Effects of neuronal variability on the phase synchronization of neural networks.

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Introduction

- Neurons are the cells responsible for information processing in the human brain.
- Signals propagate through neurons in spikes - or sequences of spikes, called bursts - , in which the electric potential difference across their membrane varies rapidly.
- When various neurons fire simultaneously, we say that they are phase synchronized.
- Phase synchronization is important in processes such as motor control, memory and conscious access [1] .
- Phase locking, in which neurons maintain a fixed relation between their oscillations, is essential for communication between neuronal areas [4].
- Most neurons have variable responses in their burst timings, given the same input. In this work, we show that this variability affects phase synchronization and especially the duration of phase-locking.

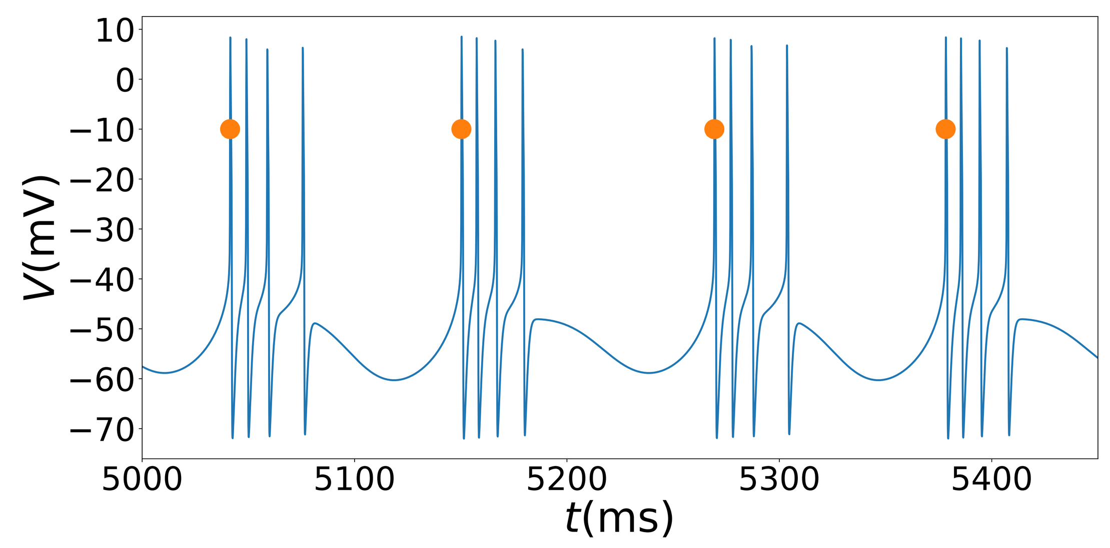
Model

The neuronal dynamics is given by the Braun model [2] , with chemical coupling. The main equations are

$$C_M \frac{dV(t)}{dt} = -J_{Na} - J_K - J_{sd} - J_{sa} - J_L - J_{coup}$$

$$J_{i,coup} = \frac{\epsilon}{\nu}(V_i - E_{syn}) \sum_{j \in \Gamma_i} r_j(t)$$

in which V is the membrane potential, J_α are currents which depend on the temperature of the cell. The parameter ϵ controls the strength of the connections, ν is the maximum degree of the network, r is the fraction of bound receptors and Γ is the neighborhood of the neuron. The network follows a small-world connection scheme, which is observed in biological networks.



Quantifiers

We associate a phase θ to each neuron firing event in such a way that it starts at zero on the first burst and increases by 2π with each burst. Then we define

$$R(t) = \left| \sum_{j=1}^{N} e^{i\theta_j(t)} \right| / N, \tag{1}$$

which ranges from 0 to 1 and is higher the more synchronized the network is.
The interval between consecutive bursts of a neuron is called the inter-burst interval (IBI). The coefficient of variability is:

$$C_v = \sigma(IBI)/\overline{IBI} \tag{2}$$

We also define an average drift between neurons' firings:

$$\Delta^l_{ij} = \left| |t_{k,i} - t_{k,j}| - |t_{k-1,i} - t_{k-1,j}| \right|. \tag{3}$$

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CNPq
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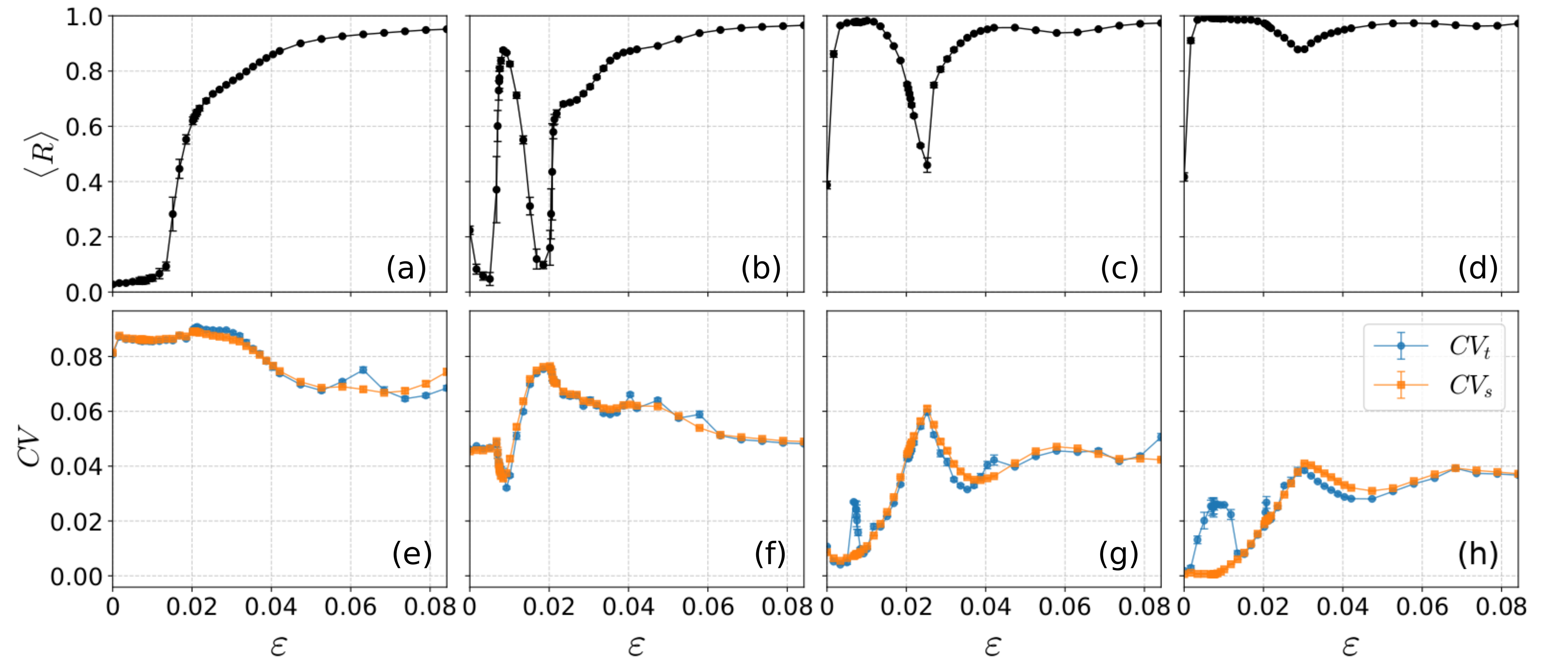
Effects of the neural variability

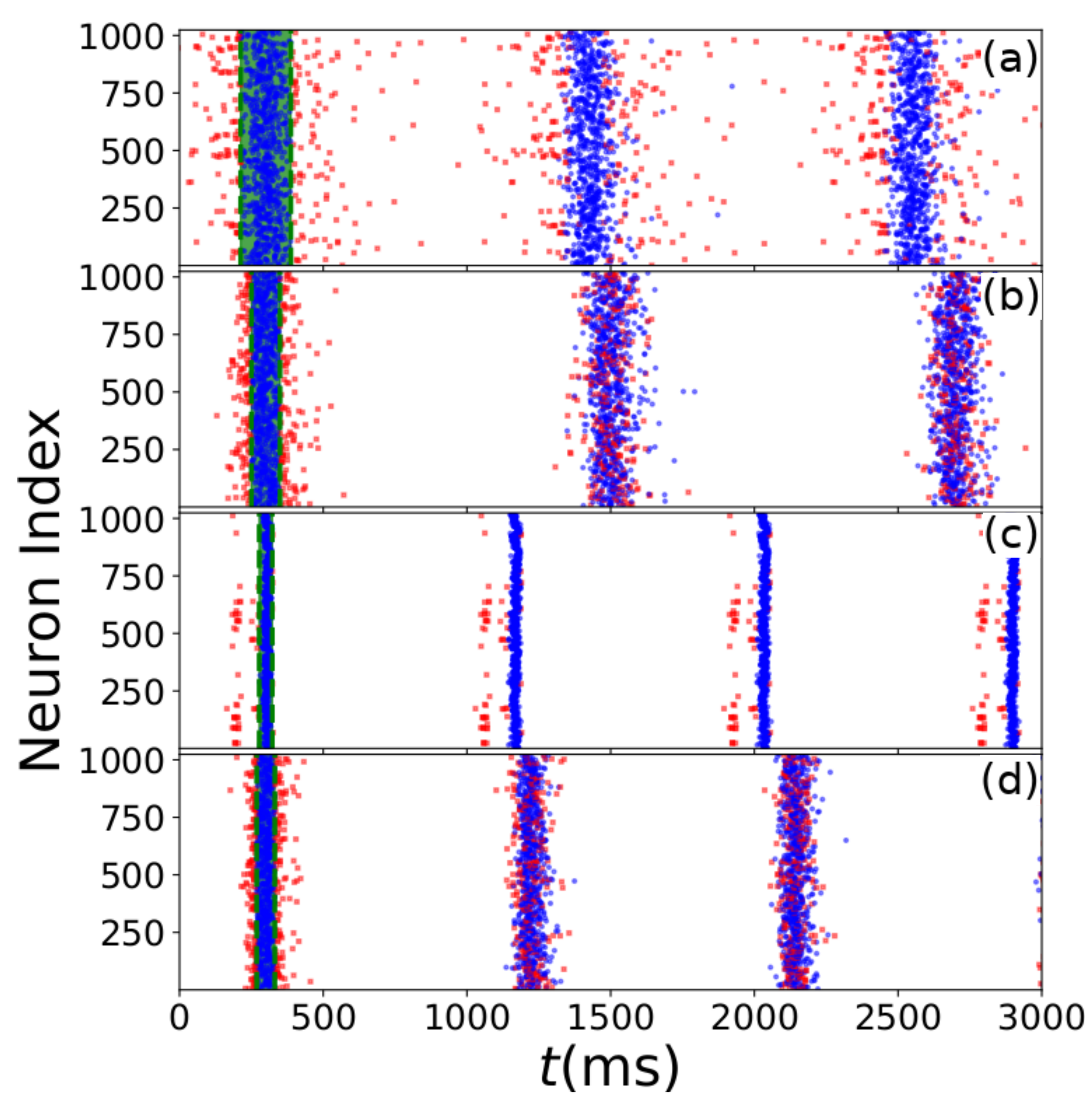
We measured the variability and degree of synchronization for 4 different temperatures and many coupling strengths. The initial synchronization behavior depends strongly on the temperature and is positively correlated to the variability.



These changes in the variability may be explained by the stability changes of the periodic orbit, seen in the individual, uncoupled, neural dynamics of each neuron [3].

Neural promiscuity

In the raster plot below, neuron's burst start times are plotted in blue for those who were in the first cluster (green region) and red for those outside. Panels (a) and (b) correspond to $T = 38\,°C$, $\varepsilon = 0.00879$ and $\varepsilon = 0.1$, while (c) and (d) correspond to $T = 40\,°C$ for the same strengths. In the right figure below, we quantify this promiscuity through the mean drift of the network, which roughly measures how much, on average, the temporal distances between neurons' firings change.



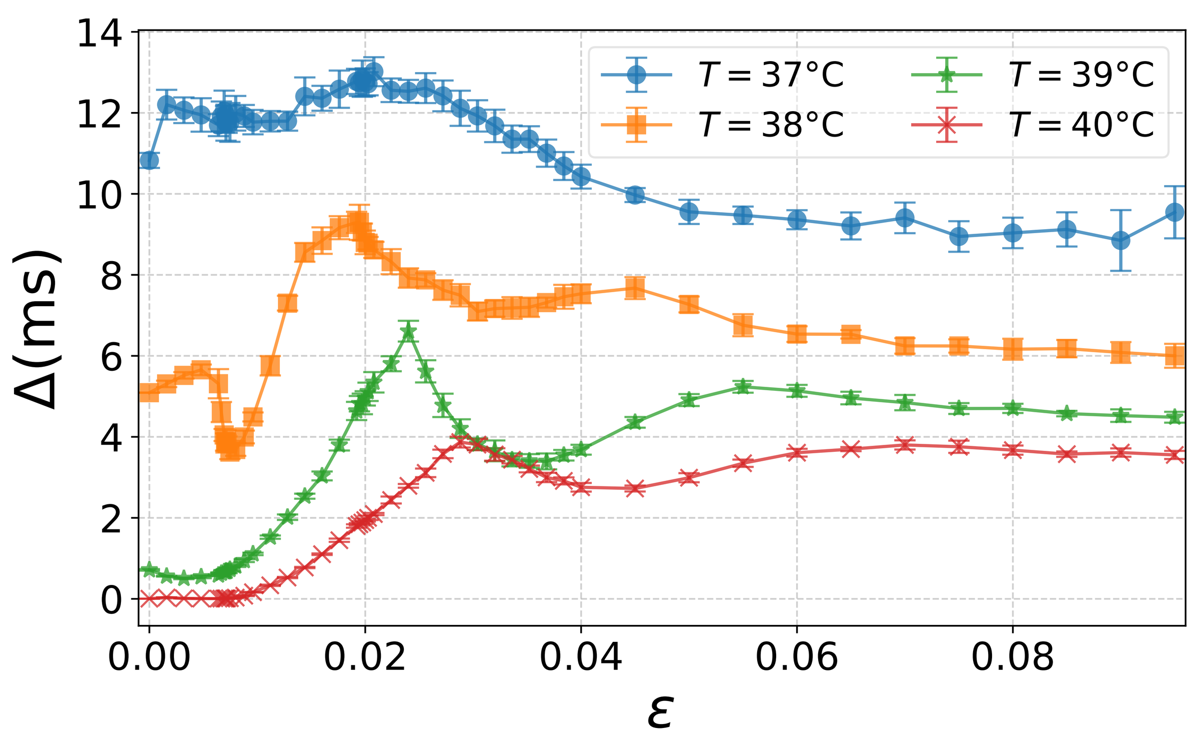


Figure 1: The left figure corresponds to the raster plot. In the right figure, the average temporal drift is shown as a function of the coupling strength.

Conclusions

- Neural firing variability is inversely proportional to the degree of synchronization of the network in this case: **networks with distinct neurons have, in this case, a harder time synchronizing than with identical neurons**.
- The neurons' tendency to stray away from each other, their promiscuity, is proportional to their variability: **neurons that are different tend to not stay together for long**.
- General behavior: The promiscuity-variability relationship is a statistical process: the variability measures the range of possible IBIs a neuron can have, which will determine the likelihood that any two neurons firing simultaneously once will do so again next. **Therefore, if a network is known to have neurons with distinct IBIs, then it can be expected to possess a degree of promiscuity**.

References

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[3] Boaretto et al. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 28(10):106304, 2018
[4] Fries, P. *Trends in Cognitive Sciences* Neuron. 2015;88(1):220-235.