Cortical Connectivity Changes Under Difficult Listening Conditions Revealed by Network Localized Granger Causality

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Introduction

- Cortical connectivity may change under difficult listening conditions
- Connectivity characterized by the temporal predictability of activity across brain regions via Granger causality (GC)
- Challenges with M/EEG: the data are low-dimensional, noisy, and linearly-mixed versions of the true source activity
- Conventional methods:

  E/MEG Data → Source Localization → GC Inference

  Drawbacks: bias propagation, spatial leakage

- Goal: directly localize GC influences without an intermediate source localization step
- Method: Network Localized Granger Causality (NLGC)
- Source dynamics as latent multivariate autoregressive model

  E/MEG Data → (Sparse) Parameter Estimation → GC Statistical Inference

Model

- MEG observation model
  \[ y_t = Cx_t + n_t, \quad t = 1, 2, \cdots, T \]
  \( y_t \in \mathbb{R}^M \)
  MEG sensor data,
  \( C \in \mathbb{R}^{M \times N} \)
  Lead field matrix,
  \( x_t \in \mathbb{R}^N \)
  Source activity,
  \( n_t \in \mathbb{R}^M \)
  Measurement noise.

- Source dynamics model
  \[ x_t = \sum_{k=1}^{n} A_k x_{t-k} + w_t, \quad t = 1, 2, \cdots, T \]
  \( A_k \in \mathbb{R}^{N \times N} \)
  Coefficient matrix,
  \( w_t \in \mathbb{R}^N \)
  Noise process.

Granger Causality

- Consider link (\( \tilde{i} \rightarrow i \))
  - Can source \( \tilde{i} \) improve temporal predictability of \( i \) ?

  \[ \mathcal{F}(\tilde{i} \rightarrow i) = \log \left( \frac{\sigma_{\tilde{x}_i}}{\sigma_x} \right) \]

  relative predictive variance explained

  \[ \mathcal{F}(\tilde{i} \rightarrow i) \gg 0 \] : GC link exists

Fig. 1. Schematic depiction of connectivity during speech processing.

Fig. 2. GC link (\( \tilde{i} \rightarrow i \)) implies temporal predictability of source \( i \) by \( \tilde{i} \).

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Parameter Estimation

- Objective: to estimate dynamic source model parameters
  \[ \theta = (A_k, k = 1, \ldots, q; \text{diag}(Q)) \]
- Challenge: source activities are unknown
- Solution: Expectation Maximization (EM)
- At the \( t \)-th iteration:
  - Perform the EM parameter estimation for full/reduced model corresponding to every source pair

Statistical Inference

- Test statistic, the debiased deviance for link \( (\hat{i} \rightarrow i) \) [3]
  \[ D_{(i \rightarrow \hat{i})} = 2 \left( \ell_i(\hat{\theta}_i^F) - \ell_i(\hat{\theta}_i^R) \right) - B(\hat{\theta}_i^F, \hat{\theta}_i^R) \]
- Hypothesis test, distributional results [4]
  - Null: \( \theta_i = \theta_i^R \) (i.e., no GC influence);
  - Alternative: \( \theta_i = \theta_i^F \) (i.e., GC influence);

Simulation Results

- False discovery rate (FDR) control
  - Reject null hypothesis at a confidence level and control FDR via BY procedure [5]
- Test strength characterization
  - Calculate Youden’s J-statistic for all links
    \[ J_{(i \rightarrow \hat{i})} = 1 - \alpha - F\chi^2(q, \nu_{(i \rightarrow \hat{i})}) (F^{-1}_\chi^2(q)(1 - \alpha)) \]
    \[ J_{(i \rightarrow \hat{i})} \approx 1 \ (\approx 0) \] implies high (low) statistical confidence
- The GC map \( \Phi : [\Phi]_{i,\hat{i}} = \begin{cases} 1, & i \neq \hat{i} \\ 0, & \text{otherwise} \end{cases} \)

Difficult Listening Experiment

- Task (see poster #71 [6]): 1-minute long speech segments from an audio book in two conditions:
  - Clean: male/ female narration
  - Mixed speech: two talker speech, male vs. female speaker
- Mixed speech task: attend to pre-specified speaker
- We analyzed the data from the first trials of these conditions

Model Specifications

- Band-passed between 0.1 – 4.5 Hz (delta band)
- Head model: morph ‘fsaverage’ source space, Desikan-Killiany atlas to identify 68 ROIs [6]
- Analyzed ROIs (in both hemispheres)
  - **Temporal** lobe
    - 'superiortemporal', 'middletemporal', 'transversetemporal'
  - **Frontal** lobe
    - 'rostralmiddlefrontal', 'caudalmiddlefrontal', 'parsopercularis', 'parstriangularis'
- We summarize the contribution of each ROI by the leading eigenvectors within the ROI
- The measurement noise covariance: empty room recordings
- Model order $q = 6$ (to fully capture the delta band)
- Sampling frequency: 25 Hz

Application to MEG Data

**Fig. 4.** NLGC estimates of neural connectivity for sites in the frontal and temporal lobes, during the last 40 s of each continuous speech listening trial, for either clean or masked speech (only significant links shown; arrows indicate direction of GC influence; N=4, FDR=1%).

- While listening to clean speech, about half (48%) of the significant causal links are frontal→frontal and about a third (32%) are top-down frontal→temporal (out of 31 significant links).
- In contrast, while listening to masked speech, almost two thirds (65%) of the 17 significant causal links are now top-down frontal→temporal, and only 12% are frontal→frontal (out of 17 significant links).
