Time Delays Organize Large Scale Brain Synchronization

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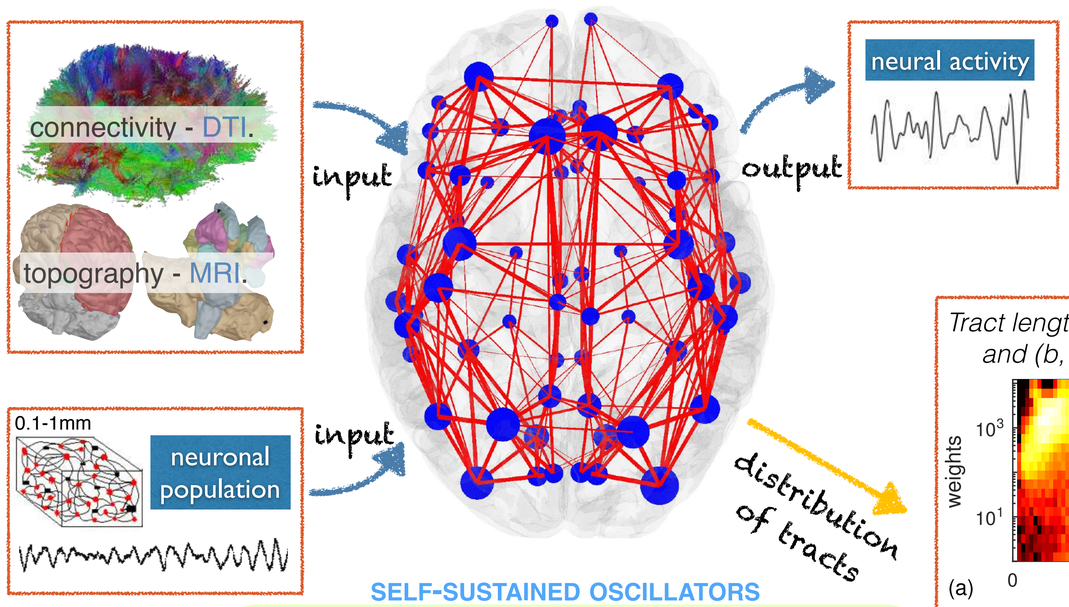
THEVIRTUALBRAIN.

Human Brain Project

Brain Network Modeling (BNM) with The Virtual Brain (TVB)

- Large-scale modeling of the brain is defined by local oscillatory dynamics that are superimposed on connectome-based architecture, thus leading to a Brain Network Model [1].
- Besides weights, time-delays due to transmissions via tracts are a crucial feature of a connectome [2].
- Diffusion tensor imaging data [2, 3], implies that tract lengths follow a multimodal distribution.
  - This allows spatio-temporal decomposition of the network that facilitates its analysis[3, 4].
- Rhythms and their synchronization, as a key mechanisms of brain function are particularly sensitive to delays [5].
- Phase locking values (PLV) used for the statistics of the phase lags and the level of coherence. [6]



SELF-SUSTAINED OSCILLATORS

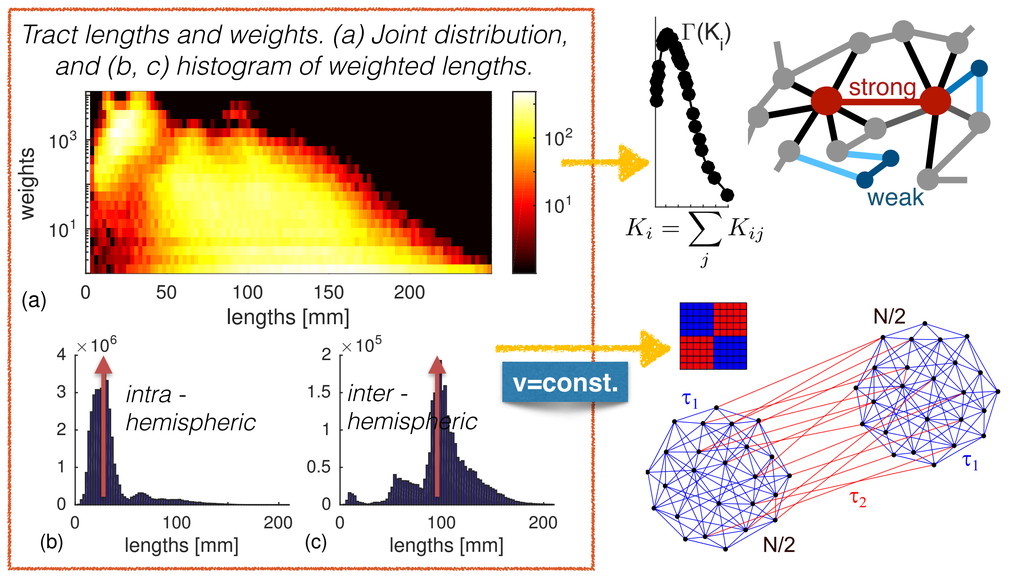
$$\dot{X}_i = \mathcal{N}(X_i) + \sum_j w_{i,j}\mathcal{G}[X_j(t-\tau_{i,j}) - X_i(t)] + \eta_i(t)$$

θ_i - phase $\quad \mu = 2\pi f$ - natural frequency

$$PLV_{ij}e^{i\phi_{ij}} = \frac{1}{M}\sum_p e^{i\Delta\theta_p} \qquad \dot{\phi}_i = \dot{\theta}_i - \Omega t, \quad re^{i\Omega t} = \frac{1}{N}\sum_j e^{i\theta_j}$$

Spatio-Temporal Decomposition

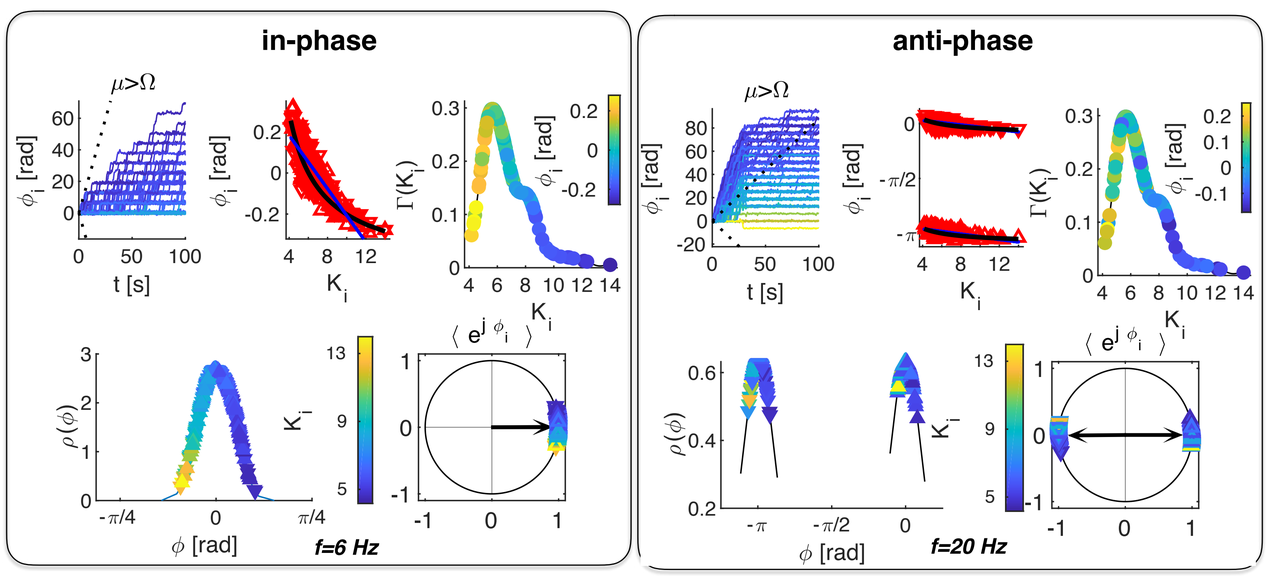
- Theoretical results for Kuramoto oscillators with bimodal δ time delays [4] and log-normal node strengths.
- Numerical simulations on the connectome (68 cortical regions) for phase [4] and amplitude oscillators [7].



Phase-lags in Networks with Distributed Delays

Bimodal δ-Delays and Lognormal Weights

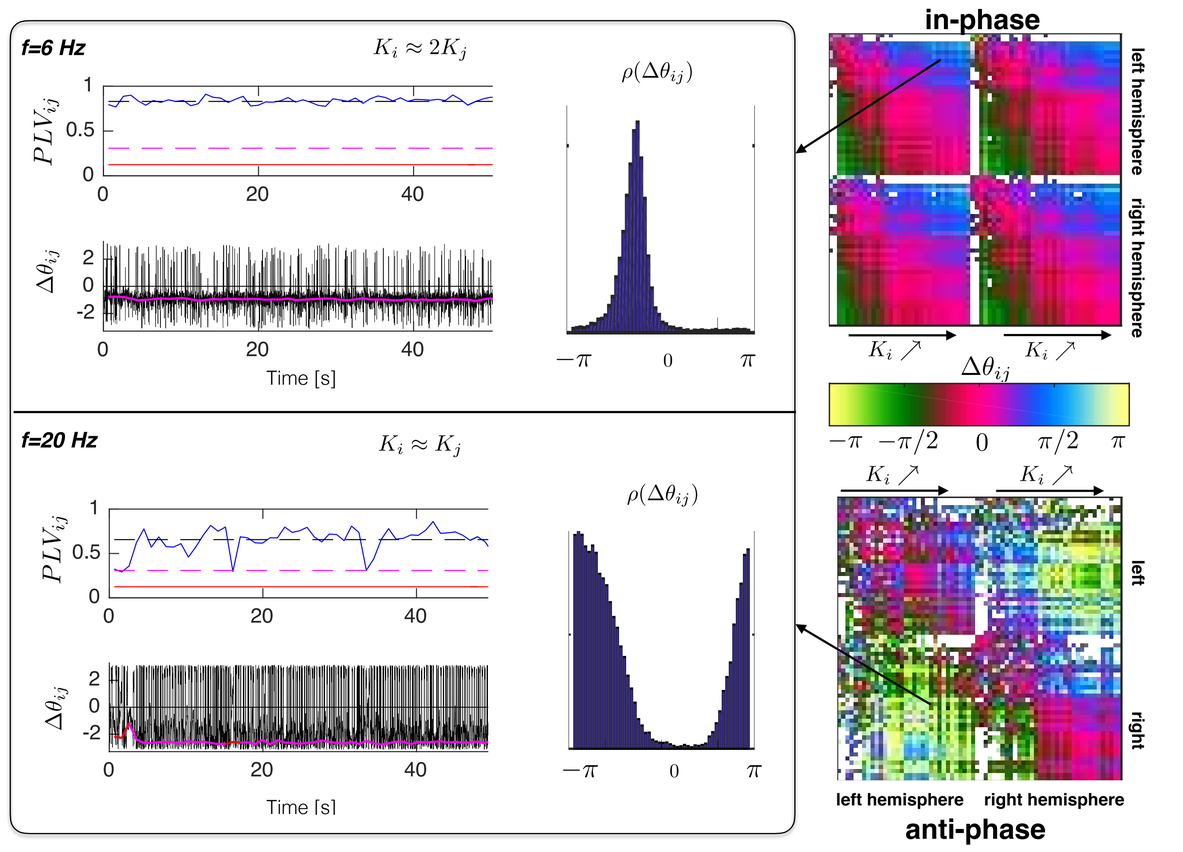
- Numerically confirmed analytical results for the spatio-temporal structure approximated by the two main modes of the delays and lognormal weights averaged over each node.
  - The regime of synchronization (**in-or anti-phase**) depends on the time-delays, whilst phase shifts are solely influenced by the coupling strengths [4].



Relative phases and strengths of the brain regions. The color code is consistent across the plots.

Connectome

- Same regimes obtained and **stronger nodes always lag in phase behind the weaker**.

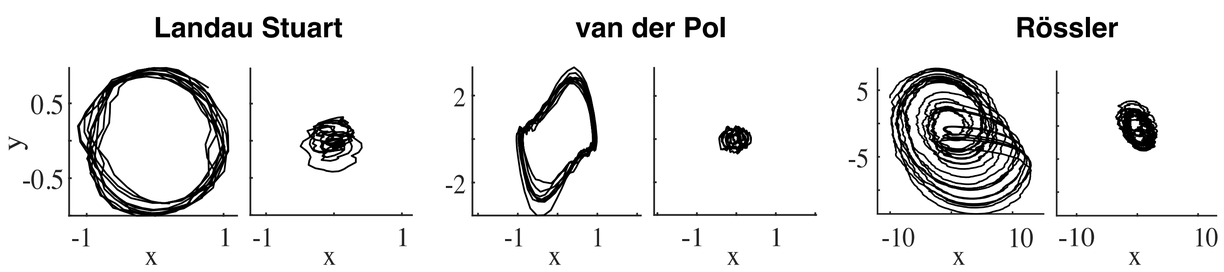


Instantaneous (black) and time-averaged phase lags (magenta), their histogram, and PLV (blue) and its mean (black).

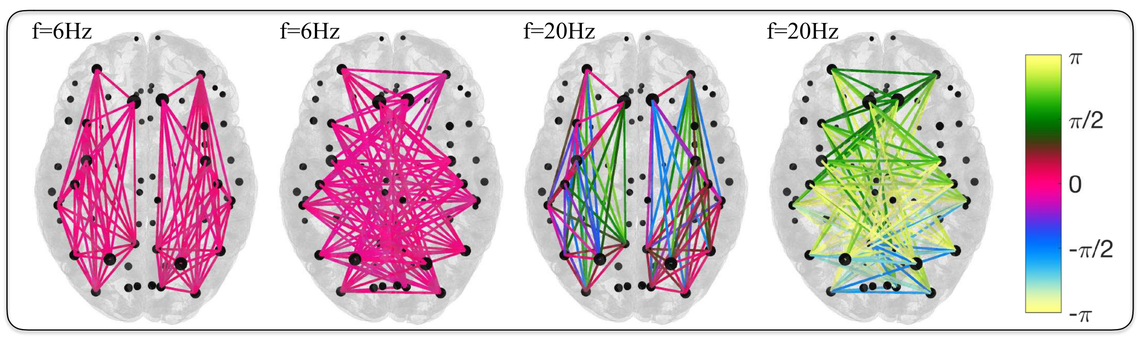
Phase lags of brain regions internally sorted by in-strength.

Amplitude Decrease in the BNM

- Increased frequency and coupling distort the oscillators by decreasing their amplitude, and stronger regions have lower, but more synchronized activity.



Phase portraits for the weakest (left) and the strongest (right) connected nodes of a oscillatory BNM.



Phase shifts between10 strongest nodes of intra- and inter- hemispheric subnetworks.

Conclusions

- Spatial patterns of time-delays are analytical tractable for Kuramoto oscillators [3, 4].
- Theoretical results for phase arrangements numerically confirmed for the connectome.
  - Stronger nodes phase lag behind the weaker [4, 7].
  - Phase-shifts are 0 or ±π centred regardless of the type of the oscillators [4, 7].
  - Qualitatively identical phases for amplitude oscillators [7].
- Amplitude decrease proportional to the strength of the nodes and the frequency [7].
- Synchronization patterns need to hold for local oscillatory dynamics and time delays proportional to the lengths of the structural pathways [4,7].

References

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