Discrete synaptic transmission impacts the onset of rhythmic network dynamics

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Rhythmic population oscillations are a ubiquitous feature of brain dynamics, with inhibitory interactions often playing a key role in generating rhythms such as inhibitory network gamma (ING) oscillations. Both hippocampal and cortical circuits exhibit these oscillations and their presence can selectively reshape the recruitment of different interneuron populations by input streams, e.g.~in the prefrontal cortex (Merino et al. 2021). Mathematically, delays in synaptic transmission strongly impact the emergence of population oscillations. Quadratic integrate-and-fire (QIF) neurons represent the normal form of the firing type of most cortical and hippocampal neurons and are known to exhibit limits in the encoding of high-frequency inputs. Recently, it has been shown that networks of QIF neurons even with undelayed synaptic interactions are particularly prone to generating oscillations (Goldobin et al. 2024).

We explored the emergence and stability of oscillations in balanced inhibitory QIF-type networks with tunable spike onset dynamics. Surprisingly, the dynamic population response for biologically realistic spike onset could not be correctly described using standard Fokker-Planck theory due to the breakdown of the underlying diffusion approximation. By employing a novel shot noise-based approach, we analyzed the network's stability systematically. Our results show that rapid spike onset stabilizes inhibitory network oscillations. Effectively, the slow spike onset in QIF neurons acts similarly to a synaptic delay, enhancing oscillatory dynamics. The results of our shot-noise theory show excellent agreement with spiking network simulations, particularly in predicting the firing rate (f-I curve), the stationary voltage distribution, and the frequency response of the neuron as well as the onset of network oscillations. These findings emphasize the importance of spike onset dynamics in shaping network oscillations. Our study opens a new avenue to dissect the local circuit basis of the distinct susceptibility of different neuron populations in the prefrontal cortex to oscillatory state-modulated information rerouting.