of extracting from their models predictions that experimentalists could test and, conversely, we hope that experimentalists, by testing these predictions, will guide the theoreticians in the direction of developing better models.

The workshop is organized so that it leaves large time slots for discussions. It will be organized in five different threads, each dealing with a specific topic. Within each thread two speakers, an experimentalist and a theoretician, will briefly present their work and views of the topic before emulating a debate between the workshop participants.

List of participants

- Jan Antolik, UNIC-CNRS, Gif sur Yvette.
- Bruno Cessac, Neuromathcomp INRIA, Sophia-Antipolis.
- Frédéric Chavane, Institut des Neurosciences de la Timone, Marseille.
- Bruno Delord, ISIR, UMR7222 UPMC-CNRS, Paris.
- Bernard Derrida, Laboratoire de Physique Statistique, ENS, Paris.
- Alain Destexhe, UNIC-CNRS, Gif-sur-Yvette.
- Olivier Faugeras, Neuromathcomp INRIA, Sophia-Antipolis.
- Yves Frégnac, UNIC-CNRS, Gif sur Yvette.
- Viktor Jirsa, TNG Team, Institut de Neurosciences des Systèmes, Marseille.
- Cyril Monier, UNIC-CNRS, Gif sur Yvette.
- Alessandro Sarti, Centre d'analyse et de mathématique sociales Ecole des Hautes Études en Sciences Sociales, Paris.
- Fabrice Wendling, team SESAME : "Epileptogenic Systems: Signals and Models" Inserm 1099 - Signal and Image Processing Laboratory, University of Rennes.

Thread 1: How do synaptic changes induce macroscopic effects ?

Bernard Derrida, Bruno Delord

Exclusion processes, large deviations and macroscopic fluctuations, Bernard Derrida

Exclusion processes are among the simplest examples of non equilibrium systems. This lecture will show how some generic properties of non-equilibrium systems (long range correlations, non-locality of the free energy) can be understood in these simple models. It will also review the different ways of computing the large deviation functions of the current and of the density, both by microscopic and by macroscopic approaches

Meanfield approaches and the global neurophysiological effects of local plastic processes, Bruno Delord

Local neuronal features are essential for the emergence of relevant dynamical regimes at the level of neural networks, i.e. spatiotemporal patterns of activity allowing for proper physiological and behavioral functions. In particular, regulating the distribution and biophysical properties of intrinsic and synaptic conductance through plastic processes is crucial to set neural excitability and propagation of activity and, in fine, the emergence of relevant neurophysiological representations within networks. I will exemplify how mean-field approaches strongly structure our understanding of the way activity dependent plastic (e.g. Hebbian and homeostatic) modifications of conductance can organize relevant synaptic architectures and dynamical regimes of activity at the macroscopic scale of the neural network. Beyond the evident explanatory power of these approaches in accounting for global dynamic regimes, I will also discuss some of their possible current limits. In particular, their relative ability to tell us more about the content of neurophysiological representations, the essential end product of learning processes, in the context of short and long-term forms of memory.

Thread 2: Which mean-field equations to describe cortical activity ?

Olivier Faugeras, Cyril Monier

Olivier Faugeras

I present two extreme approaches for the asymptotic description of large populations of neurons such as those that can be found in cortical areas. The first approach starts with spiking neurons described by Hodgkin-Huxley models, connected through chemical or electrical synapses i.e. reasonably close to biology. The second approach starts with Wilson-Cowan types of equations describing networks of firing rate neurons. In both cases I show that asymptotic descriptions (when the number of neurons goes to infinity) can be obtained by methods inspired from Sznitman's coupling in the first case and from the theory of large deviations in the second. I take a rather pedestrian approach in the presentation of the underlying mathematics and concentrate on the advantages and disadvantages of the two approaches in relation to the somewhat speculative question at the time of this writing of what kind of measurable biological predictions they can produce.

A probe for stochastic constraints in mean-field theory, Cyril Monier

We performed a multi-scale study of visually evoked dynamical states in the primary visual cortex of anesthetized cat using visual stimuli with different statistics. The visual responses were recorded at the single cell level with intracellular sharp electrodes (membrane voltage and spike) and at a more mesoscopic level with multi-electrode (local field potentials (LFP), multi-units and single units) and voltage sensitive dye optical imaging (VSD). Different types of visual stimuli of increasing complexity, and controlled spatial and temporal statistics, were presented either in full field, central or surround-only configurations: optimal drifting grating, optimal grating and natural image animated by a simulated eye-movement sequence and dense binary white noise. In order to compare the different signals, the same frequency-time wavelet analysis was applied to all these types of recordings. This decomposition allows the extraction of several time-frequency dependent measures: signal power, noise power and signal-to-noise ratio power which allows to compare directly the temporal evolution of info rate at different scales of integration. These data during different context of visual stimulation will be discussed as a possible test of stochasticity hypothesis introduced in the mean-field theory for comparing microscopic and mesoscopic scales.

Thread 3: Macroscopic aspects of cortical activity as seen by voltage-sensitive dye imaging ?

Alain Destexhe, Frédéric Chavane

Macroscopic aspects of cortical activity as seen by voltage-sensitive dye imaging, Frédéric Chavane & Alain Destexhe

We would like to discuss the voltage-sensitive dye (VSD) imaging technique, in the context of a mean-field approach to cortical dynamics at mesoscales. On an experimental point of view, we will discuss to what extent the VSD signal represents a simple average of the membrane potential activity of large populations of cortical neurons. In particular, facilitator and suppressive mechanisms may reflect population input normalization through cortical gain control rather than an excess in excitation or inhibition respectively. At the modeling point of view, we will discuss the need for mean-field approaches that include finite-size effects in the system, and discuss a possible approach to model the VSD signal at mesoscales.

Thread 4: What is the explanatory power of neural fields ?

Viktor Jirsa, F. Wendling

Canonical modeling vs. biophysical modeling in neural field dynamics, Viktor Jirsa

Spatiotemporal propagation of neural activity through a network is at the heart of brain function and dysfunction. When building a network, we typically emphasize the decomposition into network nodes and network links. Network nodes hold neural mass models that exhibit a characteristic dynamics in isolation of any connectivity. Then under coupling constraints, the local dynamics at the particular node changes and may or may not preserve its original qualitative behavior. The question arises to what degree it is necessary, or even desired, to preserve biophysical realism of the neural mass model when studying the effects imposed by connectivity upon the overall neural network dynamics. We will address this question along the example of seizure dynamics and propagation.

Measurement of neuronal excitability: from model predictions to experimental validation, Fabrice Wendling

Neural mass/field models have gained increased interest in epilepsy research over the past decades. A first requirement in the development of models is to reproduce the observed phenomena. However, this capability to replicate observations is not sufficient to guarantee that the (patho)physiological mechanisms embedded in the model are those actually occurring in real neuronal systems. A most difficult issue to increase the explanatory power of computational models is to generate predictions that can further be tested experimentally. In this perspective, combined theoretical/experimental approach is probably the ideal framework to elaborate trustable models. In this presentation, this prediction/validation loop will be illustrated through the concrete question of quantifying neuronal excitability from local field potential (LFP) recordings. In brief, starting from the simulation of neuronal populations under direct periodic low intensity pulse stimulation, we generated hypotheses regarding the mechanisms underlying evoked responses as observed in LFPs. We then combined these results with in vivo and in vitro recordings and showed that optimally-tuned stimulation parameters can specifically activate GABAergic interneurons, as predicted. Finally we derived a quantitative index characterizing the excitability of locally- stimulated neural networks (referred to as NNEI, neural network excitability index).

Thread 5: Which theory to describe V1 ?

Yves Frégnac, Jan Antolik, and Alessandro Sarti

Yves Frégnac

Introduction

Jan Antolik

Alessandro Sarti

I will recall a neurogeometrical model of the functional architecture of V1 as a Lie group. A theoretical model of the constitution of perceptual units will be introduced in terms of mean field equations defined in this geometrical structure.

Many open questions will be discussed, particularly regarding the shape of the horizontal connectivity pattern, the additional vs. modulatory character of the connectivity contribution and the problems of scalability in relation with high level visual brain.

Organization of the workshop

Wednesday 14-01

- 9h30-10h Arrival-Beginning of the workshop
- 10h-11h30 **Thread 1: How do synaptic changes induce macroscopic effects?**
- 12h-14h Lunch
- 14h-15h30 **Thread 2: Which mean-field equations to describe cortical activity?**
- Coffee break
- 16h-17h30 **Thread 3: Macroscopic aspects of cortical activity as seen by voltage-sensitive dye imaging.**

Thursday 15-01

- 10h-11h30 **Thread 4: What is the explanatory power of neural fields?**
- 12h-14h Lunch
- 14h-15h30 **Thread 5: Which theory to describe V1?**
- 15h30 -16h Foreword
- End of the workshop