

Kimberly Nestor¹, Javier Rasero¹, Richard Betzel², Andrew Gerlach⁴, Peter Gianaros³, Timothy Verstynen¹

¹. Department of Psychology, Carnegie Mellon University ². Department of Psychological and Brain Sciences, Indiana University ³. Department of Psychology, University of Pittsburgh ⁴. Department of Psychiatry, University of Pittsburgh

kanestor@cmu.edu

INTRODUCTION

A graphical analysis of the brain, denotes regions as nodes while connections between regions as edges [6,7]. Node activation is dependent on the external environment, resulting in conformational changes: can be task and state dependent, though are largely individualistic [2,6]. An integrated network is such that there are connections between nodes across multiple regions. A modular network predominantly has nodal connections within specialized regions e.g. limbic. Shine [4] hypothesizes the brain is akin to an attractor landscape, where wells indicate stores of energy. In this context a modular network indicates stores of energy within specialized regions while an integrated network has shallow wells with distributed energy stores. In this context the cerebellum (Cb) would drive network change to a modular pattern, while the basal ganglia (Bg) integration, through thalamic connections [3]. Integration is said to aid in accomplishing harder tasks while modularization easier [5,6].

Hypotheses:

1. Congruent (easier) task blocks will have higher cortical modularity than incongruent (harder).
2. The Bg will have greater influence during the incongruent task blocks, alternately the Cb in the congruent.

Figure 1. Subcortical regions basal ganglia and cerebellum are connected to cortex through gating of the matrix and core thalamus respectively. Image taken from Shine (2021).

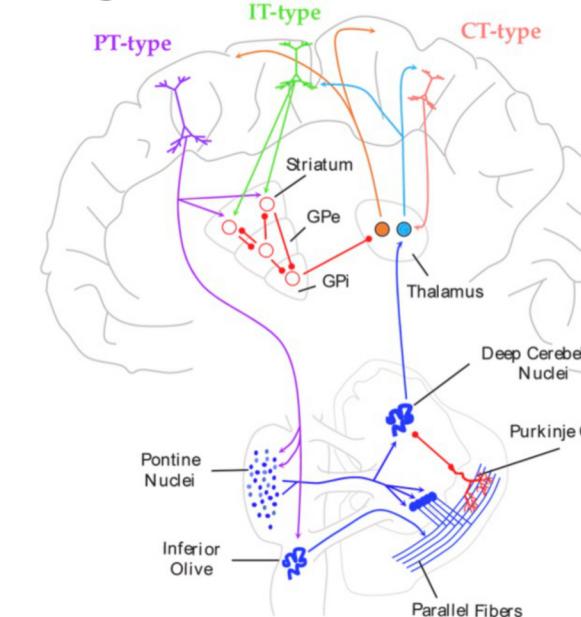
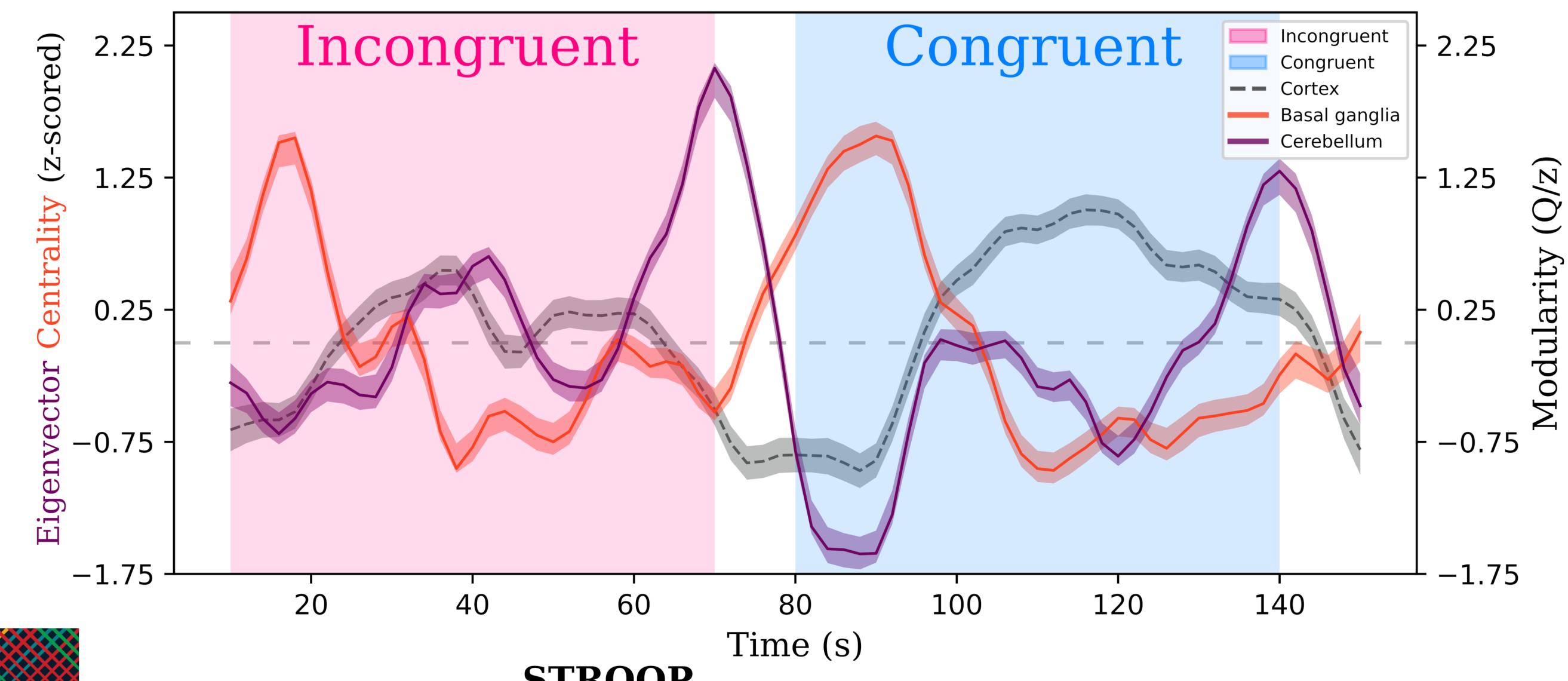


Figure 4. Gaussian smoothed z-scored basal ganglia (Bg) and cerebellum (Cb) eigenvector centrality values, averaged across subjects and task blocks. The Bg was more engaged in the beginning of the task and declined towards the end. The Cb peaked in engagement at the end of the task, decreased over the fixation and was lowest at the beginning of the subsequent task block.

RESULTS

STROOP



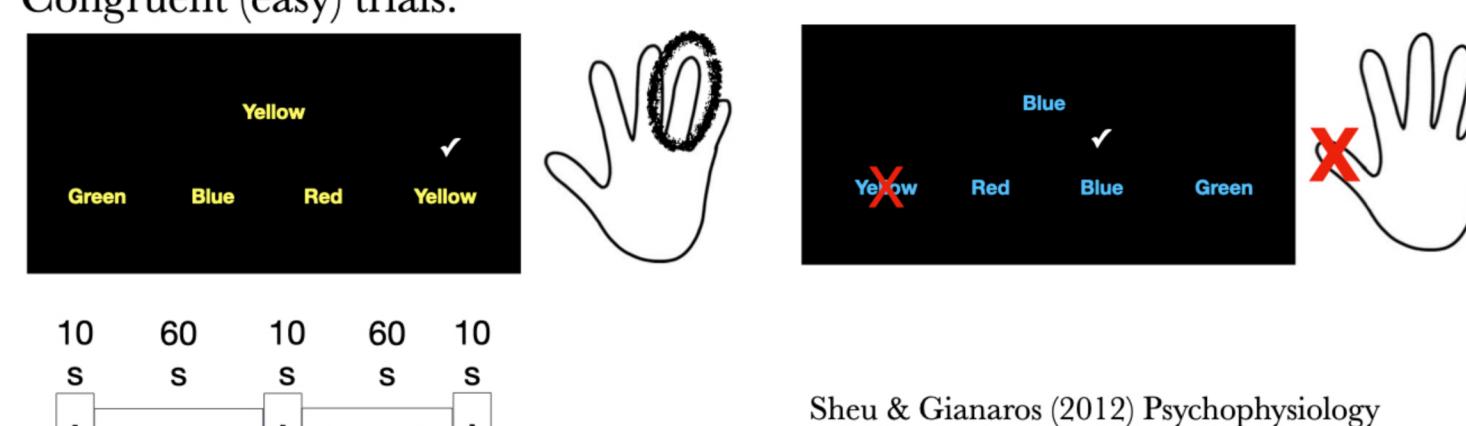
METHODS

Color-word Stroop Task

Incongruent (hard) trials:



Congruent (easy) trials:



Sheu & Gianaros (2012) Psychophysiology
Bush & Shin (2006) Nat Protocols

Figure 2. (Left) An adaptive Stroop task - to prevent habituation - was performed by participants during functional Magnetic Resonance Imaging (fMRI). Alternating task blocks (60s) were interleaved with crosshair fixation (10s) [9]. Image taken from Rasero et al. (2021).

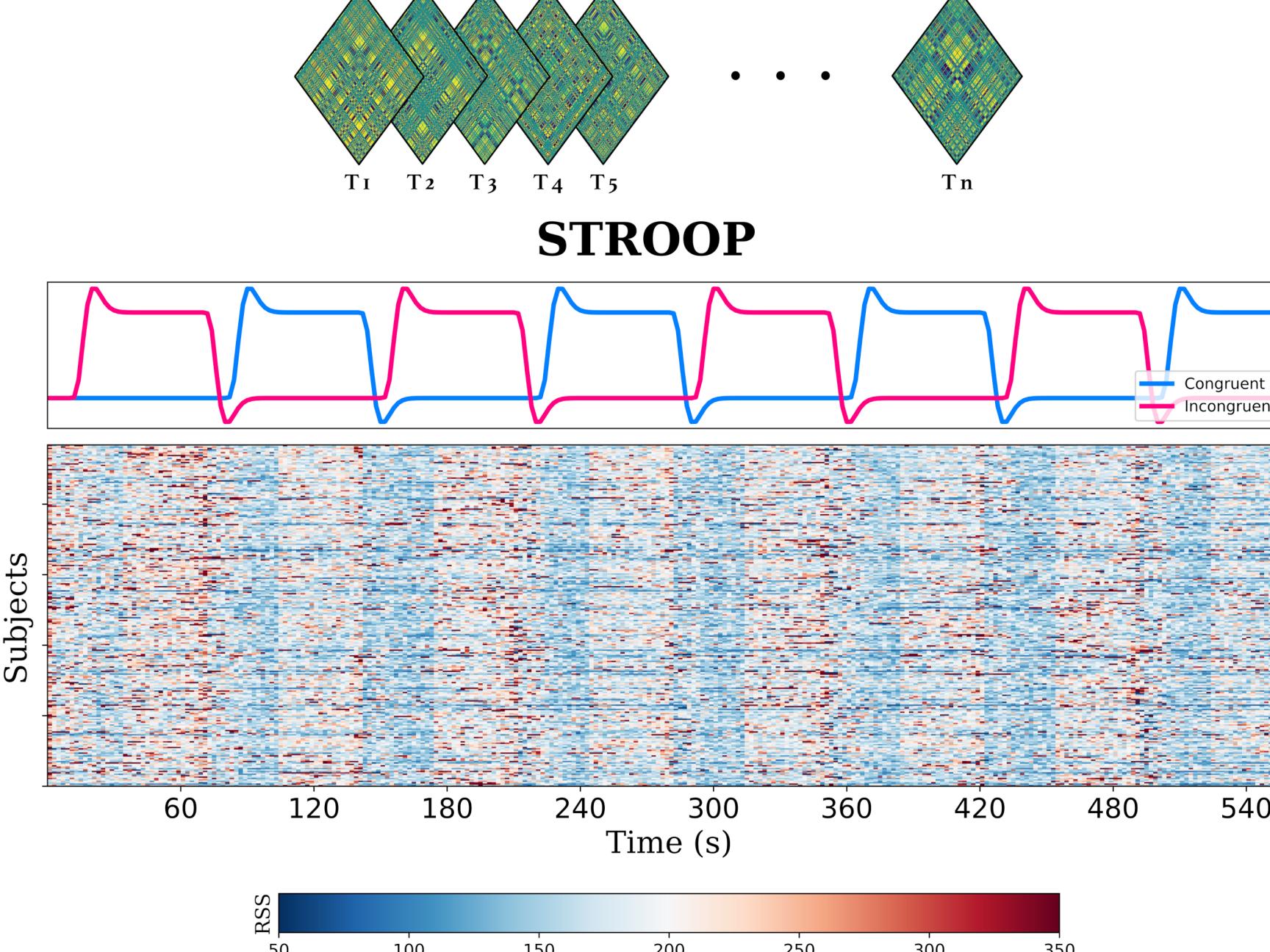


Figure 3. (Right) Stacked heat map of subjects ($n=242$) showing residual sum of squares (RSS) across the fMRI timescale (axis 2), with task paradigm (axis 1). Higher RSS indicates greater integration of networks, while lower RSS indicates less integration (modularization). Image adapted from Rasero et al. (2021).

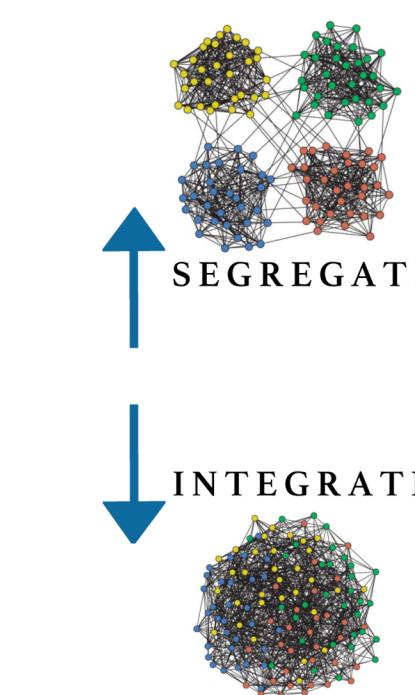
► A total of 242 subjects performed an adaptive Stroop task while being scanned for fMRI (female = 119, male = 123; mean age = 40 ± 6 ; min age = 30, max age = 51).

► The scanner used was a 3 Tesla Trio with 12-channel head coil. fMRI obtained was T2*-weighted with 3mm isotropic resolution (TR=2s, ET=28ms, Flip=90°).

► For data analysis we used the Shen atlas for region segmentation and performed edge time series analysis [1]. Modularity index [10] was obtained for cortical regions and eigenvector centrality [8] for basal ganglia and cerebellum (cortical connected nodes only).

Edge time series [1]:

$$\text{Let } c_{ij} = [z_i(1) \cdot z_j(1), \dots, z_i(T) \cdot z_j(T)]$$



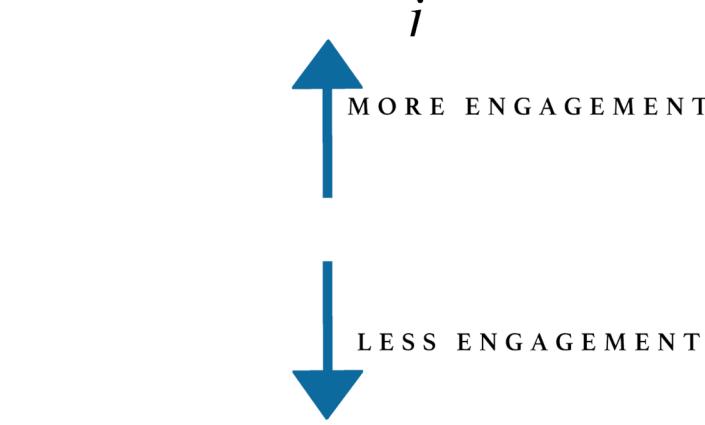
Modularity index [10,3]:

$$B = A - P$$

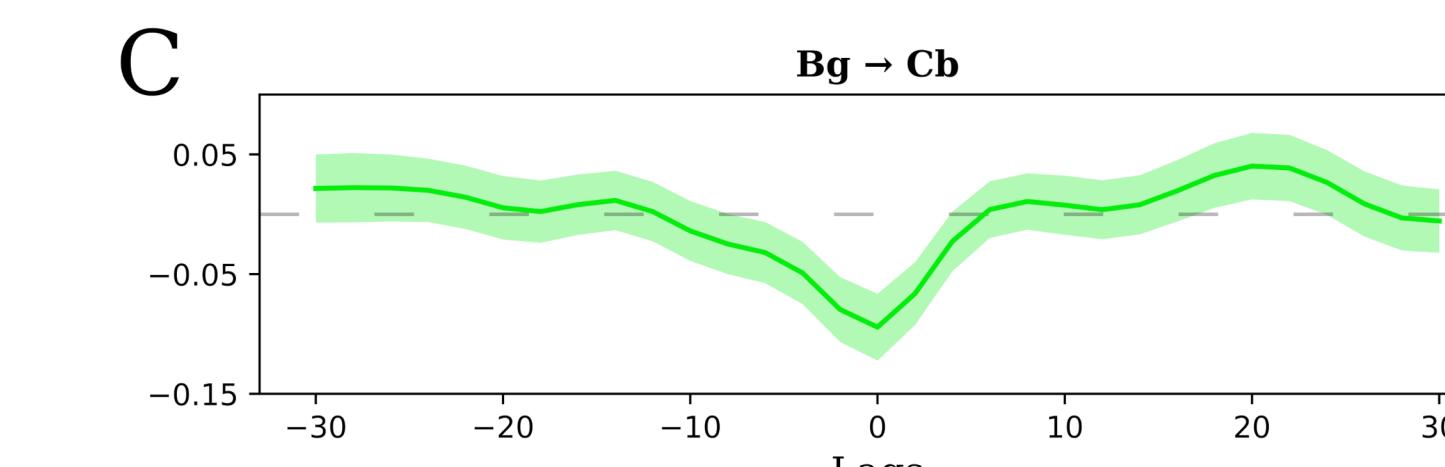
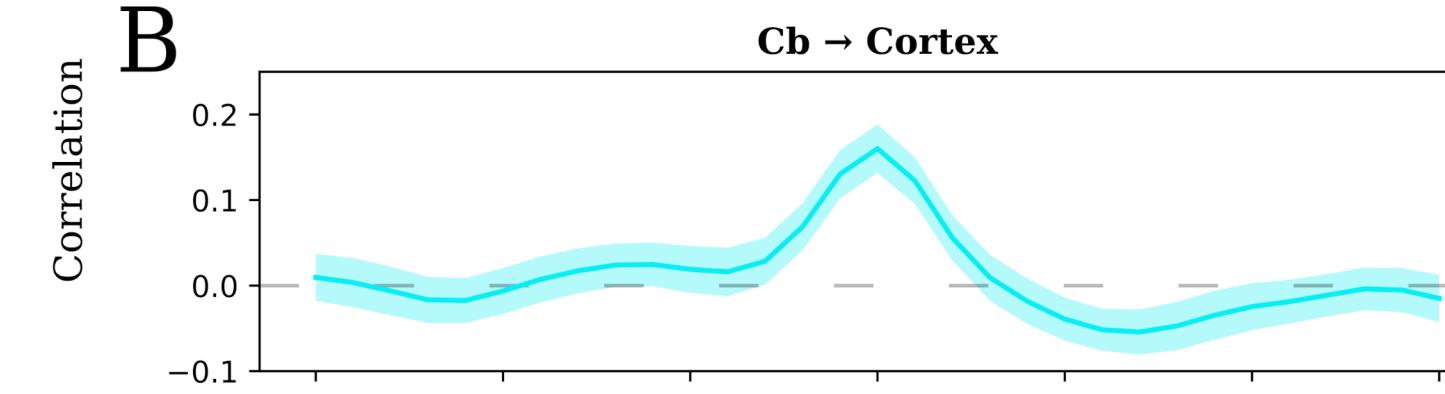
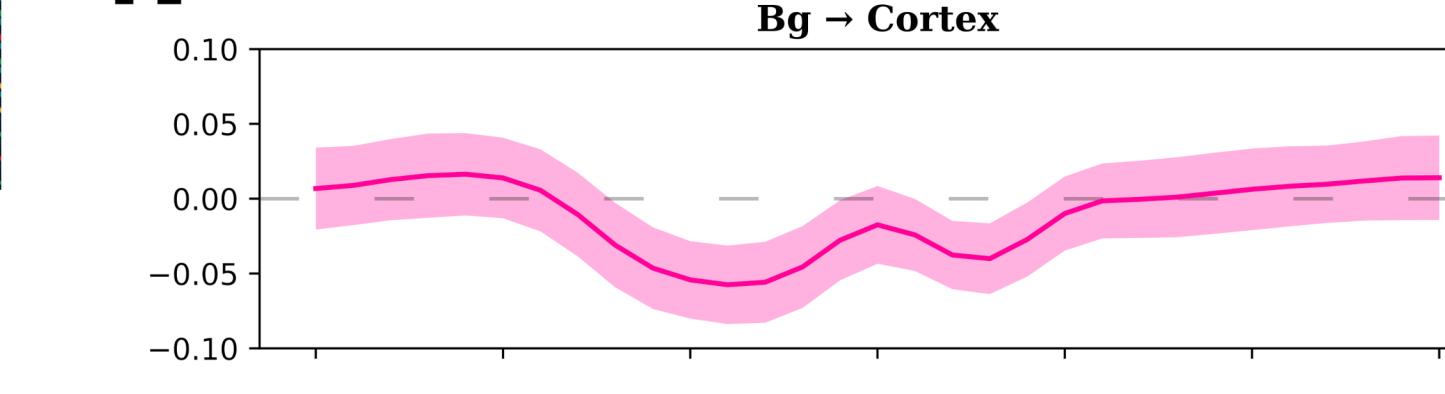
$$Q^{\text{signed}} = \sum_{ij} [B_{ij}^+ - B_{ij}^-] \delta(\sigma_i, \sigma_j)$$

Eigenvector centrality [8]:

$$x_i = K_1^{-1} \sum_i A_{ij} x_j$$



A



CONCLUSION

1. We obtained patterns of modularity in the cortex consistent with prior studies i.e. more integration in harder portions of the task (incongruent) [5,6].

2. The Bg and Cb have opposite phase engagement during trials, with the Bg beginning a control mechanism for the cortex. The Shine [4] model may be more complex than initially hypothesized.

Figure 5. Pair-wise cross correlation of our regions of interest with forward and backward lags, indicated the basal ganglia has a controlling influence on the cortex. Conversely, there was no controlling influence of the cerebellum on the cortex, but the inverse with the cortex exhibiting a control on the cerebellum. The subcortical regions exhibited no controlling influence on each other.

REFERENCES

- [1] Faskowitz, J., Esfahani, F. Z., Jo, Y., Sporns, O., & Betzel, R. F. (2020). Edge-centric functional network representations of human cerebral cortex reveal overlapping system-level architectures. *Nature Neuroscience*, 23(12), 1644–1654. <https://doi.org/10.1038/s41593-020-0770-9>
- [2] Ghosh, C., Laumann, T. O., Nielsen, A. N., Greene, D. J., Gordon, E. M., Gilmore, A. W., Nelson, S. M., Coalson, R. S., Snyder, A. Z., Schlaggar, B. L., Dosenbach, N. U. F., & Petersen, S. E. (2018). Functional Brain Networks Are Dominated by Stable Group and Individual Factors, Not Cognitive or Daily Variation. *Neuron*, 98(2), 439–452.e5. <https://doi.org/10.1016/j.neuron.2018.03.035>
- [3] Guimera, R., & Nunes Amaral, L. A. (2005). Functional cartography of complex metabolic networks. *Nature*, 433(7028), 895–900. <https://doi.org/10.1038/nature03288>
- [4] Shine, J. M., Kovicic, O., & Poldrack, R. A. (2016). The brain's gates: integrating the macrosystems of the brain to facilitate complex adaptive brain network dynamics. *Progress in Neurobiology*, 109, 102–103. <https://doi.org/10.1016/j.pneurobio.2016.01.015>
- [5] Shine, J. M., Kovicic, O., & Poldrack, R. A. (2016). Temporal metastates are associated with differential patterns of time-resolved connectivity, network topology, and attention. *Proceedings of the National Academy of Sciences*, 113(35), 9888–9891. <https://doi.org/10.1073/pnas.1604881113>
- [6] Sporns, O. (2013). Network attributes for segregation and integration in the human brain. *Current Opinion in Neurobiology*, 23(2), 162–171. <https://doi.org/10.1016/j.conb.2012.10.015>
- [7] Rasero, J., Betzel, R. F. (2016). Modular Brain Networks. *Annual Review of Psychology*, 67(1), 615–645. <https://doi.org/10.1146/annurev-psych-122414-023634>
- [8] Rasero, J., Betzel, R. F., Santis, A. I., Kravak, T. E., Gianaros, P. J., Timothy Verstynen, T. (2021). Similarity in evoked responses does not imply similarity in network states across tasks. <https://www.biorxiv.org/content/10.1101/2021.11.27.520051>
- [9] Zamani Esfahani, F., Jo, Y., Puxeddu, M. G., Merritt, H., Tanner, J. C., Greenwell, S., Patel, R., Faskowitz, J., & Betzel, R. F. (2021). Modularity maximization as a flexible and generic framework for brain network exploratory analysis. *NeuroImage*, 244, n18607. <https://doi.org/10.1016/j.neuroimage.2021.n18607>