Rate-like dynamics of memory-dependent spiking neural networks | Kasper Smeets

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Neuronal populations exhibit the ability to reliably perform complex computations and process signals despite significant trial-to-trial variability in the spiking activity of individual neurons. This observation suggests that the collective dynamics of neuronal populations are not only robust to the stochastic nature of single-neuron spiking but also approximately deterministic at the population level. Spiking neuron models such as the Leaky Integrate-and-Fire (LIF) and the Spike Response Model 0 (SRM0) with escape noise capture well the stochastic and discrete nature of spike transmission. In contrast, population dynamics are often modelled through rate-based models as a qualitative explanation of collective processing, as they lend themselves well to analytical analyses such as dynamical systems theory. The precise link between these two ends of the spectrum is still poorly understood in non-homogeneous networks of neurons, especially in the case of memory-dependent spiking neurons.

Here, we bridge the gap by showing how the dynamics of complex spiking neural networks can converge to deterministic solutions, even in the absence of neural duplicates. Further, we show that the dynamics of the limit spiking network are equal to those of a generalised rate network, which differ from the conventional rate networks by themselves also having a memory dependence.

Specifically, the activity of a generalised rate neuron here is the expected value of a corresponding spiking neuron, given the input to the neuron. As the spiking neuron itself is memory-dependent, there exists no direct mapping between the current membrane potential and

the expected firing rate. Instead, the generalised activity is itself memory-dependent, with analytical form obtained by marginalised over all possible spiking time histories of the neuron.

The noise-robust dynamics arise in part from the mixed representation of a small number of population-level driving factors (Fig. 1B), characterised by connectivity matrices of reduced rank (Fig. 1D). This is described well by latent factors theory and the concentration of measure phenomenon, which together have also been used before to explain the emergence of rate-like dynamics in duplicate-free linear-nonlinear-Poisson spiking networks, holding as long as the number of latent factors grows sub-linearly with network size.
The setup used is a multilayer feedforward spiking network consisting of SRM0 neurons (Fig. 1C). The external input to the first layer is a random, duplicate-free encoding of a set of latent factors, each generated as the formal derivative of a Wiener process. The layer-to-layer connectivity is set as a decoding and a new duplicate-free encoding of the latent factors, apart from the connectivity to the output layer which is only a decoding.

The spiking network is shown to converge to an equivalent generalised rate network as described above, with convergence measured through the mean absolute difference between equivalent output membranes (Fig. 1E-F), and not to a conventional rate network.
These findings provide a link between complex and highly variable spiking behaviour to the empirical belief of approximately deterministic population-level dynamics, as observed in behavioural studies. Furthermore, it shows that rate coding principles can hold even when individual neurons exhibit intricate and diverse dynamics, facilitating novel analytical analyses of heterogeneous memory-dependent networks.