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

Lindsay Smith[1], Harang Ju[2], & Danielle S. Bassett[1,3-6]

[1]Department of Physics & Astronomy, University of Pennsylvania; [2]Neuroscience Graduate Group, University of Pennsylvania; [3]Department of Bioengineering, University of Pennsylvania; [4]Department of Electrical & Systems Engineering, University of Pennsylvania; [5]Department of Neurology, University of Pennsylvania; [6]Department of Psychiatry, University of Pennsylvania

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:

$$\mathbf{x}(t+1) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}_{\mathcal{K}}\mathbf{u}_{\mathcal{K}}(t)$$

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

$$\mathbf{W}_{\mathcal{K}} = \sum_{\tau=0}^{\infty} \mathbf{A}^{\tau}\mathbf{B}_{\mathcal{K}}\mathbf{B}_{\mathcal{K}}^{\mathsf{T}}\mathbf{A}^{\tau} \qquad \mathrm{Trace}(\mathbf{W}_{\mathcal{K}})$$

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:

$$\phi_i^{\mathrm{slow}} = \sum_j^{\mathrm{large}\ |\xi_j|} v_{ij}^2 \qquad \phi_i^{\mathrm{fast}} = \sum_j^{\mathrm{small}\ |\xi_j|} v_{ij}^2$$

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.

References & Acknowledgements

Evelyn Tang, Graham L. Baum, David R. Roalf, Theodore D. Satterthwaite, Fabio Pasqualetti, Danielle S. Bassett. ArXiv preprint, arXiv:1901.07536 (2019)

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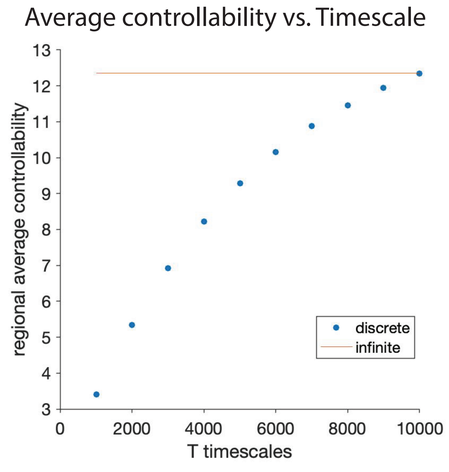
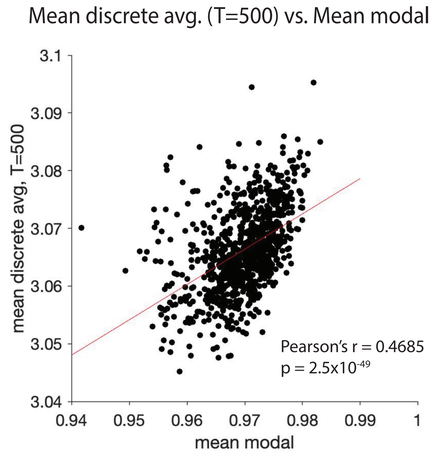
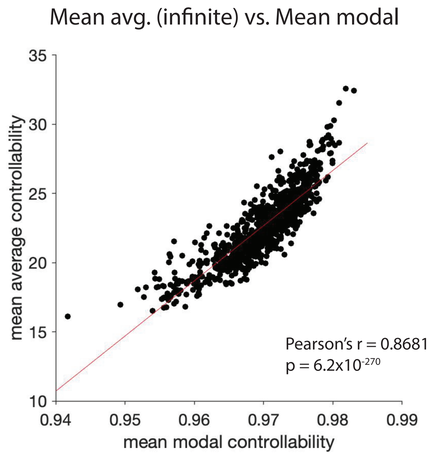
Changes in Control over Varying Timescales



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.

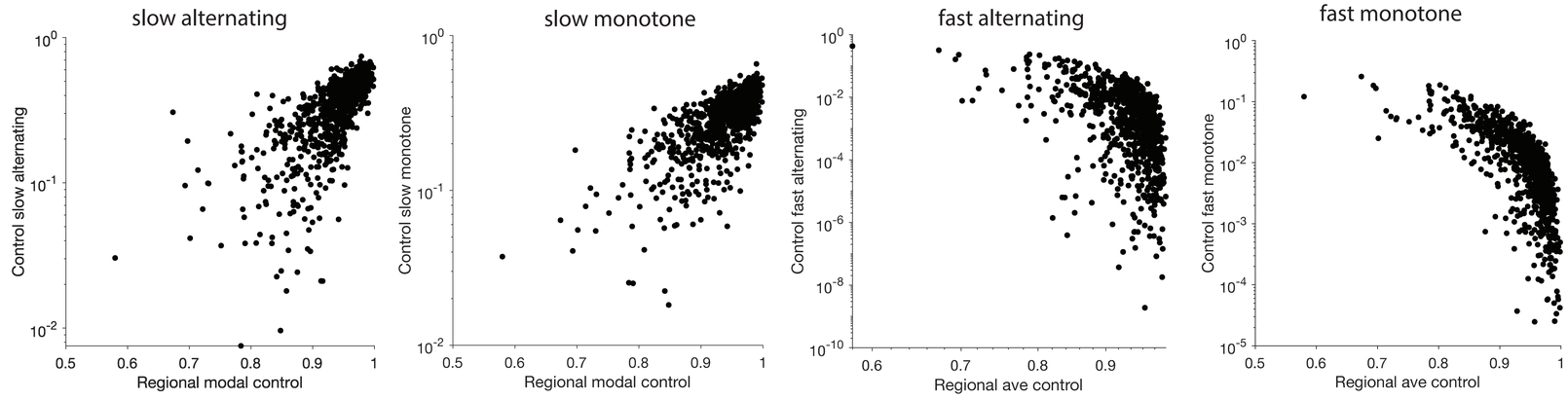




Regional Control of System State vs. System Mode

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

Region 141: Left Superior Frontal 8



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

Region 215: Left Banks STS