Development of control in brain networks over temporal and spatial scales using graph models

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Summary

Motivation: In a brain network, brain regions vary in their ability to control the state of the network. Additionally, brain regions differ in their control of modes of activity propagation.

Questions

• How does network structure affect these relations?
• How do different timescales affect these measures?
• Are these results unique to the brain’s topology?

Methods

We used a network representation of white matter connectivity from diffusion imaging data of 882 youth ages 8–22. We used a simplified noise-free linear discrete-time and time-invariant equation of state:

\[ x(t+1) = Ax(t) + B_k u_k(t) \]

Then, we measured the average controllability using the trace of the controllability Gramian:

\[ W_K = \sum_{t=0}^{\infty} A^T B_k B_k^T A^T \text{Trace}(W_K) \]

Modal controllability was calculated using the eigenvectors and values from the adjacency matrix A:

\[ \phi_i = \sum_j (1 - \xi_j^2(A)) |v_{ij}|^2 \]

For control of synchrony in the oscillatory dynamics of brain networks, or the modes of the system, we calculated the eigenvectors of the Laplacian for each subject, and then averaged the eigenvectors across all subjects:

\[ \phi_i^{slow} = \sum_{j} |\xi_j| v_{ij}^2 \quad \phi_i^{fast} = \sum_{j} |\xi_j| v_{ij}^2 \]

Summing over all the large eigenvalues gives the fast modes, and summing over all the small eigenvalues gives the slow modes. Negative eigenvalues correspond to alternating modes while positive eigenvalues correspond to monotone modes.

Changes in Control over Varying Timescales

Average controllability vs. Timescale

Average controllability calculated over discrete timescales converges to the values of average controllability over an infinite time horizon at \( T=10000 \). When comparing average controllability to modal controllability, \( T=500 \) is where the correlation approaches that of the infinite time horizon. For smaller \( T \), average and modal are anticorrelated or not correlated.

Regional Control of System State vs. System Mode

Regions with strong control of fast modes tend to have high average controllability.

Regions with strong control of slow modes tend to have high modal controllability.

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