Frontoparietal power-based connectivity analysis across different frequencies during a working memory task

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Abstract—**Connectivity in the frontoparietal network of the brain has been established as marker of neural processes related to working memory. This work evaluated a power-based correlation method to investigate the frontoparietal connectivity of 13 participants during a working memory task across the theta, alpha and beta frequency bands. The power-based method showed higher connectivity of electrodes found within functional regions compared to connectivity outside functional regions of the brain across all frequencies, suggesting that the spatial resolution of this method is sufficient to assess connectivity at a functional level. The primary finding was that frontoparietal connectivity in the alpha frequency band was higher compared to the other two frequency bands, in agreement with previous research showing alpha band as a neurophysiological marker of information processing in the brain. This method may be useful to obtain physiologically relevant features of working memory to improve EEG human-machine interfaces.**

Keywords— **EEG, working memory, connectivity, alpha**

I. Introduction

Working memory (WM) refers to the brain's limited capacity to hold and manipulate information for tasks such as comprehension and learning [1]. Features extracted from electroencephalography (EEG) recordings related to WM have a real practical application in improving human-machine-interfaces [2], attention [3],and even detecting atypical brain dynamics in patient populations [4]. From a physiological perspective, the gating by inhibition hypothesis postulates that alpha modulation in EEG signals reflects how information is gated by inhibition task-irrelevant regions and routing information to task-relevant regions during cognitive tasks such as WM [5]. Specifically, alpha wave connectivity between frontal and parietal brain regions has been correlated to performance in WM tasks [6]. However, the spatial scale of this functional inhibition is still in debate [5], as neuroimaging through EEG has been shown to have low spatial resolution [7]. Furthermore, it is unclear how or if other frequency bands are also related to this processing [5]. Connectivity analyses based on the phase of the signal are sensitive to the frequency used [7], [8], usually resulting in a bias for lower connectivity estimates at higher frequencies, making them impractical for cross-frequency analyses.

To address this, establishing a method to perform cross-frequency analysis in an unbiased way with enough spatial resolution must be developed. The aim of this study was to apply a power-based connectivity analysis robust to frequency effects to evaluate inter-electrode correlations and distance relationships across the theta (4-7 Hz), alpha (8-12 Hz) and beta (13-30 Hz) bands during a WM task. Functional spatial resolution of this method was also evaluated by comparing connectivity between pairs of electrodes from within the same functional regions of the brain compared to connectivity between electrodes across different functional regions. Finally, comparisons across each frequency band were used to determine which frequency band was able to best demonstrate the connectivity of frontoparietal regions during the WM task.

II. Methods

A. Experimental Set-Up

For this study we used a publicly-available EEG dataset acquired during a WM experiment ([9]). Thirteen participants (eight female, mean age = 28 ± 3 years) were presented an array of characters on the screen for 0.5 seconds and were asked to memorize them. A test character was shown three seconds later, and the participants were to indicate if the test character was part of the first set of characters by a button press. The experiment consisted of 240 trials, and the number of set characters of each trial was randomly set to be 2, 4, 6 or 8, determining the level of memory load. Only data corresponding to correct responses were included, resulting in 2670 trials. The original experiment was performed in compliance with the Declaration of Helsinki and was approved by the University of Memphis Institutional Review board.

B. EEG pre-processing

All the pre-processing outlined in this section was performed by [9]. EEG was recorded during the 3.5 seconds of the memory retention portion of the trial using a 64-channel system sampling at 500 Hz. Ocular artifacts (saccades and blinks) were corrected in the EEG using PCA[10].. Responses were then band-passed filtered from 1 to 45 Hz using a zero-phase (two-pass) FIR filter of order 500. The 3.5 s of data were sectioned into 7 segments of 500 ms during the information retention period of the experiment.

Changes in the theta, alpha and beta frequency bands were calculated as the mean change in spectral power (in dB) from baseline for the different frequency and latencies using a Morlet wavelet transform. The number of cycles was increased from 0.5 to 13.8 for a frequency range of 1-45 Hz. Baseline power was calculated for a 2 s reference period before stimulus presentation and was extracted using the same wavelet transform and averaging the spectra across time. Power values for each of the 7 segments for the three frequency bands from each trial were used for the connectivity analysis.

C. Connectivity Analysis

For this study, we performed a power-based connectivity analysis across theta, alpha and frequency bands. Compared to phase-based metrics, power-based connectivity is better suited for cross frequency comparisons because power-based connectivity is robust to temporal jitter, reducing the bias for higher connectivity in lower frequencies [7]. For each individual trial, a bivariate Spearman correlation was performed between the power values of all electrode-electrode combinations at all three frequency bands as an estimate of electrode connectivity. Then the connectivity and inter-electrode distance relationship was investigated by fitting a first-degree polynomial to the data at each frequency band and computing their respective goodness-of-fit statistics. Electrode-electrode distances were calculated as the space between two electrodes based on their 3D coordinates using the standard 10-10 model.

To evaluate the level of correlation of each electrode with electrodes within their functional region of interest (wRoI) and with electrodes outside their own region of interest (oRoI), electrodes were grouped into seven regions, namely the left temporal (FT7, T7 and TP7), right temporal (FT8, T8 and TP8), left central (C3, C1, CP3, CP1), right central (C2, C4, CP2, CP4), frontal (F3, F1, Fz, F2, F4), parietal (P3, P1, Pz, P2, P4), and occipital (O1, Oz, O3). Correlation values for all comparisons within a functional group (e.g., P3 with Pz or C3 with CP1), and outside a functional group (e.g., P3 with CP1, or C3 with Pz) were averaged across the theta, alpha and beta frequency bands. A two-way ANOVA [factors = comparison (wRoI, oRoI), frequency band (theta, alpha, beta)] with Greenhouse-Geisser corrections was used to highlight differences in level of correlation across frequency and type of comparisons. Finally, frontoparietal connectivity across the frequency bands was assessed through a one-way ANOVA [factors = frequency (theta, alpha, beta)]. All post-hoc test were performed with Bonferroni corrections.

III. RESULTS

The correlation between paired electrode activity decreased with distance (Figure 1). Increasing distance resulted in the fastest reduction in electrode-electrode correlation in the beta band ($y = -2.19\text{x}10^{-3}(x) + 0.705$, $R^2 = 0.279$, $p<0.001$, Figure 1.A), followed by the decrease in correlation observed in the theta band ($y = -1.57\text{x}10^{-3}(x) + 0.591$, $R^2 = 0.17$, $p<0.001$, Figure 1.B) and smallest correlation drop in the alpha band ($y = -9.61\text{x}10^{-4}(x) + 0.7184$, $R^2 = 0.089$, $p< 0.01$, Figure 1.C), as indicated by their slopes.

The mean R^2 for the grouped wRoI and oRoI comparisons for the three frequencies are shown in Figure 2. The two-way ANOVA revealed a main effect of type of frequency band ($F(2) = 55.9$, $p<0.01$) and type of comparison ($F(1) = 222.69$, $p<0.01$) and no interaction effect ($F(2) = 2.04$, $p = 0.13$). Mean correlation between electrodes was significantly higher

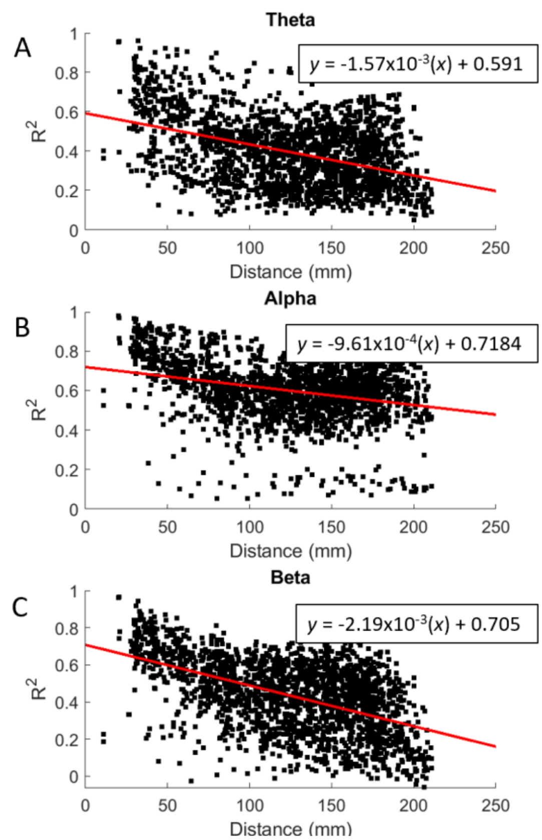

Fig 1. Inter-electrode power connectivity and distance relationships across the theta (A), alpha (B), and beta (C) frequency bands.

in the alpha band compared to the theta band in the wRoI comparisons (95% CI [-0.29 -0.08], p<0.01). For the oRoI comparisons, alpha activity had a significantly higher mean correlation compared to the theta (95% CI [-0.21 -0.19], p<0.01), and beta bands (95% CI [-0.15 -0.18], p<0.01).

Matrices of connectivity values between electrodes in different regions for theta (Figure 3.A), alpha (Figure 3.B) and beta frequency bands (Figure 3.C) are shown in Figure 3. The comparisons from electrodes in the frontoparietal regions are highlighted in red. The one-way ANOVA revealed a significant difference between the mean frontoparietal connectivity across the three frequency bands (F(2) = 37.99, p<0.001). Connectivity in the alpha band was significantly larger than in the beta (95% CI [-0.38 -0.21], p<0.01).and theta (95% CI [-0.12 -0.29], p<0.01) bands.

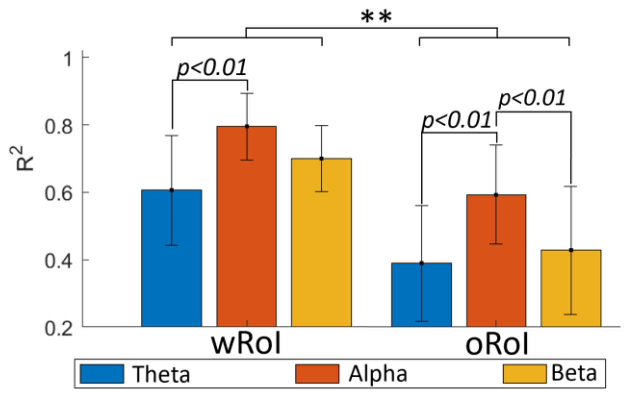

Fig 2. Mean correlation values for electrodes within the same regions of interest (wRoI) and with electrodes outside their perspective region of interest (oRoI).

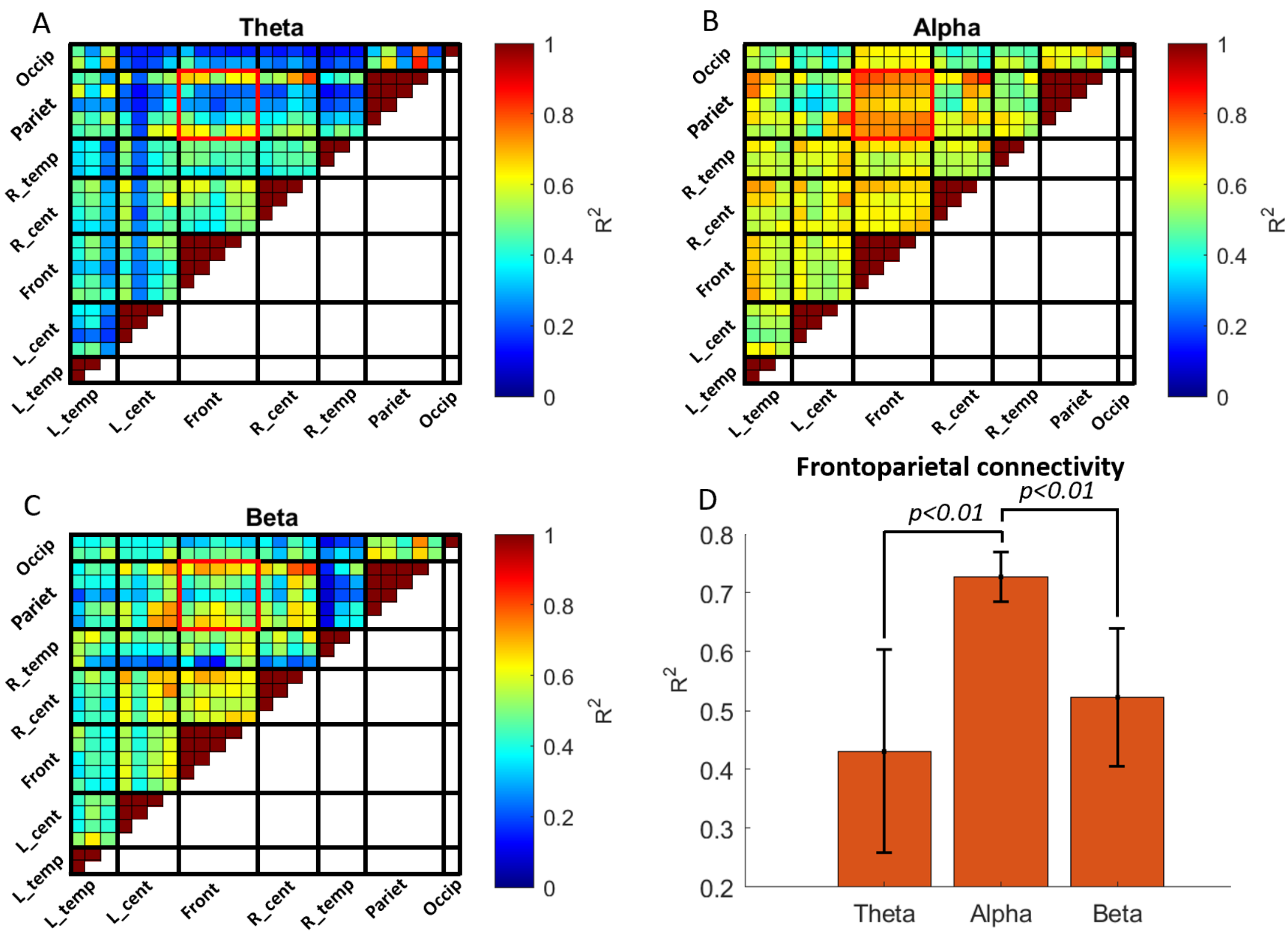

Fig 3. Electrode-electrode connectivity matrixes aross the theta (A), alpha (B), and beta (C) frequency bands, and mean frontoparietal connectivity values for all three freqeunces (D). Clusters of electrodes electrodes are ordered based on functional regions of the brain and are outlined by thick black lines (A-C).Connectivity between electrodes in the same region are filled in brown. Electrode-electrode comparisons used for the frontoparietal analysis (D) are highlighted in red (A-C).

IV. Discussion and Conclusion

Power-based connectivity in all frequency bands decreased with increasing inter-electrode distance, in agreement with previous research [11], [12]. The smallest R^2 for the fitted polynomials ($R^2 = 0.089$) was found in the alpha frequency, suggesting that the inter-electrode distance explained a relatively lower percentage in the variance of connectivity estimates in this frequency band compared to beta and theta. This is in line with the gating by inhibition hypothesis [5], as the variability of the other two frequency bands were more susceptible to inter-electrode distance effects shown by their higher R^2 values.

Our analysis also showed higher connectivity in wRoI comparisons against oRoI comparisons across all frequency bands. These results suggest that connectivity estimates based on these bands have the spatial resolution to capture how connectivity within a region differentiates with connectivity with electrodes across different functional regions.

Phase-based measures of connectivity rely on precise temporal relationships that are instantaneous (not necessarily with zero phase-lag), making connectivity estimates for higher frequency components less stable, as these are more susceptible to temporal jitter or uncertainty of timing. This results in phase based methods having a bias towards slower frequency components such as the ones found in the theta band [7]. The power-based connectivity analysis used here does not have this constraint, as it uses an estimate of power magnitude across windowed data, even allowing for the detection of relatively temporally unprecise connectivity at high frequencies. Electrodes had the highest mean connectivity in the wRoI and oRoI comparisons in the alpha band, not showing a bias towards the lower theta band, supporting the idea that power-based connectivity measures are relatively insensitive to temporal jitter during a WM task.

Mean alpha connectivity in the frontoparietal electrodes was greater compared to that observed in beta and theta bands. These results support the hypothesis that frontoparietal connectivity in the alpha band can reflect how connectivity of task-relevant areas are involved in cognitive processes related to WM [3], [5]. However, it is important to note that a limitation of this work was the limited access to behavioral data from the experiment. The analysis was performed on an open-source dataset [9] which did not contain information about accuracy or response times and therefore conclusions about the interaction of EEG connectivity, memory capacity and performance were limited.

To the knowledge of the authors, this is the first study using a power-based method to examine connectivity across different frequency bands during a WM task. Our results suggest that this power-based method was able compare cross-frequency connectivity without a low frequency bias and with a functional spatial resolution. This method can be applied to fields such as human-machine-interfaces to obtain physiologically relevant features related to cognitive processes involved in WM.

Conflict of Interest

The authors declare that they have no conflict of interest.

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