Time and space in neuronal networks: the effects of spatial organisation on network behaviour

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Complex networks in nature are often characterised by nontrivial spatial organisation. In such networks, the topology and spatial organisation are often tightly coupled to the activity on the network. In particular, spatial topologies frequently influence time delays through the network. In many real world networks, from transport systems to brains, increased distance (or wiring length) increases time delays in physical or information flow. Here we investigate this role of space on neural network dynamics.

Time delays are well recognised to influence dynamics in neural networks. It would not be surprising, therefore, if neural networks exploited spatial organisation to tune their time delays and obtain desired patterns of activity. However when we model such networks, either to study or to apply their properties to engineering problems, it is important to distinguish between two cases: either the effects of spatial organisation in the network are merely temporal, in which case the complex and computationally expensive spatial organisation can be succinctly abstracted out, or — more interestingly — spatial organisation may lead to behaviour that cannot be captured solely by temporal effects.

We investigated this question in biologically constrained spiking neural networks operating close to a critical bifurcation between stationary behaviour and population-wide oscillatory behaviour. In particular, we used a network of leaky-integrate-and-fire neurons and conductance based synapses with alpha-function kernels, operating in the so-called balanced regime, where each neuron receives similar excitatory and inhibitory drive. Specifically, we compare the transition from stationary to oscillatory network behaviour as a function of spatial organisation. The two modes of behaviour are found in biological neuronal networks and are important for qualitatively different information coding schemes (e.g. rate coding in the stationary regime and phase or temporal coding in the oscillatory regime).

First, we demonstrate that time delays play an important role in this type of network. We found that the region of parameter space for which stationary behaviour is found increases with shorter time delays. We compared this performance to that of an otherwise identical network but with explicit spatial organisation. In our networks, spatial organisation was implemented by clustering inhibitory cells in the midst of a homogeneous population of excitatory cells, in keeping with dendritic length scales of inhibitory cells in some cortical areas. In addition to introducing a spatial patterning, the central clustering of inhibitory cells also reduces the mean inhibitory-to-excitatory time delays in the network. Thus, a purely temporal effect of clustering would yield similar results to shortening the time delays in the system. In fact, with this spatial network model we found a robust reversal of the network behaviour compared to that of the non-spatial network: the shorter the time delays, the more oscillatory the network becomes. This counter-intuitive result may suggest that the gradient in time delays imposed by spatial organisation may dominate the effect of reducing mean time delays in these networks. In fact, the role of space could be further enhanced (or suppressed) by introducing spatially graded connection probabilities (e.g. with closer cells more likely to be connected).

In conclusion, we have described a novel spatial effect. While the spatial organisation described is plausible, it and the corresponding effect on network dynamics would be interesting predictions to test in cortical networks.