Local and Sparse Linear Causal Models for fMRI Resting-State Signals

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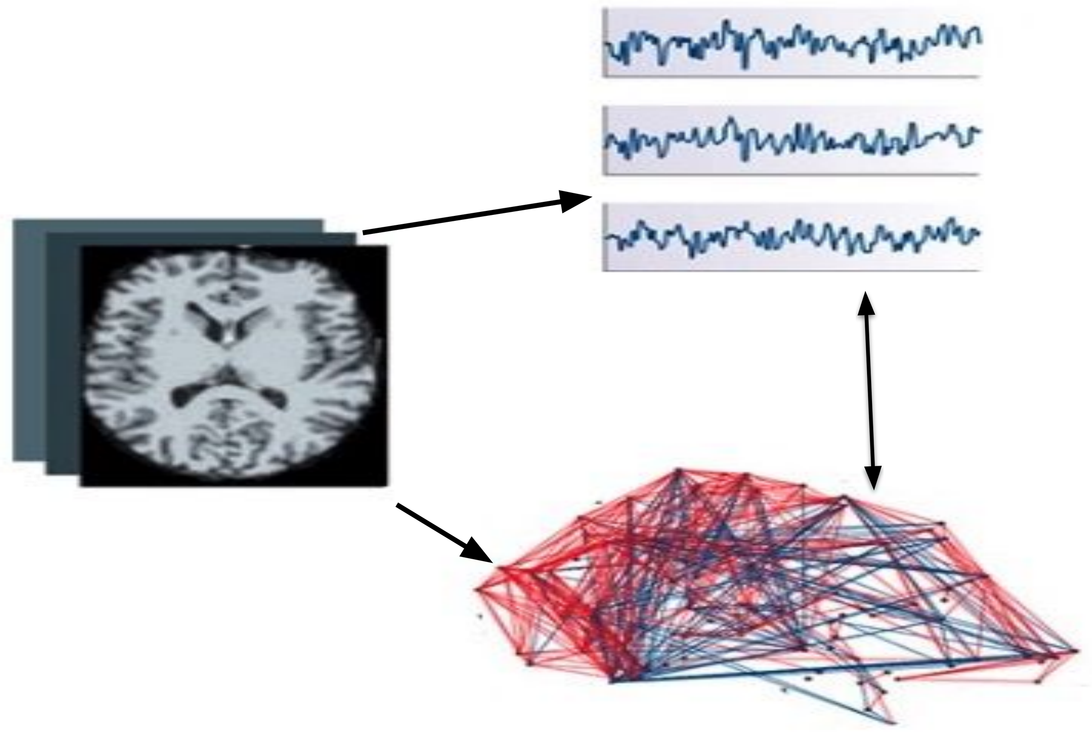


ABSTRACT

1. Modeling the human brain as a complex network (operating at many different scales) is a powerful tool to analyze both its structural and functional connections.
2. Neuroimaging techniques, such as fMRI, capture the metabolic response to neural activity within voxels encompassing hundreds of thousands of neurons.
3. Graph theory and graph signal processing provide a principled methodology to analyze the brain's functional interactions evidenced by the spatiotemporal patterns revealed by the neuroimaging.

METHODOLOGY

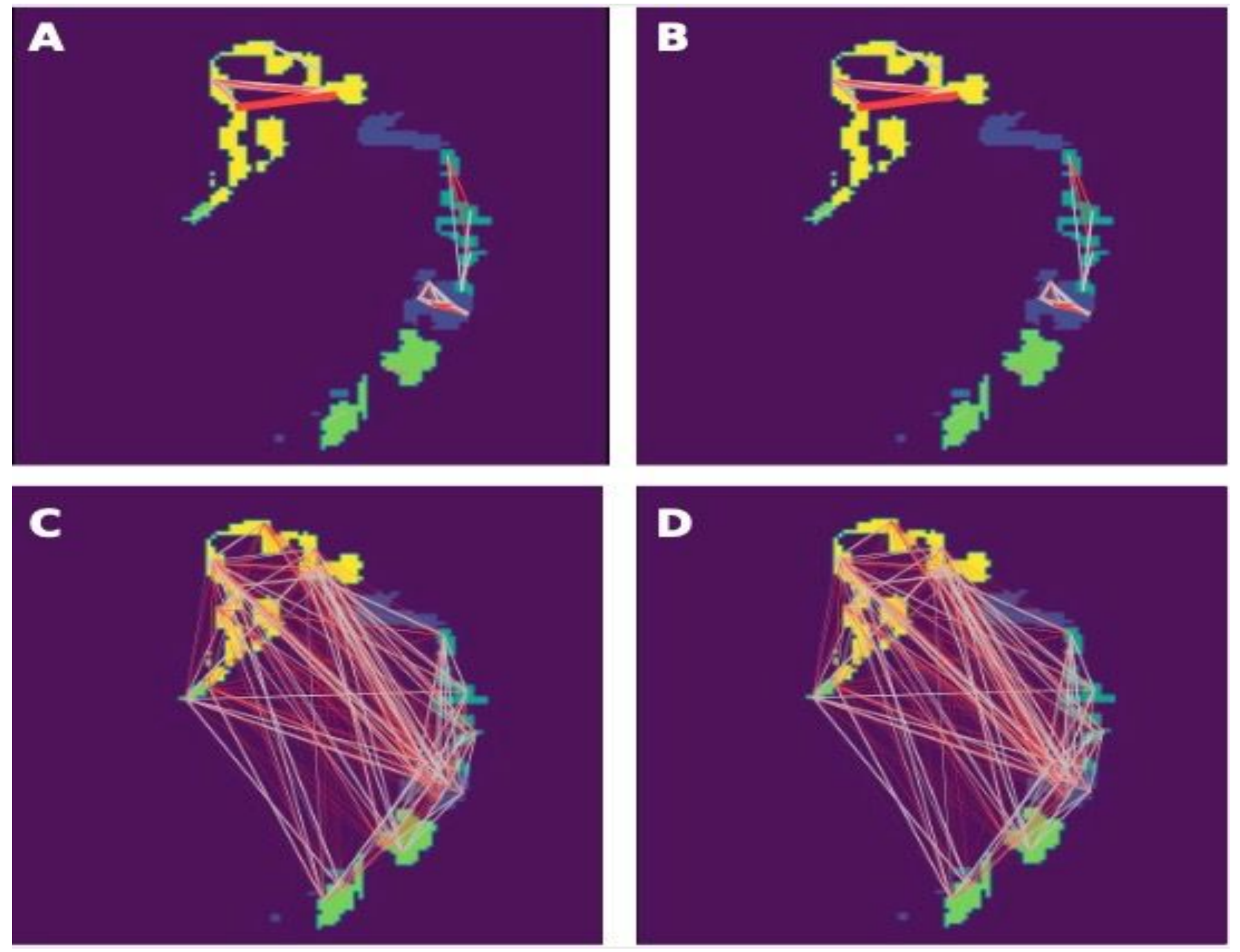
1. Since neurons interact with each other, hence voxels (i.e. nodes), we focus on analyzing the algebraic structure of the adjacency matrix using fMRI signals on the graph analyses.
2. we propose a methodology to identify a linear, first-order autoregressive model describing the causal dependence among the fMRI activity on a subset of voxels.
3. We assume the matrix of linear coefficients capturing the voxel-to-voxel interactions is a sum of two components: one low rank and one sparse.
4. We apply the low rank structure analysis to within-network voxels.
5. We then apply the sparse structure analysis on the residuals obtained after the low-rank model. In this case, we apply the analysis to all samples voxels.

$$\hat{A} = \arg\min_{A} \sum_{k=2}^{p} \|\mathbf{x}[k] - (A \circ C)\mathbf{x}[k-1]\|_2^2 + \lambda_1 \|A\|_*$$

$$R[k] = \mathbf{x}[k] - \hat{A}\mathbf{x}[k-1], \forall k \in \{2, \ldots, p\},$$

$$\hat{B} = \arg\min_{B} \sum_{k=2}^{p} \|R[k] - BR[k-1]\|_2^2 + \lambda_2 \|B\|_1.$$

FINDINGS



Low-rank connections within networks (A,B) and sparse connections between and within networks (C,D).

1. We show that our proposed methodology can model a relationship among locations in the brain in terms of dense intra-connections and sparse inter-connections.
2. Our approach is able to learn causal structure of fMRI signals during resting state.
3. The models are stable across different sessions. This demonstrates the reliability of a subsampled resting-state network measured at different times.

FUTURE WORK

We have now expanded the work to voxel-to-voxel analysis, where the main challenge is the computational power needed to optimize the linear models. For instance, the gray matter voxels are around 300,000 voxels, which means that traditional optimization methods for LASSO and trace norm regularization will not scale. Voxel-to-voxel analyses will expose the neural interaction on voxel level. Currently, we are at the stage of building the models.