Long-range coordination patterns in cortex change with behavioral context

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preprint:

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Question

- Neural networks within a cortical area comprise a large number of neurons that mostly form short-range connections [1].
- Yet, neural activity is found to be confined to low-dimensional manifolds [2] which requires strong coordination also between distant neurons that are most likely unconnected.

→ Which dynamical mechanism causes such long-range neural coordination patterns?

Answer

Using tools from statistical physics of disordered systems [3,4,5,6,7], we show that networks can operate in a "dynamically balanced critical state", where pairs of neurons interact via a multitude of parallel paths through the network, giving rise to long-range covariances between individual neurons despite short-range connections [8]. This mechanism for long-range cooperation is not imprinted in specific connectivity structures but can change over time in a state-dependent manner, which we demonstrate in macaque motor cortex.

References

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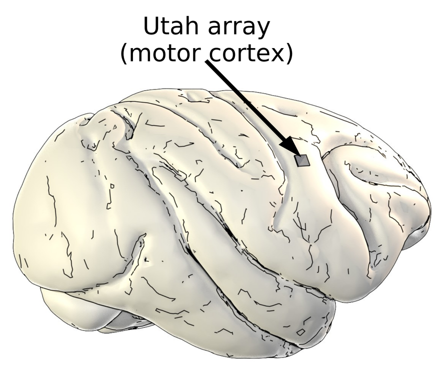
Experimental Observations: macaque motor cortex activity during rest and a reach-to-grasp task

Setup

- 10×10 Utah electrode array in macaque motor cortex ($4 \times 4\,\mathrm{mm}^2$)
- Resting state (RS) and reach-to-grasp task (R2G) [9]
- Spike sorting into putative excitatory (E) and inhibitory (I) neurons
- Binning of spike trains (RS: 1 s, R2G: 200 ms)

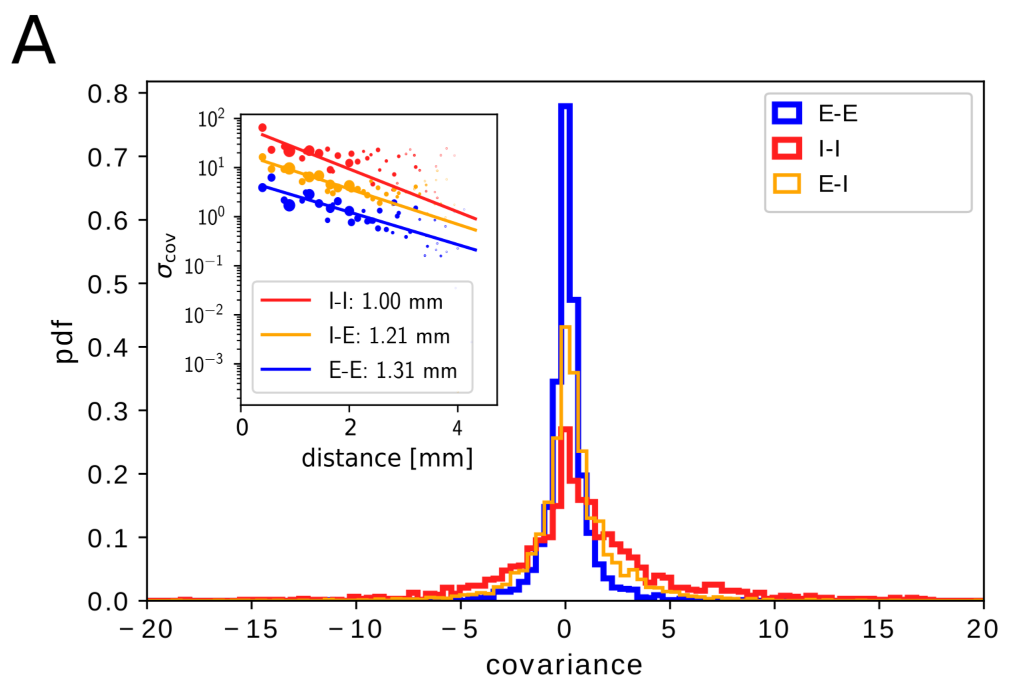
→ Spike-count covariances:

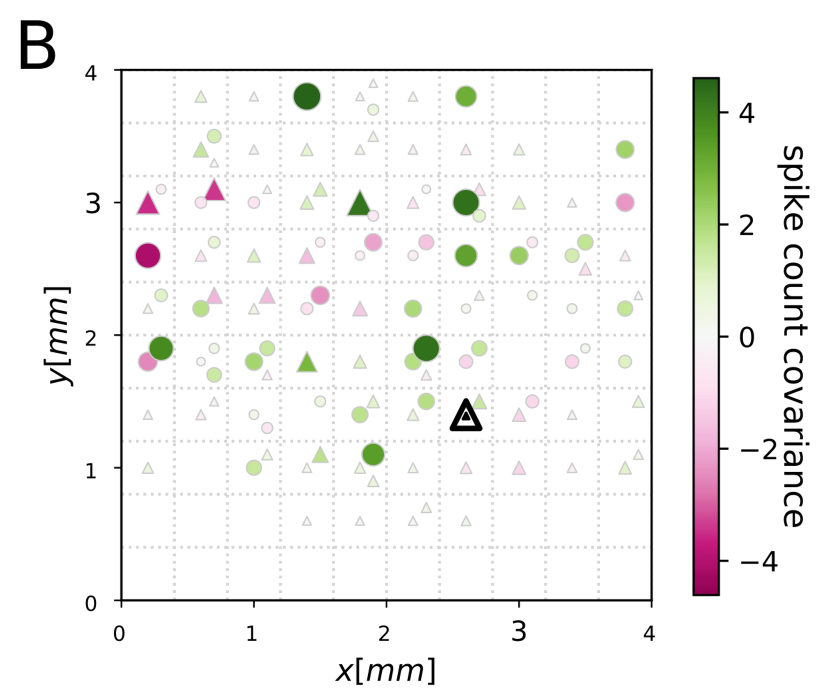
$$c_{ij} = \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle$$



What is the spatial organization of spike-count covariances on the Utah array?

Highly disperse covariances across mesoscopic distances





Covariances are:

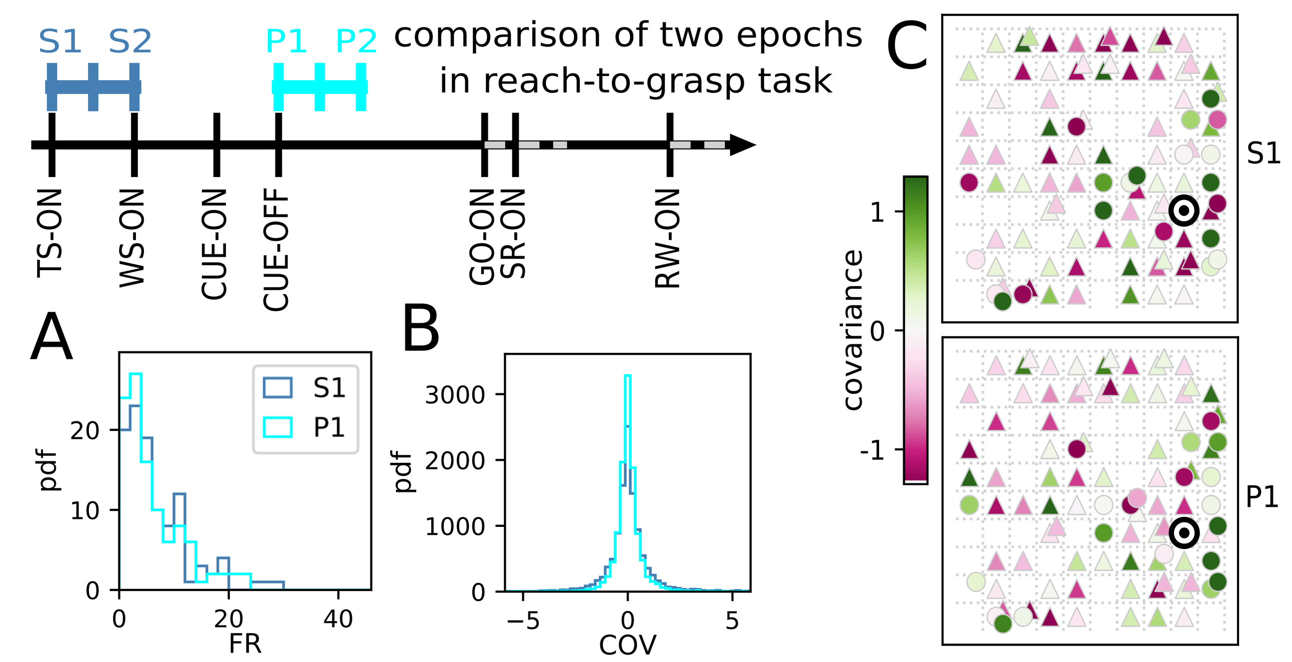
- low on average
- large (negative and positive) for individual neuron pairs (across all distances)

Exponential decay of width of covariance distribution with decay constants:

- much larger (millimeter scale) than the range of direct connections (~ 300 microns [1])
- similar across neuron types

Which mechanisms give rise to the large dispersion of covariances?
Does the long-range coordination rely on long-range connections?

Coordination patterns change with behavioral context

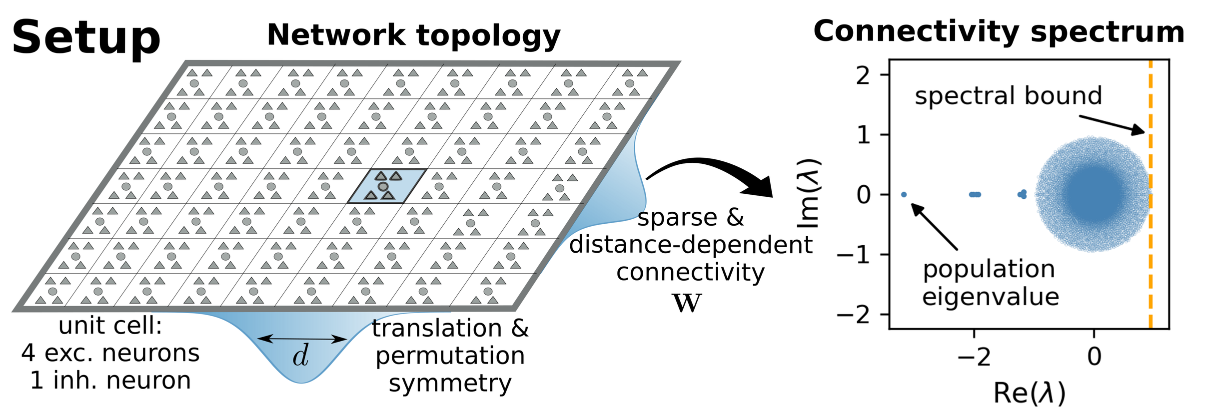


- Firing rates and covariances have overall similar statistics but largely differ on the individual neuron level (corr. coeffs.: $\rho = 0.69$ and $\rho = 0.4$)

How are changes in firing rates and covariances related?

Theory and Simulation: balanced random network model with short-range connectivity

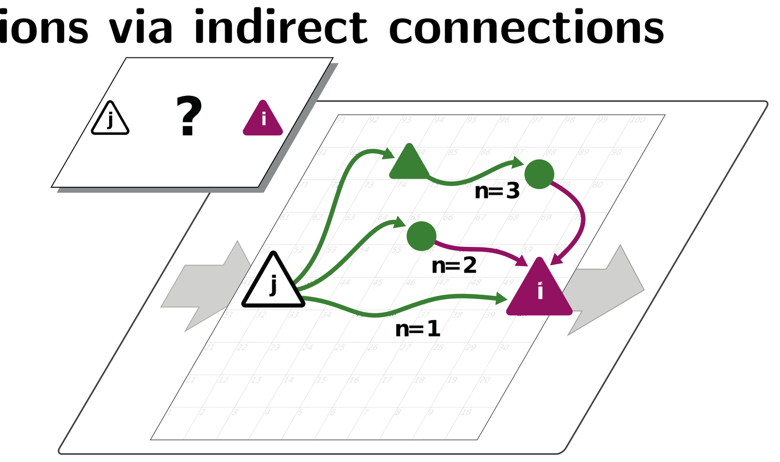
Setup



- Hypothesis: short-range (length scale d), random connectivity sufficient to explain experimental observations
- Linear response theory [10,11,12] relates spike-count covariances to the effective connectivity $\boldsymbol{W}$: $\boldsymbol{c} = [\mathbf{1} - \boldsymbol{W}]^{-1} \boldsymbol{D} [\mathbf{1} - \boldsymbol{W}]^{-T}$

There is a critical regime [7], where the maximum eigenvalue (spectral bound) $R = \max(\mathrm{Re}(\lambda)) \lessapprox 1$

Interactions via indirect connections

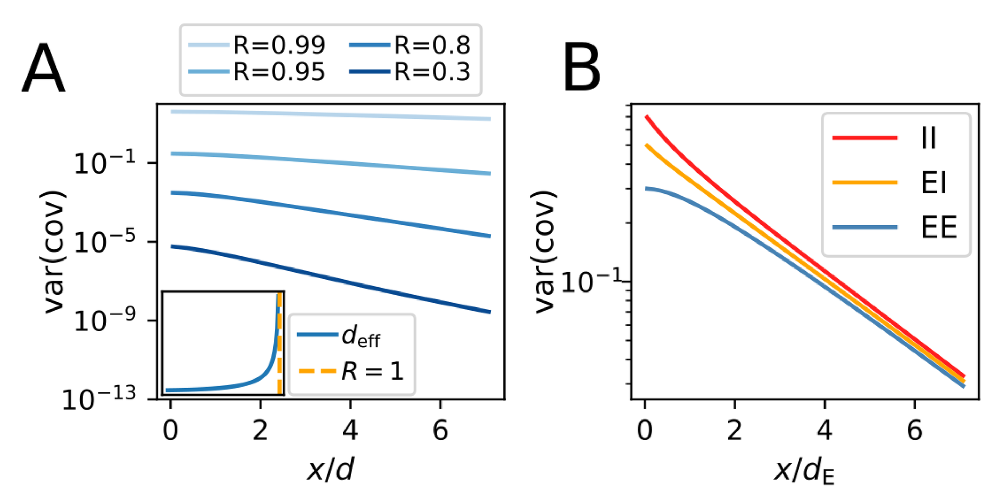


- Neuronal interactions are not only mediated via direct connections, but also via indirect paths: $[\mathbf{1} - \boldsymbol{W}]^{-1} = \sum_{n=0}^{\infty} \boldsymbol{W}^n$

→ larger reach and superposition of contributions from excitatory and inhibitory neurons

In the critical regime, covariances are dominated by multi-synaptic interactions

Decay of covariances depends on spectral bound

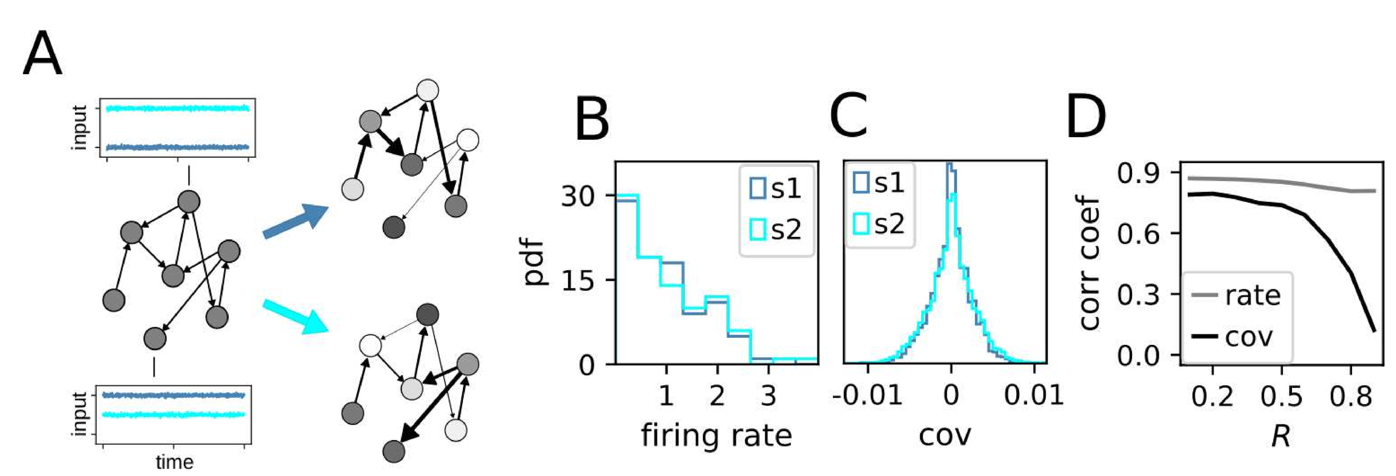


- Beyond mean-field theory for spatially organized random E-I networks:

→ exponential decay of variance of covariances on length scale d_{eff}, determined by spectral bound $d_{\mathrm{eff}}/d \sim \sqrt{R^2/(1-R^2)} + \mathrm{const.}$

Length scale of covariances diverges at critical point $R \to 1$

Covariance patterns depend on effective connectivity of network states



- Anatomical connections + firing rates → effective connections

→ Effective connectivity is dynamic ⇒ covariance patterns are dynamic

In the critical regime, small changes in firing rates induce large changes in covariances

Acknowledgments: Supported by HGF young investigator's group VH-NG-1028, European Union Horizon 2020 grant 785907 (Human Brain Project SGA2) and partially funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 368482240/GRK2416.