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Hierarchical whole-brain modeling of critical synchronization dynamics in human brain

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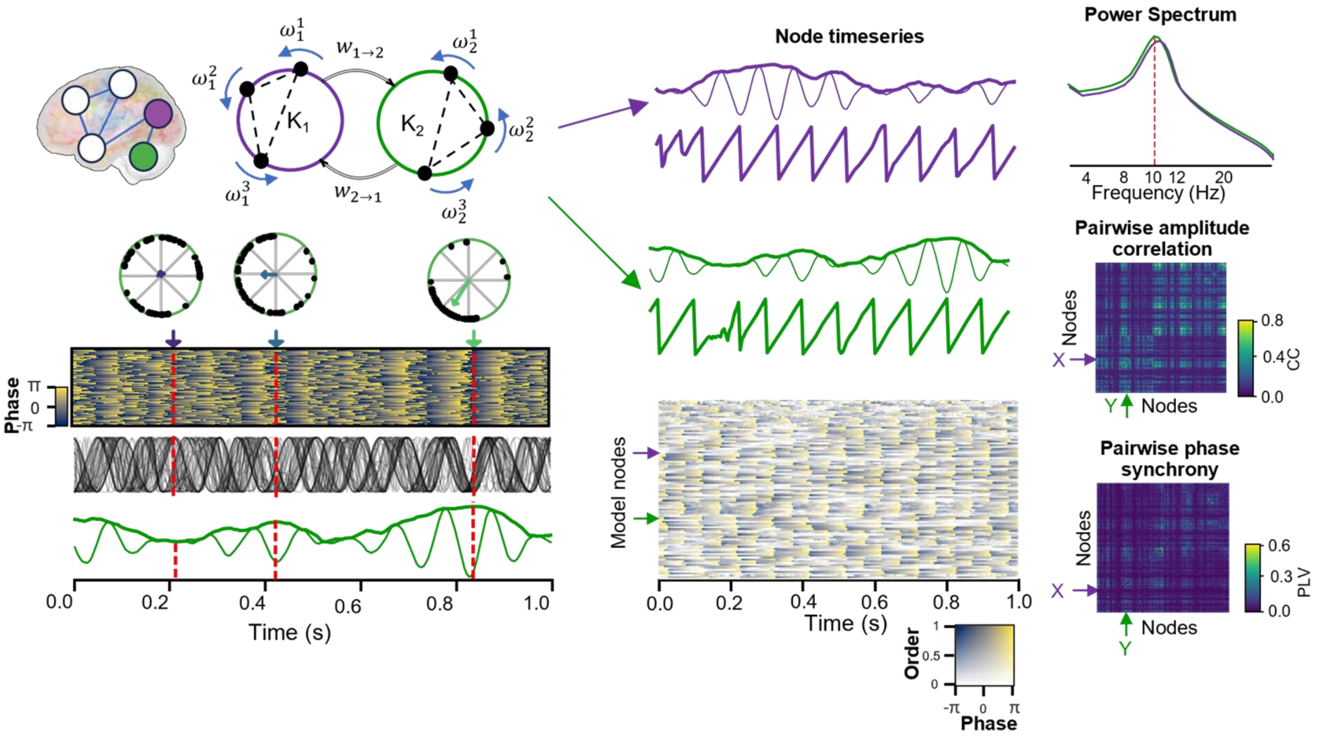
The model architecture

- Model represents a network of nodes. Each node in the model stands in for a cortical area in the brain and contains many **Kuramoto oscillators**.
- The **hierarchical structure** combines intra- and inter-nodel interactions. This layered approach allows the model to replicate the complex ways brain regions communicate and interact.
- The model produces complex timeseries and its observables can be **directly compared** to the real brain data.



Local and global control parameters shape the criticality landscape of the model dynamics

Question

How does the model behave when we vary control parameters?

Hypothesis

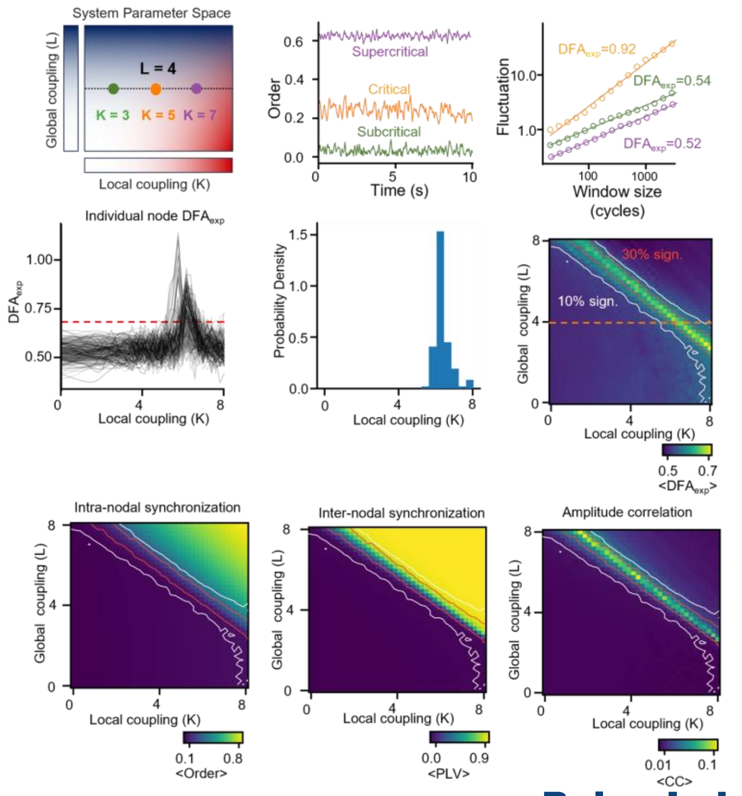
The intra- and inter-node synchronization will grow as a function of K & L

Approach

Run model simulations for different local & global coupling coefficients, compute DFA_{exp}, PLV, CC and order.

Results

- The model is able to produce critical-like dynamics operationalized with DFA exponent. We observed significant variability in criticality properties between model nodes.
- The critical transition happens between order and disorder for both intra- and inter-node synchronization, DFA exponent and amplitude correlation peaks during such transition.



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Criticality alters structure-function coupling

Question

What are the structure-function relations in the system?

Hypothesis

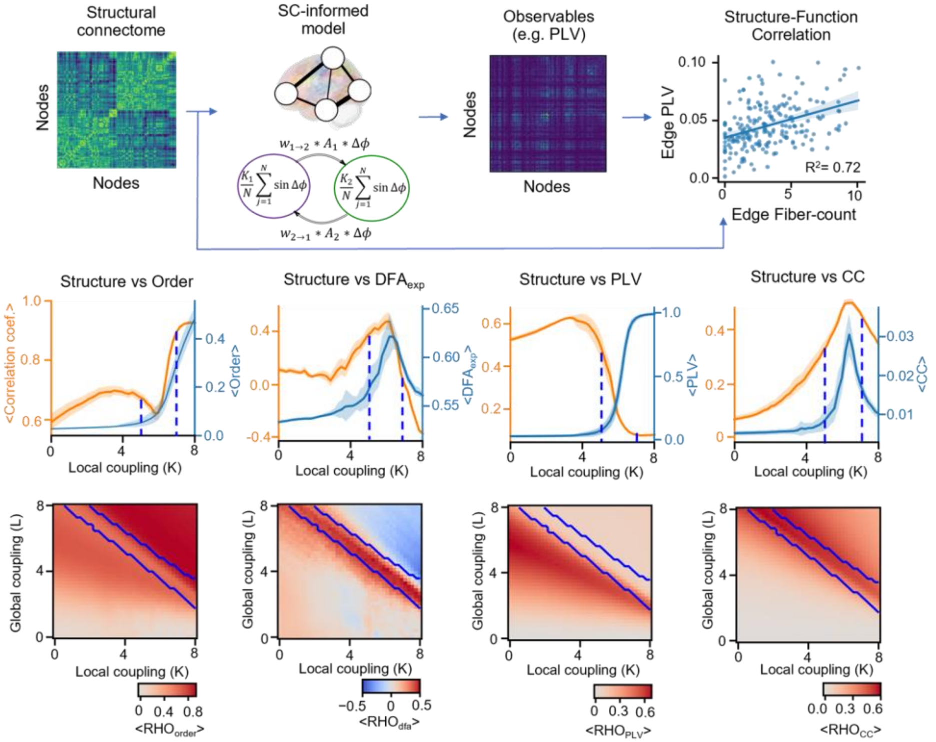
Inter-edge weights are correlated with model observables

Approach

Create structural connectome-informed models, compute observables for different K&L and their correlation with edge weights (PLV, CC) and node strength (DFA_{exp}, order)

Results

- The correlation between observables of critical-like dynamics such as DFA exponent and CC peaks at criticality and decays in sub- and supercritical regions.
- In the other hand, the correlation between order and SC is growth from subcritical to supercritical state but dips in criticality.
- Interestingly, PLV achieves the highest correlation with SC at subcritical-slightly critical state.



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Brain dynamics during the resting-state is the most correlated with observables in subcritical-critical region

Question

How similar is the model dynamics to MEG-observed data?

Hypothesis

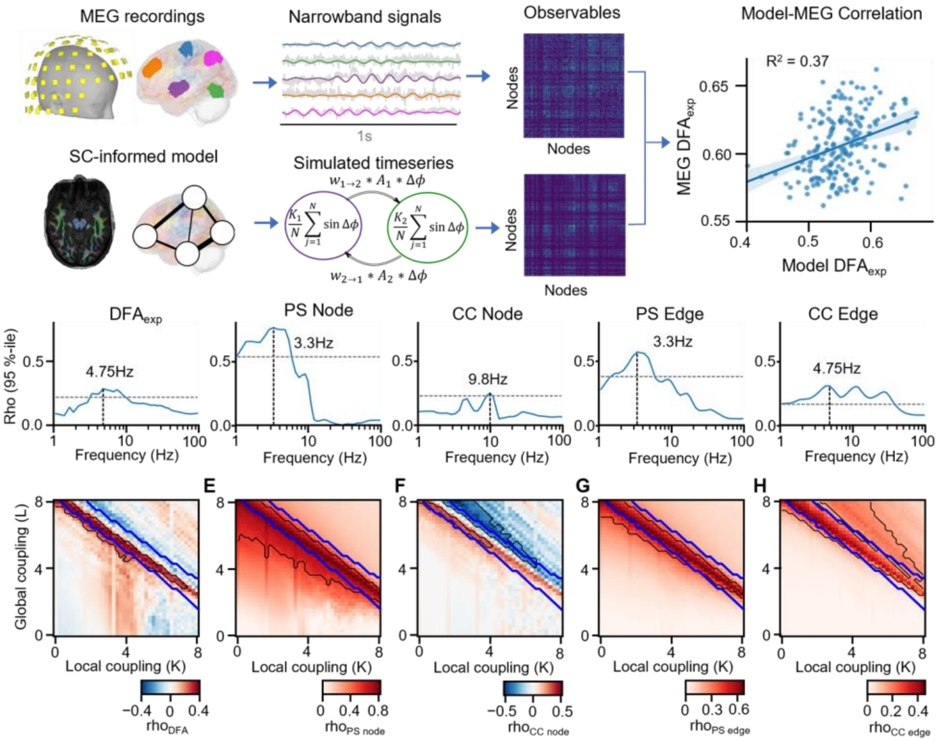
Inter-edge weights are correlated with model observables

Approach

Create structural connectome-informed models, compute observables for different K&L and their correlation with observables derived from narrow-band filtered MEG at different frequencies

Results

- Model dynamics closely resemble low-frequency MEG activity, especially in theta (3-8 Hz) for DFA and phase synchrony, with amplitude correlation showing peaks in theta, alpha (12.3 Hz), and beta (28.3 Hz) bands.
- Highest model-data similarity for phase synchronization occurs near the subcritical-critical boundary, particularly in low-theta (3.4 Hz).
- DFA dynamics best match MEG in the theta band (4.8 Hz), aligning closely with the critical ridge, suggesting brain dynamics operate in a subcritical-critical regime.



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Conclusions

We introduce a novel framework for generative hierarchical simulation of critical-like brain dynamics

- **Critical Dynamics**
  The model replicates critical-like dynamics, including long-range temporal correlations (LRTCs) and amplitude correlations that emerge at the phase transition between subcritical and supercritical states. The model not only replicates criticality phenomenologically, but also it replicates the inter-areal heterogeneity in criticality

- **Structure-Function interaction**
  The model reveals the interaction-specific breakdown or maximization of structure-function coupling at criticality, correlation between inter-edge weights and DFA exponent peaks at criticality while correlation between structure and intra-/inter-node synchronization dips at critical regime

- **Comparability with neuroimaging Data**
  Model dynamics closely match experimental MEG data, particularly within the theta frequency range, supporting the hypothesis that the brain operates near a critical state.

- **Future usage**
  This model provides a scalable framework for understanding physiological brain dynamics and offers potential applications in clinical and personalized neuroscience such as stimulus outcome prediction

Preprint https://www.biorxiv.org/content/10.1101/2024.05.08.593146v2
The code will be published after the paper (you can also write me an email)

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