How far can correlations take us when modeling neural activity?

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Much of what know about how neurons represent information has been learned by characterizing responses of single neurons and what triggers their activity. Nevertheless, a growing body of evidence suggests that a significant part of the transmitted information in the brain is represented over groups of neurons, by their joint activity patterns. We constructed a minimally-constrained model to shed light on the collective behavior of neurons in the mouse hippocampus. Our model makes surprisingly accurate predictions verified by the data, such as predicting individual neuron's firing based on the collective activity, even when that neuron does not code a known variable.

Information theory; random matrix theory; hippocampus; place cells; large-scale calcium imaging; virtual reality.

I. Motivation

THE technological progress has dramatically increased our access to the neural activity underlying memory-related tasks. These complex high-dimensional data call for theories that allow us to identify signatures of collective population-level coding in the networks that are crucial for the emergence of cognitive functions. This work focuses on the brain region hippocampus. Discussions of this area often focus on place cells [1], but many neurons are not place cells in any given environment and are often referred to as silent cells [2-4].

II. Modeling the Neural Activity

During the first stage of our work we describe the collective activity in that mixed population, treating place and non-place cells on the same footing. We start with optical imaging experiments of dorsal hippocampus in mice as they run along a virtual linear track, and use maximum entropy methods to approximate the distribution of patterns of activity observed across ensembles of up to 100 cells, matching the correlations between pairs of cells but otherwise assuming as little structure as possible [5]. These models, which are equivalent to Ising models with competing interactions, make surprisingly accurate predictions for the activity of individual neurons given the state of the rest of the network, and this is true both for place cells and for non-place cells. Additionally, the model captures the high-order structure in the data, which cannot be explained by place-related activity alone. These and other results suggest that place cells are not a distinct sub-network, but part of a larger system that encodes, collectively, more than just place information. Finally, we compare how much information the activity of each neuron provides about the state of the rest of the network versus about the animal's position. We find that for place cells, these two information measures are roughly equal, while non-place cells carry more info about the network state than about position. Thus, it appears that place cells and non-place cells are part of the same patterns of collective activity.

For the next stage of our work we study much larger populations, with up to 2000 neurons imaged simultaneously in the mouse virtual reality setup. The dimensionality enormity of such system compels us to consider the eigenvalue spectrum of the network's correlations. However, since the number of time points and the number of neurons is of the same order of magnitude, we turn to random matrix theory to determine which of the eigenvalues are significant, and which should be discarded as a result of spurious correlations introduced due to finite size effects. After assessing the real dimensionality of the problem, we can inform our models by the true correlation structure.

III. Conclusions

Searching for simplified models to characterize and predict key features of the neural activity in hippocampus has proven successful – we conclude that information shared among neurons in the hippocampal network goes beyond being just place-related. For populations of ~2000 neurons, we utilize a random matrix theory approach to estimate the true correlation structure.

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