Input spike trains suppress chaos in balanced target circuits

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Abstract A longstanding hypothesis claims that structured input in neural circuits enhances reliability of spiking responses. While studies in single neurons well support this hypothesis [Mainen 1995], the impact of input structure on the dynamics of recurrent networks is not well understood. The high dimensional and often chaotic dynamics of large recurrent networks requires a type of analysis that can systematically asses the role of recurrent interactions and characterize the networks collective dynamics. Studies in rate chaotic networks suggest a suppression of chaos by structured input [Molgedey 1992], but in spiking input, this has not yet been thoroughly analyzed.

To address this challenge, we here describe how the analysis of dynamical stability and entropy production can be generalized for examining balanced networks driven by streams of input spike trains. Previous studies of the dynamic stability of the balanced state used a constant external input [v.Vreeswijk 1996; Monteforte 2010] or white noise [Lajoie 2013, 2014]. An analytical expression for the Jacobian enables us to calculate the full Lyapunov spectrum. We solved the dynamics in numerically exact event-based simulations and calculated Lyapunov spectra, entropy production rate and attractor dimension. We examined the transition from constant to structured input in various scenarios, varying the input spike rate and/or coupling strength, while keeping the firing rate of the target population fixed.

In general, we find a suppression of chaos by input spike trains. This finding holds both for variations of input rate and coupling strength and is robust to deviations from Poisson statistics. We also find that both independent bursty input spike trains and correlated input more strongly reduce chaos in spiking networks. Our work extends studies of chaotic rate models to spiking neuron models and opens a novel avenue to investigate the role of sensory streams in shaping the dynamics of large networks.

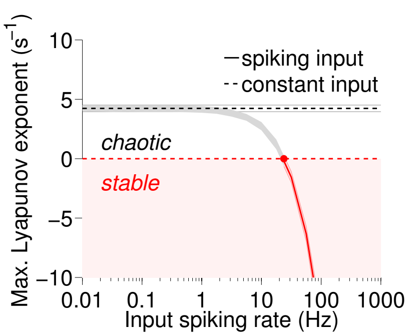

Figure 1: The largest Lyapunov exponent as a function of input rate.

Poisson input spike train suppress chaos in balanced circuits. Each theta neurons in a random balanced network receives an independent spike train from a Poisson process with weak synaptic coupling. The mean firing rate of the target network is fixed by adjusting a constant external input. The value of λ_{max} crosses zero at a critical input rate, above which the network dynamics is stable. A similar transition occurs for an increased external synaptic coupling strength and both for excitatory, inhibitory and mixed input spike trains.

Methods We use the canonical type I neuron model, with an active spike generating mechanism. The network consists of N theta-neurons on a random graph, average indegree $K \ll N$ and weak synaptic coupling $\mathcal{O}\left(1/\sqrt{K}\right)$:

$$\tau_m \dot{V}_i \quad = \quad V_i^2 + I_{\text{ext}} + I_i^{\text{rec}}(t) + I_i^{\text{stoch}}(t)\tau_m \sum_{j\in\text{pre}(i)} J_{\text{rec}_{ij}}\delta(t - t_j^{(s)})) + \tau_m \sum_{k\in\text{pre}(i)} J_{\text{stoch}_{ik}}\delta(t - t_k^{(l)}))$$

In numerically exact event-based simulations, we evaluate an analytic map of phases $\vec{\theta}$ between spike times $\{t_s\}$. The phase representation of the theta model is $V = tan(\frac{\theta}{2})$. To assess the dynamical stability, we evaluate the Jacobian of the flow of the dynamics [Monteforte 2010]. It measures, how infinitesimal perturbation of the network state $\vec{\theta}$ evolve from one spike to the next. The Lyapunov exponents are calculated in the standard procedure [Benettin 1980]. The dynamical entropy production rate is give by the sum of positive Lyapunov exponents (Pesin's formula). The attractor dimension is give by the number of Lyapunov exponents that sum to zero (Kaplan-Yorke conjecture). Preliminary results indicate that our findings are robust w.r.t. to network size N and mean indegree K.