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SUMMER RESEARCH TECHNICAL REPORT

Weighted Phase Lag Index (WPLI) as a Method for Identifying Task-Related Functional Networks in Electroencephalography (EEG) Recordings during a Shooting Task

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14. ABSTRACT
Weighted Phase Lag Index (WPLI) is a methodology used to identify nonzero phase lag statistical interdependencies between electroencephalography (EEG) time series from pairs of electrodes. Identifying nonzero phase lags may be useful to identify neural interaction among regions based on the known delay for brain region-to-region communication. This project applies WPLI analysis to previously collected EEG data from a Soldier performing a shooting task. WPLI was examined on EEG data epoched around trigger pull events, which includes both brain activity and movement artifacts from weapon recoil. This functional connectivity measure was compared to a traditional time-frequency analysis at individual electrode sites. In the individual studied, WPLI identified a left lateralization in the network communication as well as neural activity from the occipital electrodes. Both of these findings were not evident in the channel-based analysis. This project suggests that WPLI may be able to detect task-related functional networks, despite artifactual contamination that is typical in real-world environments.

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Abstract

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I wish to acknowledge the mentorship of Dr. Jean Vettel, Dr. Kaleb McDowell, and Dr. Scott Kerick. I also wish to acknowledge the collaboration of Samantha Luo.

Student Bio

I just completed my junior year at the Massachusetts Institute of Technology in Cambridge, MA. I am currently studying Brain and Cognitive Sciences and Management Sciences with a minor in Economics. I have previously worked at the Columbia University in the Program for Imaging and Cognitive Sciences as a summer intern. There, I ran Volume Based Morphometry, an application of Statistical Parametric Mapping that was new to the Hirsch lab. I specifically used the program to contribute measurements of cortical volume to the project that studied the cognitive basis of social anxiety disorder. This effort resulted in second authorship on a presentation entitled "Regional differences in brain volume in panic and social anxiety disorder" that was presented at the conference of American College of Neuropsychopharmacology, 2009. I am a Science, Mathematics & Research for Transformation (SMART) scholar and look forward to joining the U.S. Army Research Laboratory (ARL), Human Research and Engineering Directorate (HRED) as a fulltime employee in the Translational Neuroscience Branch in the summer of 2012.

1. Introduction/Background

Electroencephalography (EEG) records electrical activity from the brain by placing electrodes along the scalp, and the study of this activity through EEG is a prevalent methodology used in neuroscience. EEG has several advantages over other prevalent methodologies, in that it can be used outside of the laboratory and has a high temporal resolution. EEG data have been analyzed at individual electrode sites to identify patterns of brain activity when an event occurs. However, the brain relies on communication between brain regions, so developing analysis methods to investigate brain activity between regions may provide additional information over analyzing electrical activity at single locations. Specifically, identifying the communication between brain regions that occurs during tasks may provide information regarding the cognitive processes involved in the tasks. The brain regions and their connectivity involved in this communication during a task are referred to as the task-related functional network.

One approach to identify task-related functional networks is to investigate the synchronization of neural activity between different brain regions. A common approach calculates statistical interdependencies between electrical activity recorded from pairs of electrodes. Each electrode can capture electrical data from different local regions of the brain, so the interdependencies between two electrodes may suggest neural communication. Although neural communication is fast, occurring in milliseconds, EEG has a high temporal resolution, making it a suitable method for identifying communication among brain regions. However, EEG often has a low signal-to-noise ratio based on movement and muscle artifacts. Another phenomenon that contributes to the low signal-to-noise ratio is often referred to as the volume conduction problem, when two nearby electrodes tend to pick up activity from the same source, giving rise to false correlations between the time series.

To address these problems, Stam and colleagues (*1*) introduced a measure called Phase Lag Index (PLI) to address volume conduction issues. PLI is based upon the idea that nonzero phase lag between two time series is not caused by volume conduction from a single source. Therefore, it may capture the communication between brain regions, as these communications have a delay, or a nonzero phase lag due to axonal transmission properties. The delay exists because brain regions must communicate through a physical biological medium, neurons, and thus cannot communicate instantly. PLI is less affected by common source problems than the traditional measures of functional connectivity (*1*).

However, according to Vinck and colleagues (*2*), PLI is limited by the discontinuity of phase lag estimates between zero and infinitesimally small non-zero phase lags. They claimed that both the sensitivity to noise, including volume conduction, and the capacity to detect changes in phase synchronization is hindered by the discontinuity of PLI. To improve upon PLI, the Weighted Phase Lag Index (WPLI) was introduced by Vinck and colleagues (*2*). In WPLI, the contribution of the observed phase leads and lags is weighted by the magnitude of the imaginary component of the cross-spectrum (*3*). Vinck and colleagues (*2*) demonstrated two advantages of WPLI over PLI, reduced sensitivity to noise sources and increased power to detect changes in phase synchronization.

The advantage offered by WPLI of eliminating noise in EEG data is particularly useful for Army purposes because it allows for future studies and product development based on noisy EEG data that would be encountered in real-life situations outside of the laboratory. Artifacts introduced in real-world settings seriously exacerbate the low signal-to-noise ratio, but the ability to identify cognitive activity within the noisy data may allow for discovery of cognitive processes in real-world settings. Identifying nonzero phase lag statistical interdependencies via WPLI may allow for the identification of this cognitive activity. WPLI, therefore, presents itself as a methodology to provide functional connectivity data in studies performed in real-world conditions.

Accordingly, this project applies WPLI analysis to previously collected EEG data from a Marine performing a shooting task. WPLI was computed on epochs of data surrounding the trigger pull event, which consists of both brain activity and movement artifacts from the weapon recoil. This project evaluates the use of WPLI as a method to provide functional connectivity data that identifies task-related cognitive activity not identified using traditional time-frequency analyses.

2. Experiment/Calculations

2.1 Participants

In the original study (*3*), 18 participants volunteered, and 17 of the participants were U.S. Marines and 1 was a U.S. Army Ranger. All had completed basic training and shooting qualifications. The data collected from 1 participant of the 18 was selected for analysis.

2.2 EEG Acquisition

Data were previously collected by Kerick and colleagues (*3*). Data were acquired at 500 Hz using a Neuroscan system with 34 active electrodes, including 2 horizontal and 2 vertical eye channels and 2 mastoid reference channels. These analyses use the 28 non-reference electrodes.

2.3 Task and Event Extraction

The EEG data analyzed in this paper were acquired from the participants during a simulated shooting task. The original study by Kerick and colleagues (*3*) involved eight shooting conditions. The conditions included single and dual task conditions in which the Soldier was required to perform only a shooting task or a shooting task while performing an arithmetic task; with short (2–4 s) and long target (4–6 s) exposure, and all enemy targets or mixed enemy and friendly targets (*3*) . However, this paper investigates only the condition that had a single task load, all enemy targets, and a long target exposure.

The shooting scenarios were a simulation of an outdoor shooting range at Aberdeen Proving Ground, MD, and the rifle provided to the participant was demilitarized to emit a laser beam for fire. The rifle also simulated the recoil that follows an actual shot in order to imitate the type of artifact obtained in a real-world shooting scenario. A digital terminal board sent event markers, including onset and offset times of targets, trigger responses, and target hits and misses, from the simulation system to the EEG recording system. Since all targets were enemy targets, no decision to shoot was necessary. The participant had to search for the enemy target, orient the weapon towards the target, aim, and pull the trigger.

Thirty trials of the event type in which participants aimed and shot successfully were extracted by epoching the data around the event from –3 to 2 s, where 0 s corresponds to the event marker from the digital terminal board indicating that a shot was fired at the enemy target.

2.4 EEG Pre-processing

All pre-processing, including bandpass filtering and some data rejection, was performed and described by Kerick and colleagues (*3*). EEGLab scripts were used to automatically remove bad channels. Independent components (ICs) were obtained from independent component analysis (ICA) decomposition. Those with eye movements or muscle artifacts were removed. The channel data without the eye movement and muscle artifact ICs were then analyzed.

2.5 Analysis

WPLI and time-frequency data in six frequency bands, delta through gamma, were calculated. The derived WPLI and time-frequency was extracted in the epochs surrounding the trigger pull (–3 s to 2 s). For each electrode (pair) and frequency band, significance was determined by comparing each time point (–3 to 0 s) across all 30 shots to a baseline determined by averaging across the whole data epoch. The significance level was obtained by dividing 0.05 by 501 ($p < 9.98003992 \times 10^{-5}$) to account for the chance occurrence of a significant test (Type I error). To further correct for the Type I error, at least five consecutive time points had to be significant in order to be considered a significant point grouping for WPLI and at least 25 consecutive time points were required for significance in the time-frequency analysis. The requirement for consecutive time points for significance is based on the estimated time course of communications between brain regions.

3. Results and Discussion

WPLI and time-frequency measures were calculated from EEG data acquired from a Soldier during performance of a shooting task. This project attempts to identify task-related functional networks to further understand cognitive processes that occur before the trigger pull; however, the movement artifact caused by the simulated recoil makes the signal-to-noise ratio low. A technique that is impervious to artifacts of this type may allow for identification of cognitive processes occurring concurrently with the movement artifact. In this project, we investigate WPLI to determine if task-related functional networks can be identified after removing the zero phase lag statistical interdependencies between pairs of channels. A traditional time-frequency analysis at individual channel locations is used as a point of comparison.

The channels that were identified as significant in time-frequency data are indeed different from the ones identified in WPLI. Twenty-seven groups of points were significant prior to the trigger pull in the 28 electrodes and 6 frequency bands studied using time-frequency analysis. Fifty-eight groups of points were significant in the 378 electrode pairings in the 6 frequency bands studied using WPLI analysis. In figure 1, the results are plotted on a schematic view of the electrodes on the head, where the front of the brain is located at the top of the graph (Fz). In (a), all electrodes are present and labeled on the figure in red. The Fz electrode is marked by a larger red circle. The significant channels that were identified in time-frequency data are highlighted in black. Figure 1(b) illustrates the significant channel pairs identified by WPLI with black lines between the independent electrodes. The location of each electrode in (b) is the same as in (a).

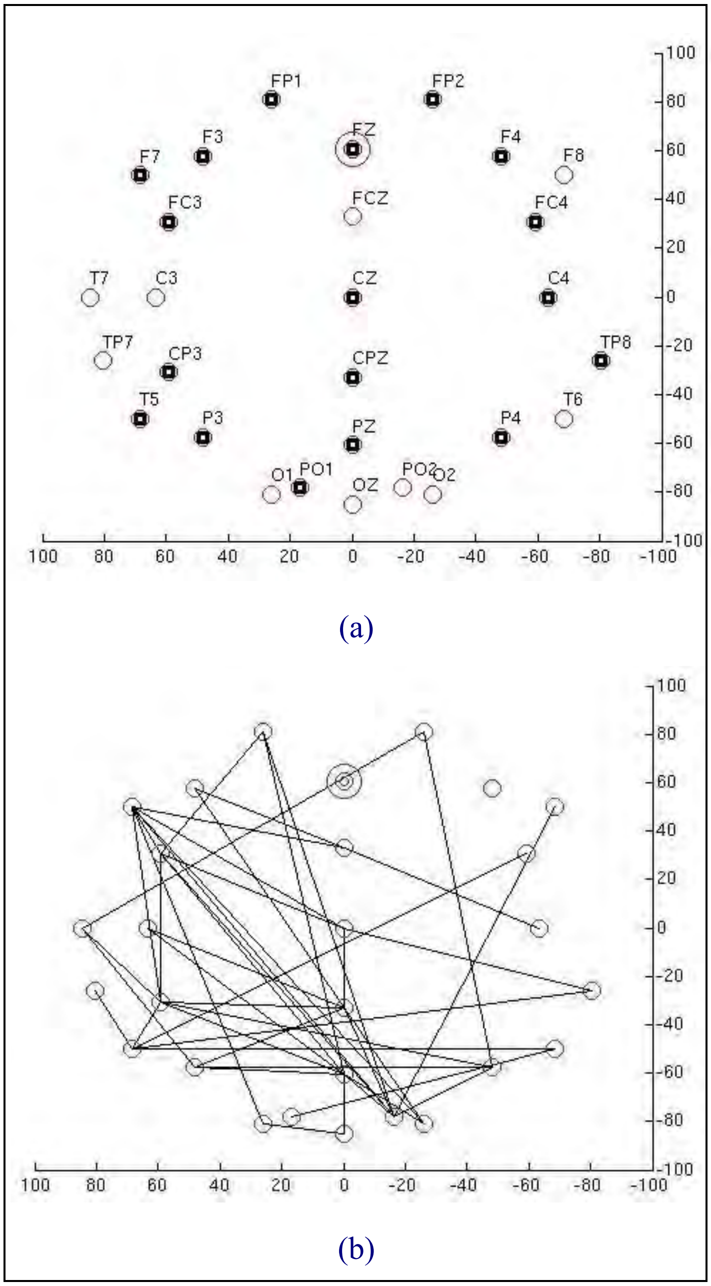

Figure 1. (a) The map of electrodes depicted highlights the electrodes with significance in black. (b) The map of electrodes depicted highlights the nonzero phase lag statistical interdependencies identified by WPLI with black lines between the interdependent electrodes. The location of each electrode is the same as in figure 1(a).

The differences between figure 1(a) and (b) highlight the additional information provided by the WPLI measure. The significance of individual channel locations indicated by the electrodes highlighted in black in figure 1(a) appears to be distributed symmetrically. However, the distribution in the WPLI analysis in figure 1(b) is more heavily localized to the left hemisphere. Interestingly, the WPLI analysis reveals a left lateralization of the paired network communication among brain regions, providing an insight not captured in the channel analysis.

The involvement of the frontal motor cortex and the parietal cortex suggests that the cognitive activity identified may be motor-spatial planning, as the frontal cortex is involved in planning and motion and the parietal cortex integrates sensory information from different modalities, particularly for spatial sense. The increased interdependencies in the left hemisphere is consistent with previous literature, as left temporal alpha power is consistently observed in marksmen few seconds before the trigger pull (*1*).

In addition to the lateralization, the WPLI analysis also revealed activity in the occipital electrodes not found in the channel-based analysis. All occipital electrodes show interaction with the F7 electrode, suggesting communication between the visual cortex and the frontal cortex. This communication may reflect that the shooting task requires planning in response to a visual target before the trigger pull. However, the possibility that communication between the occipital electrodes and the F7 electrode reflect the eye movements occurring near the F7 electrode must be addressed in further research, as this paper does not address the potential issue of brain activity correlated to muscle activity.

Figure 1 highlights the promise of WPLI to reveal network communication among brain regions. The plots show all pairs of electrodes that are statistically significant point groupings, but we were also interested in what pairs reveal an extended window of communication during the 3 s before the trigger pull. As a preliminary exploration, we plotted the four longest groups of significant periods, which are illustrated in figure 2. The blue line represents the WPLI waveform and the black lines enclosing the blue line represent the confidence interval.

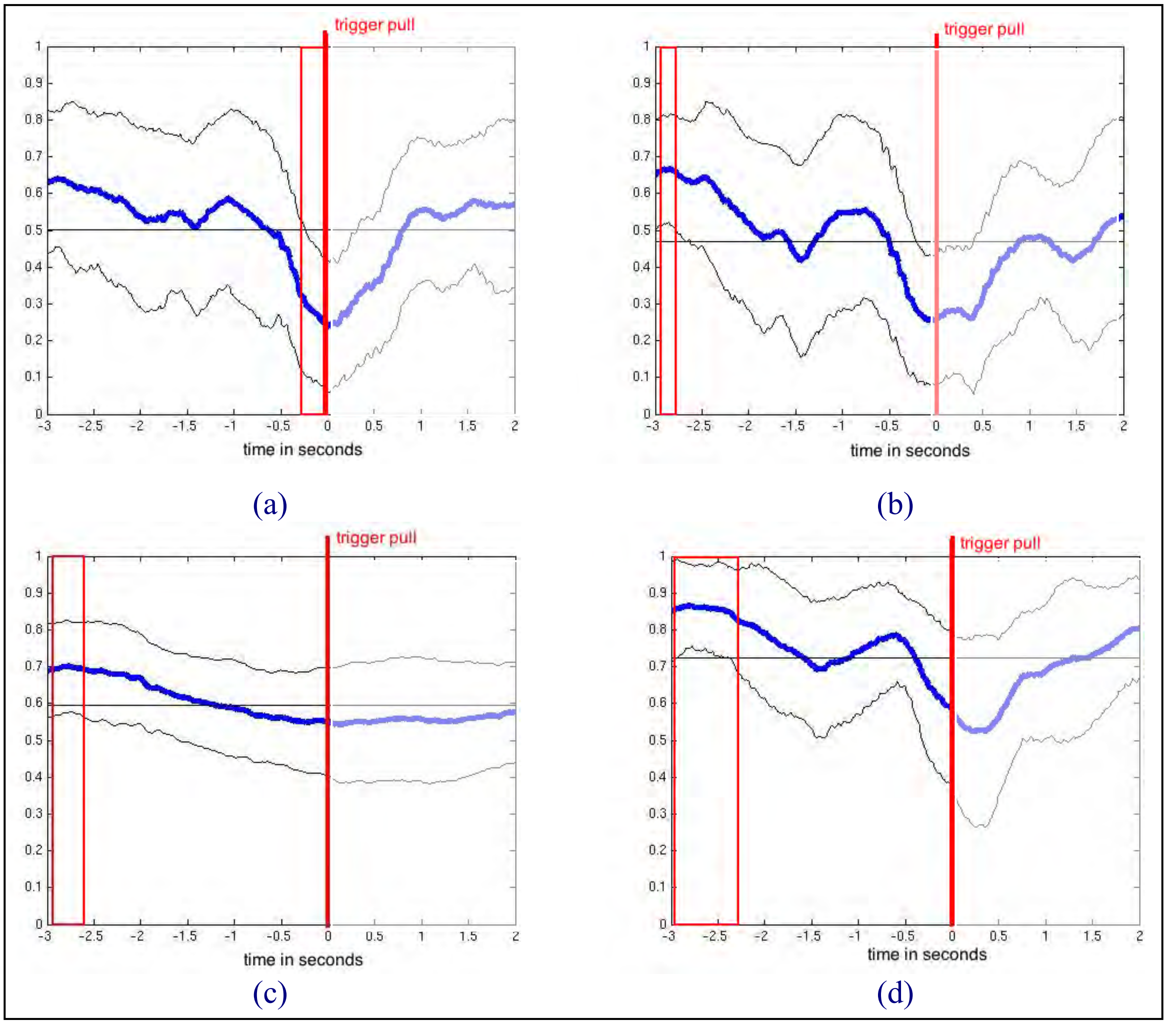

Figure 2. (a) The WPLI analysis depicted was conducted in the theta band, 4–8 Hz, on the Fz and CP3 electrode. Thirty significant points were found from 290–0 ms before the trigger pull. (b)The WPLI analysis depicted was conducted in the theta band, 4–8 Hz, on the FC3 and Pz electrode. Thirty significant points were found from 2990–2700 ms before the trigger pull. (c) The WPLI analysis depicted was conducted in the delta band, 1–4 Hz, on the F8 and P02 electrode. Thirty-two significant points were found from 2,910–2,600 ms before the trigger pull. (d) The WPLI analysis depicted was conducted in the theta band, 4–8 Hz, on the C3 and Pz electrode. Sixty-four significant points were found from 2,990–2,360 ms before the trigger pull.

All four pairs included a frontal and parietal electrode (Fz and CP3, FC3 and Pz, F8 and P02, and C3 and Pz). All waveforms follow a similar downward trend from 3 s before the trigger pull to the trigger pull. However, the first pair (2a) contains a significant point grouping immediately before the trigger pull, while the other three pairs (2b–d) contain significant groupings around 3 s before the trigger pull. Another similarity is the frequency bands in which the significant point groupings occur, as three of the four longest groups occur in the theta (4–8 Hz) band. Figure 2(c) is the only significant point grouping that occurs in the delta (1–4 Hz) band. Further analyses are needed to clarify the significance of these pairs, although these particular pairs reflect the general pattern of communication between parietal and frontal regions shown in figure 1.

There are several ways to improve on these preliminary results. Primarily, all 18 participants in the study must be analyzed. The patterns observed in the single participant strongly support the extension of these analyses to all participants. Secondly, the statistical approach may have been suboptimal. As was discussed regarding figure 2, all four waveforms followed a generally similar pattern, yet the statistical approach revealed significance at different times relative to the trigger pull. Alternative approaches conducted in all 18 participants may reveal a clearer result. Finally, this paper does not address the potential issue of brain activity that is correlated to muscle activity, which may be the case for the activity of the F7 electrode due to the electrode's proximity to the eye. However, further research is necessary.

4. Summary and Conclusions

WPLI analysis suggests that the measure may be able to capture task-related functional networks during cognitive tasks, even in the midst of large-scale movement artifacts. Further research looking across more individuals and at more tasks is needed to provide more definitive results. However, the results from this one participant support that conducting pair-wise electrode analysis in addition to individual electrode analysis may provide more information than individual electrode analysis alone. While EEG time-frequency reveals a symmetric distribution of electrodes with significance, WPLI analysis finds statistical interdependencies more heavily lateralized to the left hemisphere. In addition, WPLI reveals communication with occipital electrodes, whereas these individual channels are not marked significant in the time-frequency analysis. The preliminary findings reported here suggest that the F7 electrode may be a hub of communication, with several significant pairings with other electrodes. Therefore, the methodology used in this project shows that WPLI may provide functional connectivity data not accessible in time-frequency data. WPLI provides an interesting method for investigating how the brain performs cognitive tasks even with large artifacts in the signal, allowing for further investigation and understanding of Army tasks performed in complex environments.

5. References

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