Meditation Based Induced Changes In Spectral Dynamics and Phase-Synchronization in EEG systems

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***Abstract*— Event related spectral perturbation (ERSP) can reveal aspects of event related brain dynamics not contained in the same epoched ERP averages. To study a self-regulating attentional practice known as Mindfulness Meditation (MM), ERSP and EEG phase synchrony were used to reveal aspects of the EEG spectrum induced by MM. Four subjects participated in a two-session study completing a MM task. In the first session, they were asked to complete the MM task with their eyes open, and the second session with their eyes closed. Time frequency analysis of EEG signals for meditation showed strong event-related synchronization of beta and alpha bands during the MM motor imagery task. It also showed event-related desynchronization before imagination during resting state. Phase synchrony analysis showed marginal significance between open and closed conditions, compared to the synchrony site.**

Keywords—ERSP, Phase Synchronization, EEG

I. Introduction

Mindfulness meditation (MM) is a self-regulating attentional practice that invokes an altered cognitive state through awareness of one's internal states.1 Through consistent practice, meditation has demonstrated its efficacy in diminishing stress, alleviating anxiety, and enhancing concentration among practitioners. Body-scan meditation (BSM) emerges as an interoceptive practice, guiding individuals to focus their attention through various body locations and sensations, such as pain and muscle tension [1,2]. Prior studies have highlighted that BSM leads to increased beta and delta power during resting conditions following an 8-week BSM training period. In comparison to control groups, participants exhibit enhanced regulation of attention in the somatosensory alpha rhythm, suggesting that BSM contributes to an improved somatosensory attentional capacity. Additionally, individuals show heightened performance on the somatic signal detection task (SSDT) following brief BSM sessions, signifying an enhancement in somatic perception. While existing research delves into the effects of both short-term and long-term BSM on sensorimotor rhythms (SMR), there remains a scarcity of studies exploring the impact of BSM specifically during SMR tasks.

In meditative EEG studies, it has been found that the time-course of event-related attenuations in band-specific frequencies can be found in resting states [3]. This attenuation is known as event-related desynchronization (ERD). A well-known example of this attenuation is a reduction in occipital alpha-band EEG amplitude that normally occurs when the eyes are opened. Since MM implements motor imagery, it is possible there is cortical excitability during the MM task. EEG shows the spatiotemporal dynamics of cortical connectivity in the task at hand. Which is especially important when evaluating for phase differences in the signal. Phase Synchronization (PS) of a signal can be used to interpret functional connectivity of neural responses [4]. The Phase Synchronization Index (PSI) can be used to quantify this functional connectivity. In 2011, a new calculation of the PSI was introduced to include the weighted values [5]. This calculation has advantages due to its reduction in sensitivity to uncorrelated noise and is used to calculate PS value in this study. It has already been demonstrated that meditation tasks in EEG improve classification of accuracy of EEG patterns. This study aims to explore the specific event related spectral perturbation among different electrodes and evaluate this phase synchrony among neural populations duration MM tasks to determine efficacy of classification in future studies.

II. Methods and Materials

A. EEG Recording

In this study, four subjects participated in a 2 session recording task. Each recording lasted one hour. 16-channels worth of EEG data were recorded using BCI2000 with sampling rate at 256 Hz. These channels are displayed in Figure 1Impedance of each electrode is under 5 kΩ and saline-based electrode gel will be used to increase conductivity. The EEG montage location was inspired by the previous motor imagery experiments [6].

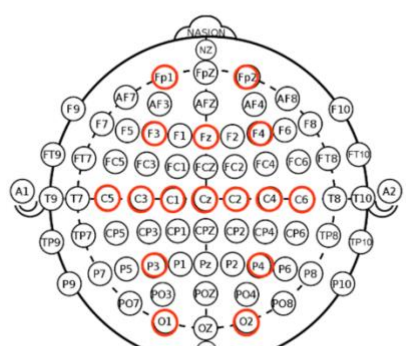

Figure 1: EEG Montage Location

B. Procedure

Figure 2 shows the experiment setup. Each session consisted of 2 parts (eyes closed [EC] and eyes open [EO]), with each part containing 6 trials. Each trial began with a 30 second resting period with no stimulus to the user followed by a 42 second guided BSM task of the left or right arm.

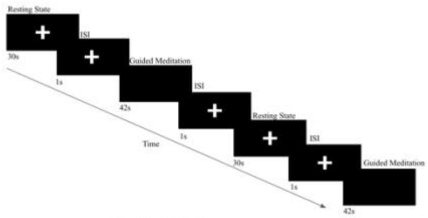

Figure 2: Experiment Design of One Run

The BSM has been directed by a recording of Yoga Nidra guiding the awareness of the subject down the shoulder to the fingers. The order of the left arm BSM and right arm BSM trials will be randomized, as will the order of the EO (i.e., focusing on fixation cross in the center of screen) or EC.

C. Analysis

The preprocessing protocol was custom-tailored for the current study, commencing with an initial EEG processing step known as the prep pipeline, which prioritizes the identification and exclusion of faulty channels. Subsequently, line noise was mitigated through high pass filtering set at 1Hz. After the removal of line noise, artifacts were meticulously eliminated through manual inspection of the data. Finally, Independent Component Analysis (ICA) was conducted, resulting in the exclusion of data instances in which over 70% comprised eye blink-related artifacts.

After preprocessing, two methods of analysis were used. The ERSP, and Phase Synchrony.

ERSP was used for spectral analysis. To compute the ERSP, each trial was divided into sub windows, and a moving average was computed from -1500ms to 2500ms for each sub window. Baseline spectra was estimated preceding the MM trial, and the spectra was obtained by dividing the mean baseline from the activity. Normalized spectra for many trials were then averaged together to get the ERSP at each electrode. We then used EEGLAB toolbox *newtimef* function to visualize the ERSP.

We used the Weighted Phase Lag Index (WPLI) to examine phase synchronization. The WPLI returns a time-based average from zero to one, with one being completely synchronized, and zero not being synchronized at all. The formula for the WPLI was calculated using the explanation of Vinck et al [5]. First, we calculated the Hilbert transform of the channel.

$$\tilde{\psi} = H(\psi_{n,t}) \tag{1}$$

Then, we computed instantaneous phase.

$$\varphi_{n,t} = \tan^{-1}(\frac{\tilde{\psi}_{n,t}}{\psi_{n,t}}) \tag{2}$$

Next, the phase difference between channels were calculated. This is calculated for each time stamp.

$$\Delta\phi_{ni,nj,t} = \varphi_{ni,t} - \varphi_{nj,t} \tag{3}$$

Lastly, WPLI was calculated over 3500ms sliding windows with 1000ms of overlap.

$$WPLI_{n_i,n_j,t} = \left| < \frac{\left|\sin\left(\Delta\Phi_{n_i,n_j,\tau}\right)\right|}{\sin\left(\Delta\Phi_{n_i,n_j,\tau}\right)} > \right| \tag{4}$$

Where $\Delta\Phi_{n1,n2,\tau}$ is a vector of phase differences spanning the 3500ms window and is the time index. The WPLI was used because of its ability to ignore amplitude and remove phase synchronization-based artifacts. Thus, only phase lagging interactions are preserved because all signals associated with temporally acute uniformly driven sources are removed from the final computation, and thus removed from consideration of processing.

III. Results

The spectral dynamics recorded through the ERSP are displayed in Figure 3.

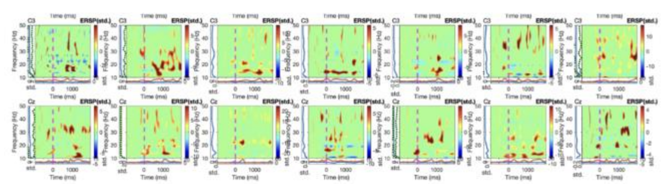

Figure 3: ERSP of electrode C3 and Cz

In this figure, you can observe event-related synchronization in the alpha band (8-12Hz) post-imagination. This synchronization is typically associated with activity of motor cortices [6] , and are well known to be associated with attention and alertness. We can also see temporally-short beta bursts occurring throughout the meditation task, which is theorized to be associated with coming in and out of the meditation state. Furthermore, pre-imagination event-related desynchronization was also observed in the alpha band focused at position C3 and Cz across all tasks.

For Phase Synchronization, the results yielded a marginally significant difference between whether eyes were open or closed, and site associated. Meaning the synchrony in which neuronal population fires plays a role in engaging one's mind in the meditation state. In other phase synchrony studies related to mediation in EEG analysis, it has been found that long-time meditators have lower phase synchronization than non-meditators, due to their ability to localize brain usage through practice. Our study did not observe whether participants were meditators.

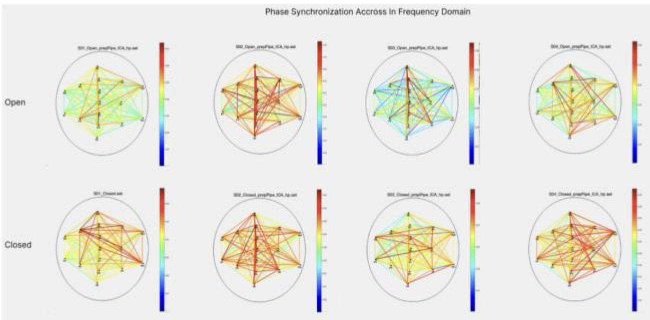

Figure 4: WPLI across all participants

Figure 4 Shows phase synchronization values across all participants for eyes open and eyes closed conditions.

Table I. The results of the two-way ANOVA using permutations on EEG Phase Synchronization Values across all frequency bands.

	df	Sum_sq	Mean_sq	F	p
Open/Closed	1	0.29	0.29	51.73	0.001
Location (Site)	255	1.79	0.01	1.27	0.001
Open/Closed:Site	255	1.63	0.01	1.15	0.06
Residual	1440	7.97	0.01		

Table 1 shows the marginal significance ($p<0.05$) of the condition and site using a two-way ANOVA. This was computed using the moving average of a 3500ms window over all trials, which yielded inter-electrode phase synchronization values based upon the WPLI.

In conclusion, the ERSP showed event-related synchronization in alpha band values and short-lasting burst in beta. The ERSP also showed event-related desynchronization in alpha band in pre-imagination phases. The WPLI showed marginal significance in differences between EO and EC conditions compared to site synchronization.

IV. Discussion

The presented study aimed to investigate the event-related spectral perturbation (ERSP) and EEG phase synchrony associated with Mindfulness Meditation (MM) to elucidate aspects of the EEG spectrum induced by this self-regulating attentional practice. The findings reveal distinct patterns of EEG activity during MM tasks, shedding light on both spectral dynamics and functional connectivity among neural populations.

For ERSP, Eskandari et al. [3] observed a similar pattern of spectral dynamics in a meditation study involving auditory cues. This backs up our findings of event-related synchronization in alpha bands, and short-lasting beta bursts in post imagination. These findings are closely related to attention, meditative state practices and activity in the motor cortices [7]. The event-related desynchronization observed in the pre-imagination phase was also observed by Eskandari. This desynchronization is likely associated with inattentiveness during rest state.

In Phase Locking Synchrony, previous studies have shown the effectiveness of classifying non-meditators versus meditators. Lehman et al. [8] recorded from experienced meditators and was able to find a global reduction in functional connectivity between site locations in different frequency bands. They found that this change was likely due to reduced processing of self-awareness. While we did find marginal significance between EO and EC conditions compared to the site, we did not collect information on whether participants were experienced meditators, or not experienced meditators. Subsequent studies should investigate the impact of WPLI specifically on individuals with extensive meditation experience, as this aspect remains unexplored in the existing literature.

While our study has yielded valuable insights into the neural correlates of MM, it is crucial to recognize various limitations that could affect the interpretation and general applicability of our findings. The small sample size and a restricted number of trials per participant pose challenges to robust data analysis, primarily due to limited data availability. As outlined in the introduction, each session consisted of six instances of left-hand meditation and six instances of right-hand meditation, totaling 12 active trials. The relatively low number of trials may have implications for the conclusiveness of our results, and a higher number of trials could have provided a more nuanced understanding based on our current findings.

In conclusion, this study has shown it is useful to decompose meditative state signals to evaluate spectral and phase synchronous patterns in EEG. This means determining meditative patterns through machine learning could be a viable classification method to determine meditative skill and state for people. Future research could include developing machine learning methods for classification of meditative states.

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