



A Comparative Analysis of Brain Functional Connectivity and Effective Connectivity based on EEG data

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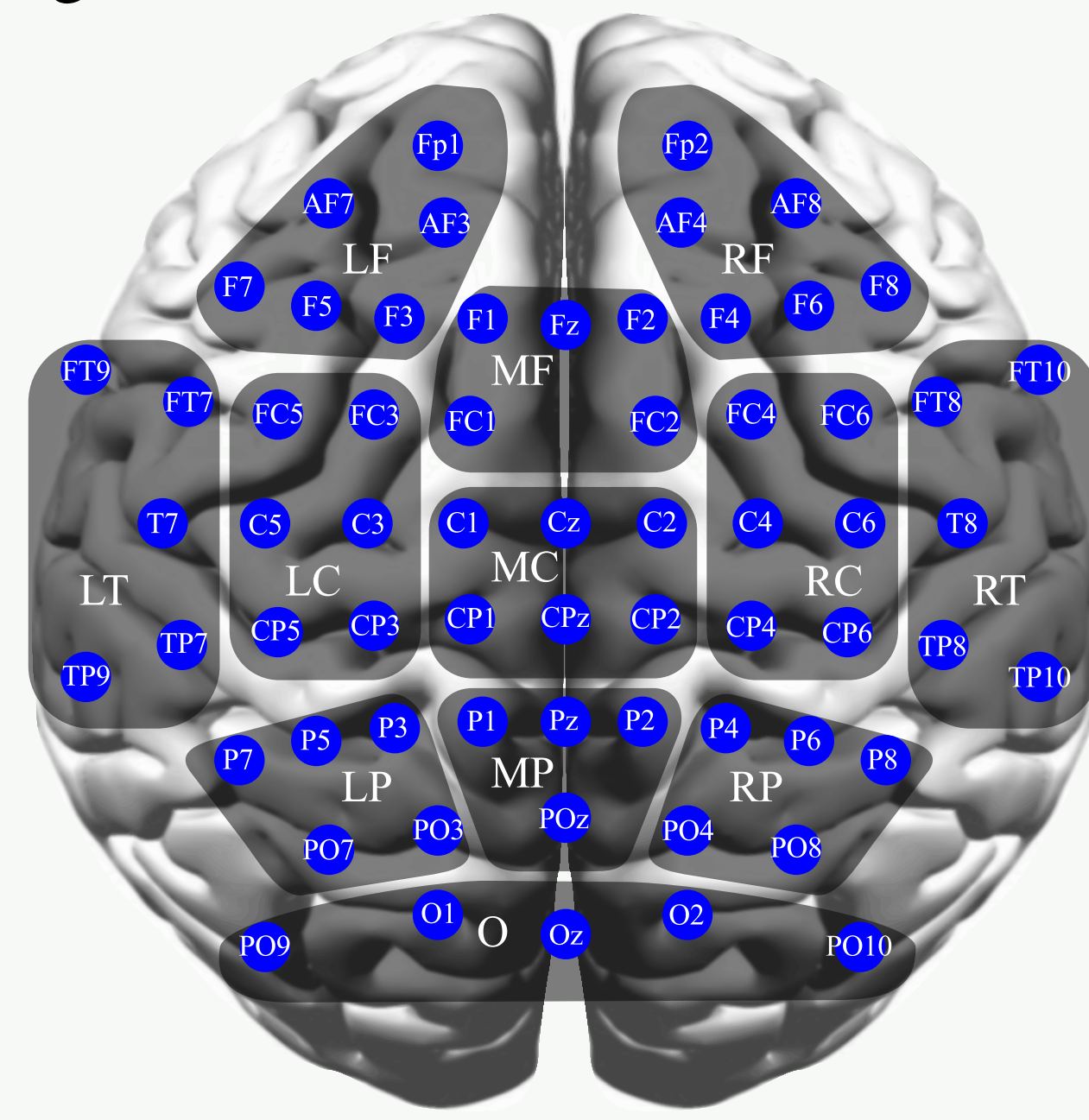


Background

- Brain connectivity is generally modeled using both functional and effective connectivity.
- Prior work on brain connectivity analysis has largely been focused on functional connectivity, which quantifies the mutual dependence between brain regions via measures of Pearson correlation, or mutual information, and is inherently non-directional.
- In this study, we present a comparative analysis of brain functional connectivity (measured using Pearson correlation) and effective connectivity (estimated via causalized convergent cross-mapping (cCCM)) based on EEG data.

Data Acquisition and Preprocessing

- We studied 56 consensus-diagnosed, community-dwelling African Americans with subjective cognitive complaints (ages 60-90 years, 28 normal controls (NC) and 28 MCI patients) recruited through the Wayne State Institute of Gerontology and Michigan Alzheimer's Disease Research Center
- Participants were asked to perform a motion direction discrimination task. Each participant was given two 3-minute resting-state EEG periods, between which they were asked to perform a motion direction discrimination task with random dot stimuli.
- Prior to further analysis, the current source density (CSD) was computed from the scalp voltage of the EEG signal for all the ROIs.



Quantifying Effective Connectivity using Causalized Convergent Cross-Mapping (cCCM)

- cCCM is a robust and effective tool for measuring effective connectivity and evaluating the directed information transfer in the brain network.
- Consider two dynamically coupled variables X and Y which share the same attractor manifold $\mathbf{M}$. Let $\mathbf{X}^n = [X_1, X_2, \dots, X_n]$ and $\mathbf{Y}^n = [Y_1, Y_2, \dots, Y_n]$ be the time series consisting of samples of X and Y , respectively.
- Construct the shadow manifolds with respect to $\mathbf{X}^n$ and $\mathbf{Y}^n$, $\mathbf{M}_x$ and $\mathbf{M}_y$.

cCCM-based effective connectivity (Cont.)

- For each vector $\mathbf{x}_t$, find its $E + 1$ nearest neighbors and denote the time indices (from closest to farthest) by $t_1, \dots, t_{E+1}$, where $t_i < t$ for $i = 1, 2, \dots, E + 1$.
- If X and Y are dynamically coupled, then the nearest neighbors of $\mathbf{x}_t$ in $\mathbf{M}_x$ would be mapped to the nearby points of $\mathbf{Y}_t$ on $\mathbf{M}$. The estimated $\mathbf{Y}_t$ based on $\mathbf{M}_x$, or say the cross-mapping from X to Y , is defined as:

$$\hat{\mathbf{Y}}_t | \mathbf{M}_x = \sum_{i=1}^{E+1} w_i \mathbf{Y}_{t_i}$$

where

$$w_i = \frac{u_i}{\sum_{j=1}^{E+1} u_j}, \text{ with } u_i = \exp\left\{-\frac{d(\mathbf{x}(t), \mathbf{x}(t_i))}{d(\mathbf{x}(t), \mathbf{x}(t_1))}\right\},$$

here d denotes the Euclidean distance between two vectors. The cross-mapping from Y to X can be defined similarly.

- As n increases, it is expected that $\hat{\mathbf{X}}_t | \mathbf{M}_y$ and $\hat{\mathbf{Y}}_t | \mathbf{M}_x$ would converge to $\mathbf{X}_t$ and $\mathbf{Y}_t$, respectively.
- The cross-mapping correlations are defined as $\rho_{cCCM}(X \rightarrow Y) = \rho(\mathbf{Y}^n, \hat{\mathbf{Y}}^n)$ and $\rho_{cCCM}(Y \rightarrow X) = \rho(\mathbf{X}^n, \hat{\mathbf{X}}^n)$ where ρ denotes the Pearson correlation.

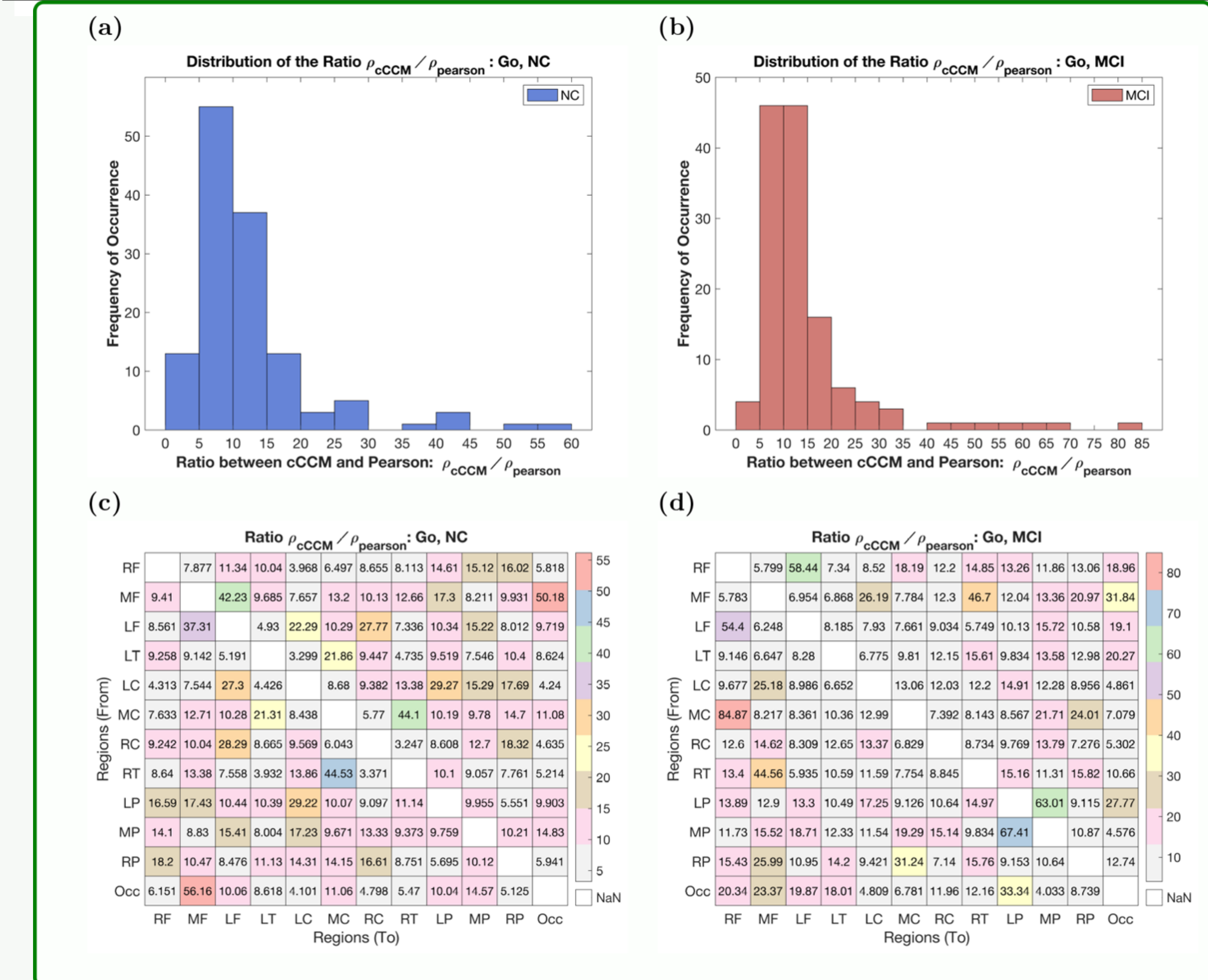
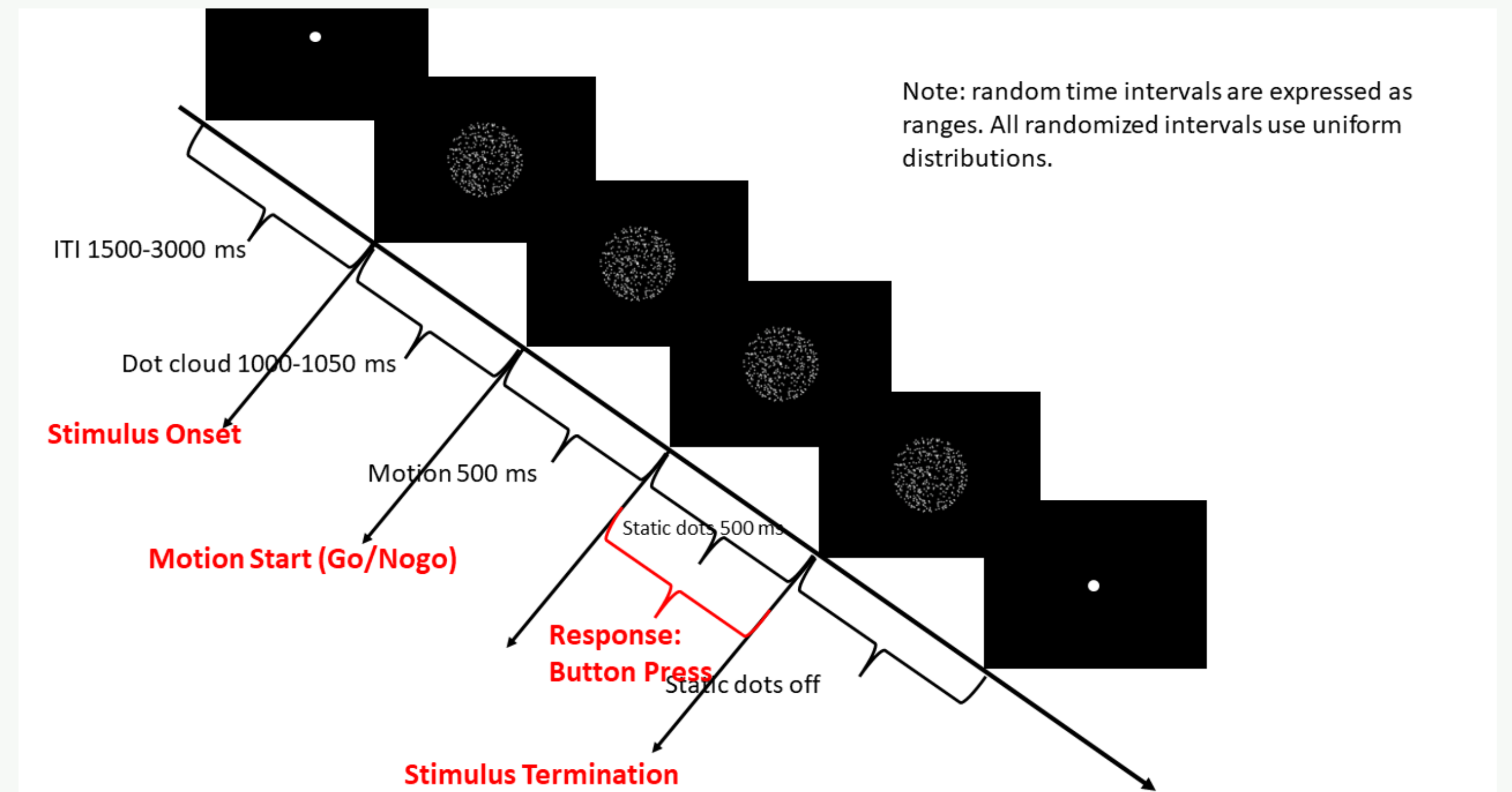
Motion Direction Discrimination Task

- The specific time period types being examined include: (i) Stimulus Onset to Go/No-Go indication, (ii) Go indication to Motion-Stop, (iii) No-Go indication to Motion-Stop, (iv) the Button-Press period.
- The cCCM-based effective connectivity and functional connectivity were evaluated across all the $12 \times 11 = 132$ region pairs
- For each trial, effective and functional connectivity were evaluated for every task period.
- Then, a comparative analysis was performed between cCCM and Pearson correlation values across all the possible ROI region pairs during all the task periods.

Results

- It was found that, across every task period, there were numerous region pairs where cCCM values were much larger than their corresponding Pearson correlation values for both NC and MCI cohorts.
- For example, for the NC group at the Go period, 119 out of the 132 directional region pairs yielded a cCCM to Pearson correlation ratio ($\rho_{cCCM} / \rho_{pearson}$) exceeding 5, while 64 pairs exceeded a ratio of 10, with one instance even reaching as high as 84.87.

Results (cont.)



Conclusions

- Overall, our study showed that cCCM-based effective connectivity can capture the directed information transfer between brain regions, which may not be captured by Pearson correlation, thus demonstrating the importance of studying brain effective connectivity as a complement to functional connectivity, and highlighting the unique advantages of cCCM as a metric of brain information transfer.