Analyzing cortical network dynamics with respect to spatially realistic connectivities

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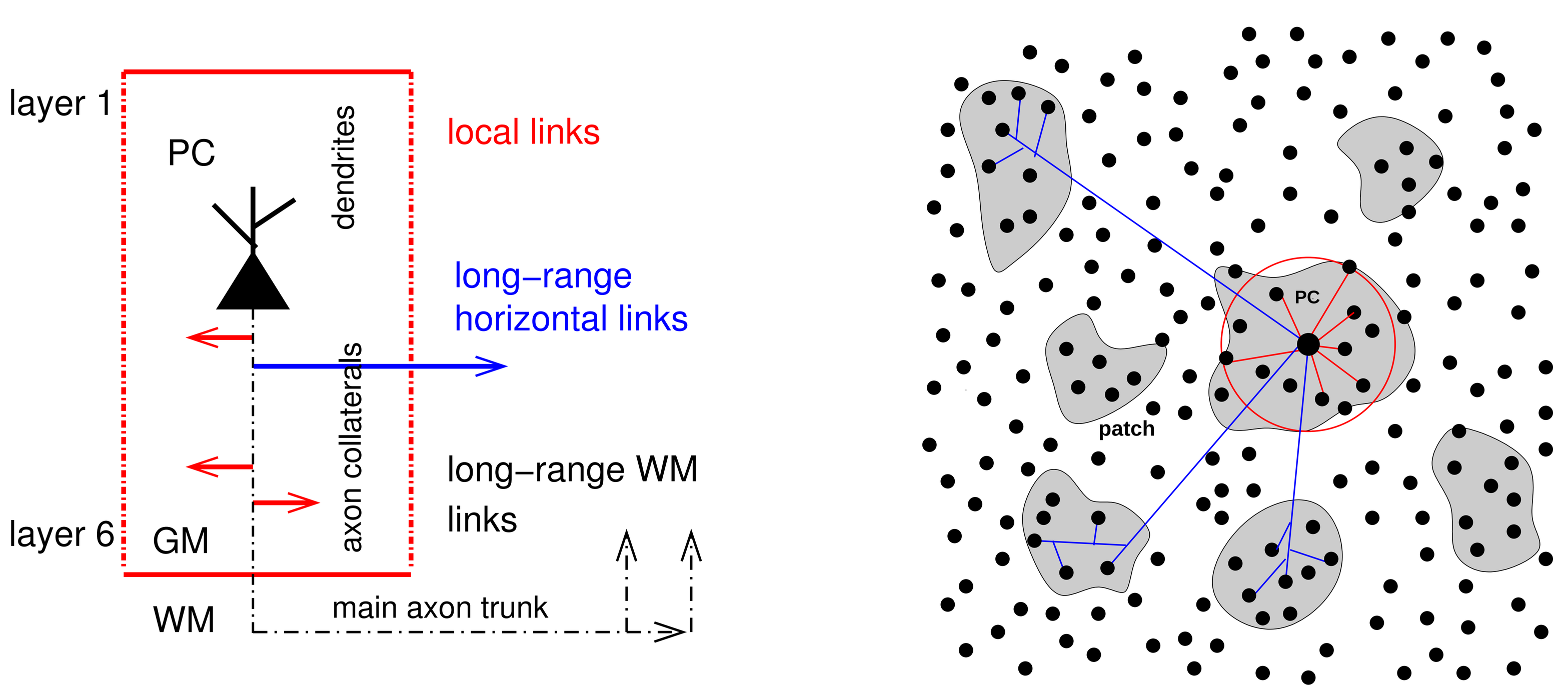
Abstract

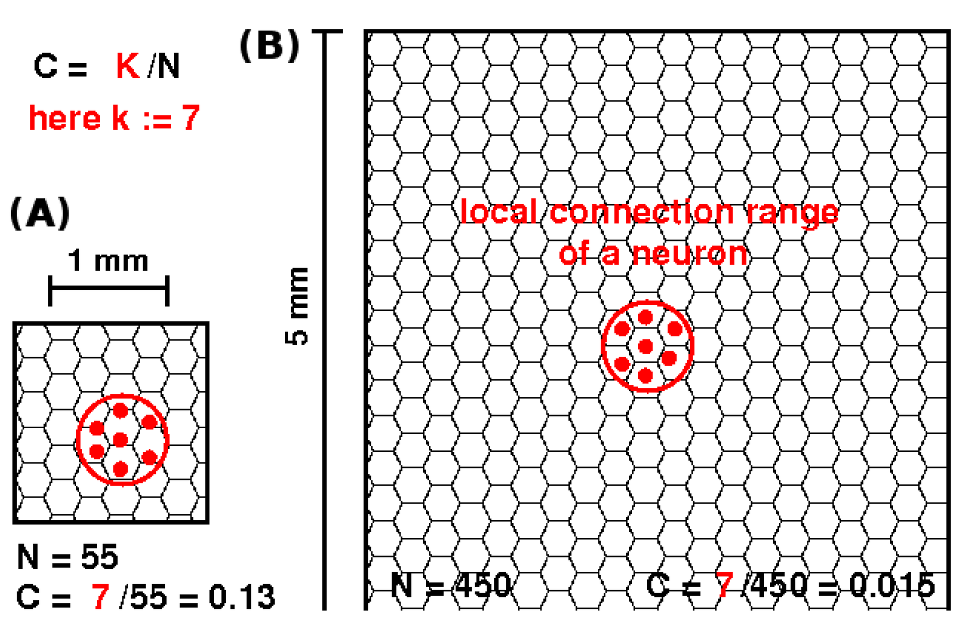
Most studies of cortical network dynamics are based on purely random wiring. Generally, they are focused on a local spatial scale, where approximately 10 percent of all possible network connections are realized. In reality, however, neuronal connections in the cortex show a complex spatial structure composed of local and long-range patchy couplings [4, 1].
Here, we ask to what extent such geometric traits influences the dynamics of cortical network models in a large 2D piece of cortex (representing layer 2/3 of cat VI). We assume various distinct connectivity types, ranging from purely random to distance dependent couplings including long-range connections. To do this, we have to enlarge the usual spatial scale of about 1 mm side length. Thus, compared to [5, 6], one neuron of our cortical network model is connected to a much smaller fraction of other neurons: approximately one instead of ten percent.
The aim of this project is to investigate whether the results of previous studies on network dynamics are still valid for such spatially extended networks. As it is our focus to utilize realistic models and parameters, we consider two different types of conductance based integrate-and-fire (iaf) neurons. Analyzing the characteristic measures describing spiking neuronal networks (e.g., firing rate, correlations), we explore and compare the dynamical state spaces of different types of network models.

Horizontal connectivity in cortex



Cortical projections: Local (red), intrinsic long-range (blue) and extrinsic long-range connections. Left: Top view on 2D piece of cortex with a schematic extracellular tracer injection showing patchy projections [4, 1].

Spatial range and connectivity



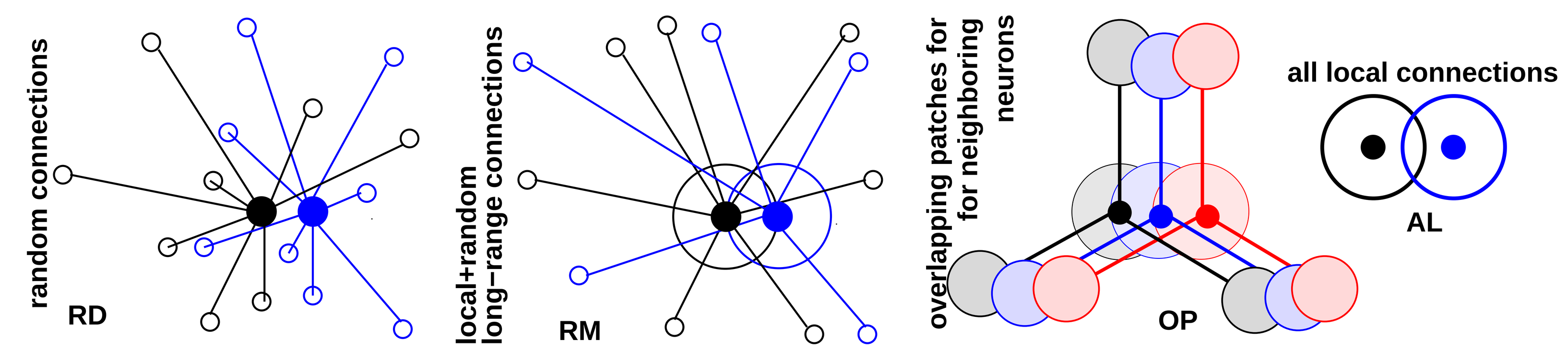
Global connectivity $c = k/N$, with N neurons and k synapses per neuron. 2D cortical sheet $R\,\mathrm{mm}^2$, connectivity range of a neuron $r < R/2$.

(A) Common: randomly or locally connected network with $\mathbf{c \approx 0.1}$.

(B) Here: including longer-range projections leads to $\mathbf{c << 0.1 \approx 0.015}$

The network simulations presented here are performed with $N \approx 50.000$, randomly distributed in $R = 5\mathrm{mm}^2$ with a global connectivity of $c \approx 0.015$ (i.e., $\bar{k} \approx 750$).

Connectivity assumptions



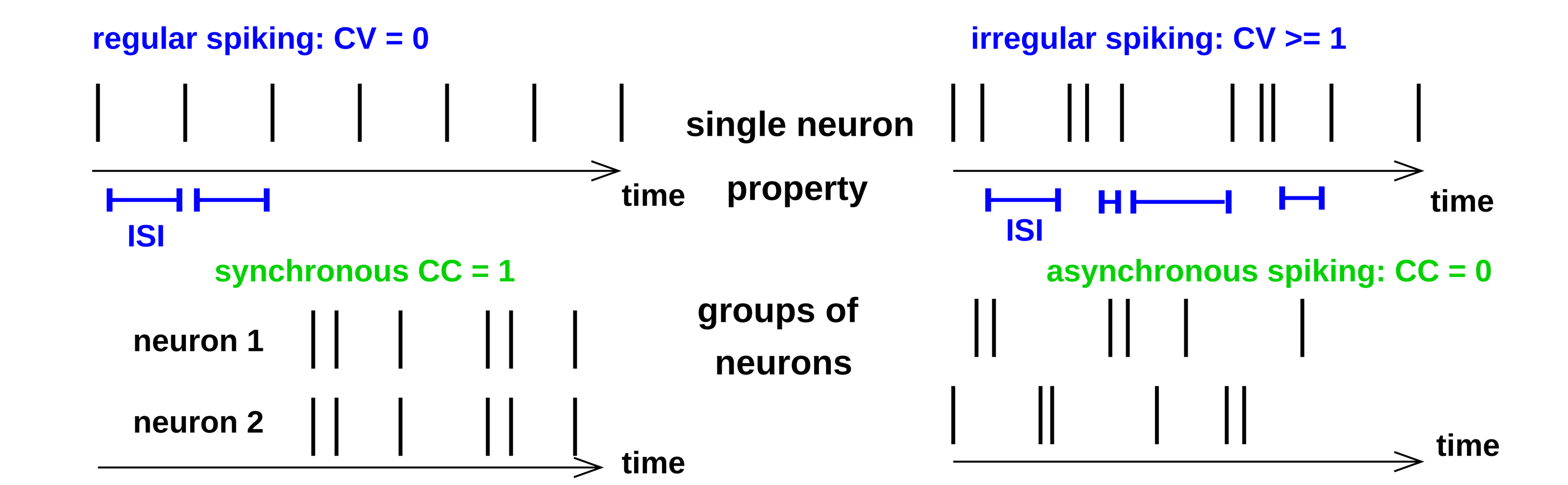
Dynamical state space analysis

The following parameters were used setting up the networks:

- Fixed parameters: 78% exc. & 22% inh. neurons; 60% local exc. and 73% local inh. connections with 71% ee, 10% ei, 16% ie, 3% ii synapses [2]. Conductance based I&F neuron model $(V_{th}, C_m, g_L, \tau_{syn} \ldots)$ with regular spiking exc. & fast spiking inh. neurons.
- Varying parameters: Poissonian input rates ν_{ext} $(0.66 \cdot \nu_{\mathrm{ext}}$ to inh. cells) and $\mathbf{g = w_i/w_e}$ defining the synaptic strength of inh. synapses (EPSP amplitude 0.1 mV).

To characterize network dynamics the following measures were calculated:

- Coefficient of variation $\mathrm{CV} = \mathrm{Var(ISI)}/\,\mathrm{E(ISI)}^2$ and alternatively $\mathrm{CV}_{KL} = \exp(-\,\mathrm{KL})$, with the Kullback-Leibler divergence $\mathrm{KL} = \sum \mathrm{P(ISI)} \ln(\mathrm{P(ISI)}/\,\mathrm{Q(ISI)})$. As reference distribution we use an exponential Q(ISI) provided by poissonian spike trains.
- Correlation coefficient CC of pairs of neurons, firing rates FR, membrane potentials V_m, total conductances g_L.

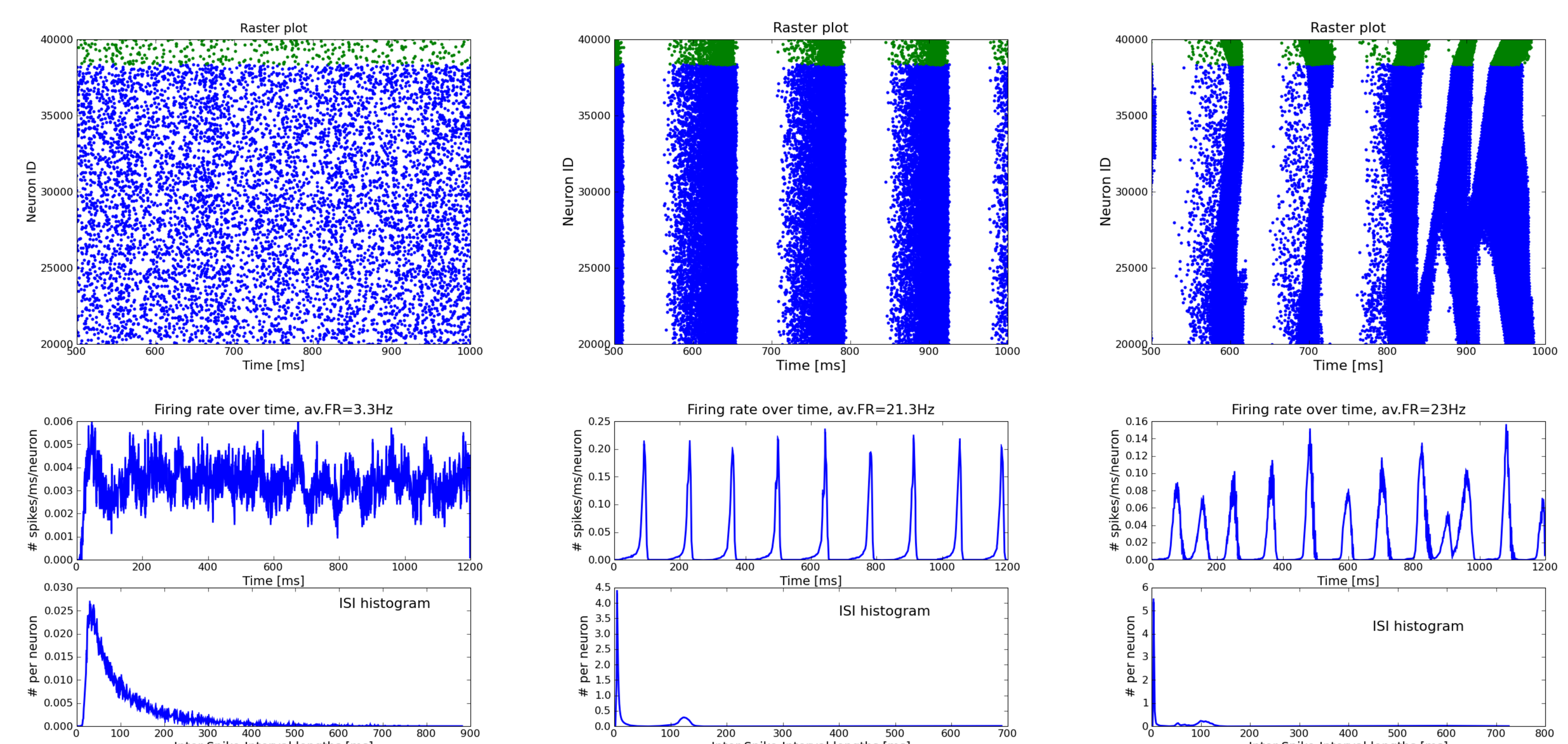


Raster plots

(RD) ν_{ext}=10 000 Hz, g=5
CV=0.42, CV_{KL}=0.82, CC=0.0003

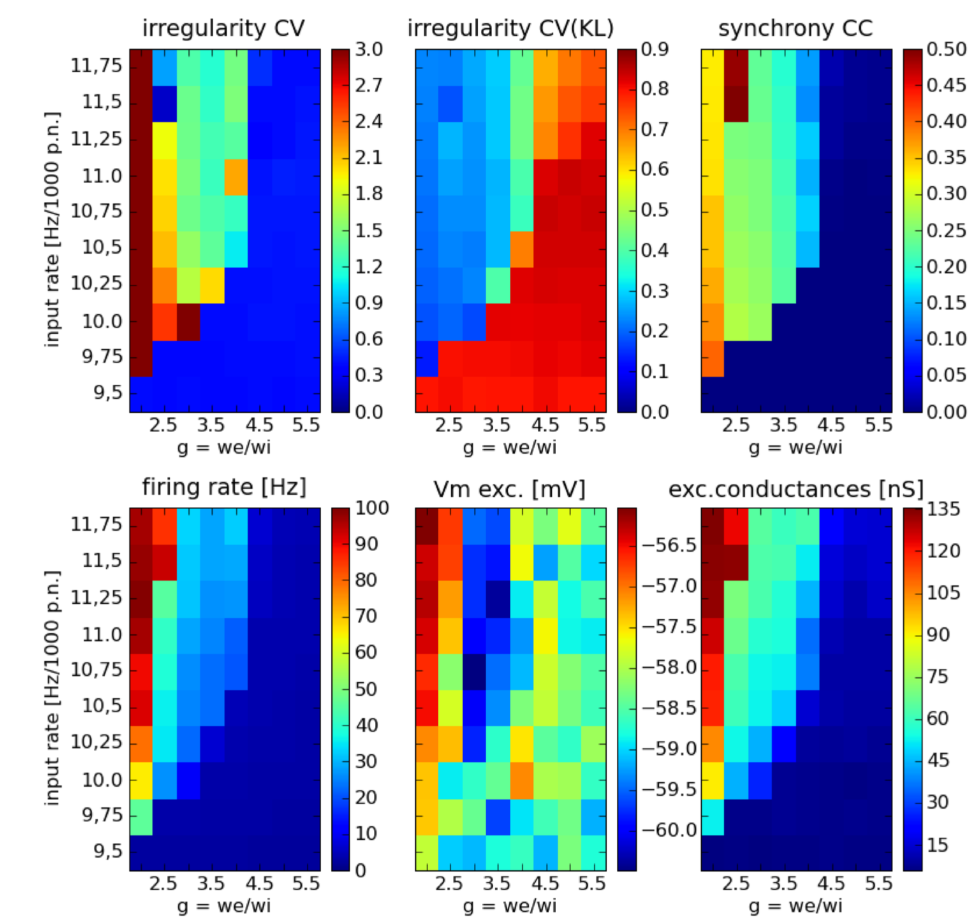
(RD) ν_{ext}=10 500 Hz, g=3.5
CV=1.4, CV_{KL}=0.28, CC=0.22

(AL) ν_{ext}=10 000 Hz, g=3.5
$\Rightarrow CV$=1.2, CV_{KL}=0.28, CC=0.1



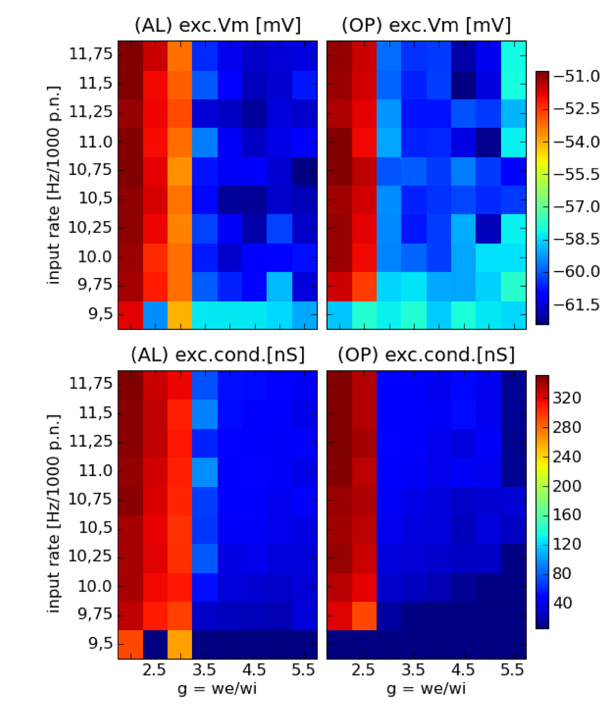
Dynamical state space analysis

Simulation results for the RD network model



RD networks (*left*) show a smooth transition from high to low values of all measurements. AL & OP networks (*bottom*), however, exhibit a sharp border concerning V_m, g_L: Either all neurons are permanently above their firing threshold (V_m >55mV) or much below.

Results for AL & OP networks



Conclusions

Varying ν_{ext} and g, we explored the dynamical state space of our network models. Compared to previous studies, our networks were predicated using an exceptionally small amount of internal connections. Moreover, they were composed of different neuron types. Nevertheless, our results principally agree with [5, 6]. Depending on ν_{ext} and g different dynamical states are possible: large external input rates and low inhibition lead to high firing rates and a synchronous and regular firing ('SR' state), while small ν_{ext} combined with large g results in asynchronous irregular firing ('AI' state).

To describe the (ir)regularity in neuronal spiking in our data the usual CV did not work. Thus, we suggest to use an alternative measure, CV_{KL}, that characterizes the deviation of P(ISI) from an exponential distribution.

Preliminary results indicate that the existence of local connections (vs. random wiring) induces important changes in the dynamical state space: In case of AL or OP connectivities, the transition between 'SR' and 'AI' state is very sharp while for the RD model all measurements show smoother transitions. These results indicate that a purely random connectivity is not appropriate for simulating cortical network dynamics.

References

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