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Extensive chaotic dynamics in neural networks in the balanced state

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Neurons embedded in operational cortical networks fire action potentials in highly irregular sequences [1]. The balanced state of cortical networks provides an attractive explanation of this temporally irregular behaviour [2]. In this state, neurons are driven by large input fluctuations, resulting from a dynamically achieved balance of excitation and inhibition. It has been shown that the balanced state can robustly emerge from the collective dynamics of spiking neuron networks [2]. The detailed dynamics of the balanced state, however, is not well understood. Initially, Vreeswijk and Sompolinsky [2] found a kind of "hyper"-chaotic dynamics in networks of binary neurons, characterized by an infinite positive Lyapunov exponent, which is hard to reconcile with classical notions of nonlinear dynamics. More recently, Zillmer et al. [3] and Jahnke et al. [4] reported stable dynamics in networks of leaky integrate and fire neurons. Notably, all of these previous works neglect a major cellular mechanism of dynamic instability, the instability of the membrane voltage near the spike threshold.

To clarify which kind of balanced state dynamics is expected in networks of neuron models describing such dynamic spike generation, we analyzed networks of pulse-coupled theta neurons in sparse, random networks in the balanced state. The theta neuron model is a standard model of type I neuronal excitability [5]. Based on the analytic solution of the single neuron dynamics, we derived a map that was used for event based simulations and obtained the exact single spike Jacobian matrix for the entire network. This Jacobian was used to calculate the whole set of Lyapunov exponents, following the standard procedure [6]. From the Lyapunov exponents we acquired the entropy production via Pesin's formula and the attractor dimension via the Kaplan-Yorke conjecture.

In general, the studied networks in the balanced state exhibited chaotic dynamics. The largest Lyapunov exponent was positive and finite, giving evidence to conventional chaos. The entropy production and dimension of the chaotic attractor both scaled linearly with the number of neurons in the networks, hence chaos in the balanced state appears to be extensive spatio-temporal. Furthermore, we found a high attractor dimension, corresponding to many effective degrees of freedom that may potentially encode information in the network. Yet, this is accompanied by a rapid loss of information of 0.5 bits per spike. We conclude that extensive chaos should be expected in general for networks of type I neurons in the balanced state. If information loss in cortical networks is as high as in our model, information could hardly be encoded in detailed spiking patterns beyond the immediate stimulus response.

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