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Fast and richly structured activity in cortical networks with local inhibition

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Spiking models of small areas of the neocortex have so far mainly been studied under the assumption that neurons are sparsely and randomly connected. The absence of structure allows for the use of powerful mean-field approximation techniques, whereby statistical properties of spike trains such as the average firing rate and the interspike interval coefficient of variation are described in terms of their distributions across neurons [1,2]. Such approaches cannot offer a more detailed description as to what patterns of activity the network spontaneously produces. The macroscopic state is unstructured with predictable mean, while during the asynchronous irregular firing the microscopic dynamics is chaotic. It therefore becomes hard to think of the representation of information in cortex if its activity is neither structured nor reproducible.

Connectivity in cortex is not purely random: published data on synaptic connectivity suggests a model of cortical connectivity in which excitatory neurons make long-range patchy projections while inhibitory neurons only target their close neighbours [3]. How does this structure affect the dynamics of the network? Can we hope to describe it in terms of activity patterns, therefore going beyond the mean-field predictions mentioned above? Recent theoretical considerations [4] have suggested a positive answer, by showing that balanced networks should be expected to transiently amplify certain activity patterns without slowing the dynamics down ("balanced amplification"). Underlying this theory is the nature of the connectivity matrix, "nonnormal" in the mathematical sense [5]. The amplified patterns depend on the details of the connectivity and are best revealed by a Schur decomposition of the connectivity matrix.

We examine the dynamics of linear networks with patchy connectivity structures. With long-range patchy inhibition, about 25% of the eigenvalues of the connectivity matrix have strictly positive real parts. Since real parts must be smaller than one for stability, the overall magnitude of the connections, and therefore also the amount of transient amplification, need to be constrained. The presence of eigenvalues with real parts close to one also predicts dynamical slowing with a small number of modes (typically < 5) completely dominating the dynamics and limiting the representational power. If inhibition is kept local, as it seems to be in nature, the connectivity matrix has the nice property that all its eigenvalues have negative real parts. The network can thus be arbitrarily rescaled and yet remain stable. Strong amplification can coexist with fast network dynamics that yields a rich repertoire of transient spatial states.

Extensive simulations of the noise-driven linear networks confirm the theoretical insights. Importantly, we also ran large-scale simulations of conductance-based spiking neurons with sparse connectivity spatially organized as mentioned above. Despite the strong deviation from linearity, the network activity matches the linear predictions remarkably well, in terms of both speed and amplification of the Schur modes. We conclude that the activity in spatially organised networks is highly structured and can be described on the level of two-dimensional activity patterns. Local inhibition, but not long-range inhibition, enables rapid state switching on the time scale of a few milliseconds.

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