Final Report

Overview

Our perceptions, thoughts, and actions emerge from the activity of billions of neurons in our brains. Neurons are, however, relatively simple biological devices that respond to stimulation with a stereotypical and well-understood response. Understanding how a collection of such simple cells can give rise to the sheer complexity of animal and human behavior is one of the challenges of brain science today. Of course, neurons are not isolated but they are interconnected forming a vast complex network composed of different brain regions, subregions, and nuclei that are, in turn, organized in smaller local circuits. These local circuits consist of several thousands of neurons densely interconnected, and are thought to be the computational building blocks of the brain. To understand how the brain processes information, therefore, it is essential to understand the dynamics of local circuits and thus the dynamics of networks of neurons.

A starting point for this endeavor is to make minimal assumptions regarding the the dynamics of isolated neurons and the way neurons are connected—i.e., their *connectivity*. With simplified assumptions one can get insight into the system with analytical tools and, more important, one can identify the relevant variables governing the system at hand. In this spirit, lots of progress have been made with network models in which neurons are single points characterized solely by their membrane potential and connections are as generic as possible. By generic connections we mean that no particular structure is assumed or, more concretely, that connections are random. Models of this type have shed light into the irregularity of neuronal activity in the cortex, the presence of oscillating activity in large populations of neurons, or the neural substrate of short term memory, to name just a few.

Our project involved a step towards biological reality by modifying the assumption of random connections. Electrophysiological experiments carried out this last decade have consistently shown that, while cortical neurons are connected randomly as a first approximation, neuronal connections follow some nontrivial statistical patterns. One particular pattern stands out: if a neuron connects to another neuron, the second neuron will connect back to the first more often than one would expect by chance. In more technical words, there is an overrepresentation of bidirectional connections. The goal of our project was to understand how this overrepresentation affected the dynamics of neuronal networks and to analyze its potential functionality.

Results

To study the effects of overrepresented bidirectional connections in networks, we concentrated the analysis on the dynamics of random networks where the connections between any pair of neurons are not independent but correlated. Put differently: networks where, if you pick any two neurons, which we call a and b, and you find that connection $a \to b$ is strong, then it is likely that connection $b \to a$ is strong as well (and analogously if the connections happen to be weak). This 'likeliness' is measured by the correlation of pair-connecting strengths.

Because we wanted to isolate the role of connectivity in shaping the dynamics of neuronal networks, we first investigated the dynamics of networks of simple rate units, in which the neuronal activity is characterized by the average emission rate of action potentials of the individual units (firing rate models). These simplified neuron models represent a departure from biological reality, but they are easier to analyse than the so-called spiking neuron models, in which the activity of neurons is described by the time evolution of the membrane potential and the precise timing of the action potentials emitted (spiking neuron models). Despite the apparent simplicity of firing rate models, they display a rich repertoire of dynamical activity, a richness that has been later observed in spiking network models. Specifically, large networks of nonlinear rate units and random connections exhibit two different regimes of activity: decay a steady configuration of neuronal activity, or ongoing chaotic activity. These two regimes may have important functional implications in cortical activity.

We have investigated how correlated weights modifies the neuronal dynamics in the two regimes exhibited by these networks. Correlated weights modify the spectrum of eigenvalues of the system linearized around a steady configuration (a fixed point), and the spectrum of eigenvalues has in turn a strong influence on the dynamics of the network. More specifically, increasing the correlation between weights flattens the spectrum of eigenvalues and this can be linked to the decrease of the onset of chaotic activity and the increase the characteristic timescale or reberveratory activity—that is, period over which the network keeps trace of its own activity. We have analyzed the dependence of of characteristic timescale and the correlation weights using dynamical mean-field techniques and checked the agreement with numerical simulations. To better understand the nature of the slowing down of reverberating activity, we also considered even simpler networks composed of linear units, and studied the effect of the overlaps among eigenvectors in shaping the time course of transient perturbations, again seeing agreement between analytical results and simulations. Finally, we have seen that for sufficiently correlated weights dynamics in the chaotic regime exhibit 'aging', a situation in which the relaxation time of the system grows as time goes by.

Conclusions

Potential impact

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