Modulation Effect of Transcranial Direct Current Stimulation on Phase Synchronization in Motor Imagery Brain-Computer Interface

Wei He, Pengfei Wei, Yi Zhou and Liping Wang

Abstract—**Transcranial direct current stimulation (tDCS) has been demonstrated that it can enhance the cortex excitability and modulate the event-related desynchronization (ERD) in motor imagery (MI). Phase synchronization is an important signature in the brain that reflects the neural interaction and integration, which has been adopted as an important EEG pattern for Brian-Computer Interface (BCI) control. In this study, we designed an experiment paradigm and investigated whether the tDCS can modulate the phase synchronization between the primary motor cortex (M1) and the supplementary motor area (SMA) in MI. Ten healthy subjects were selected and separated into two groups randomly. They performed the left and right hand MI task in two successive sessions. According to the different groups, anodal or sham stimulation were administrated to the right side of the M1. The phase locking value (PLV), which is a reliable measurement of phase synchronization in MI, was calculated. The pre and post-stimulation normalized PLV in the left hand MI task were compared. The result manifests that the normalized PLV of the entire subjects in anodal stimulation group increases after the stimulation, which shows a statistically significant difference (paired t-test p = 0.0371, n = 5). Our study reveals that the tDCS can impact the neural coupling between different brain regions and modulate phase synchronization in MI. Moreover, intervention of phase synchronization by tDCS might contribute to the rehabilitation of people with motor disorder and neurological disorders.**

I. Introduction

Transcranial direct current stimulation (tDCS) is a kind of noninvasive brain stimulation method. It supplies weak direct current to the head and selectively activates or inhibits specific cortical areas [1]. During the recent years, there is a rapid increment in the application of tDCS for research and clinical practices [2-3]. Several studies manifested that anodal tDCS is able to increase the excitability of the primary motor cortex (M1) [1, 4]. Some studies have reported that tDCS can enhance mental task performance [5], motor learning ability [6, 7] and modulate the event-related desynchronization (ERD) in motor imagery (MI) [8].

Motor imagery is one of the most popular control strategies in electroencephalogram (EEG) brain-computer interface (BCI) systems [9]. In a MI based EEG BCI system, ERD is the commonly used signal pattern representing as rhymes amplitude changes in the M1 during MI [10]. Simultaneously, synchronization of brain activity from different brain regions is an underlying mechanism of the dynamic brain, which enables the brain to accomplish various motor and cognitive functions [11]. Phase synchronization in mu rhythm (8-12Hz) between M1 and supplementary motor area (SMA) is another important EEG pattern, which has been used to differentiate multiple mental tasks [12]. Distinct phase synchronization potentially contributes to the MI tasks classification in BCI application. Our previous study has demonstrated that tDCS can enhance the ERD and facilitate the BCI control [13]. Therefore, whether the external method could module the phase synchronization is an exciting question not only for the BCI application but also for the understanding of the modulation mechanism of the tDCS. Moreover, intervention of phase synchronization by tDCS might contribute to the rehabilitation of people with motor disorder and neurological disorders, such as depression and schizophrenia [2-3]. In order to answer this question, we designed an experiment paradigm to investigate the tDCS impact on phase synchronization in MI BCI. The phase locking value (PLV) between the right side M1 and SMA, which is a common method to quantify the phase synchronization [14-16], was used to evaluate the effect of the tDCS.

A cursor movement MI BCI paradigm containing anodal tDCS stimulation was designed [13]. Two successive MI sessions were conducted by each subject. The subjects performed the first session of MI task before the tDCS, then the anodal tDCS was applied to right side of the M1, and the subjects conducted the second MI session immediately. The subjects were divided into right hemisphere sham stimulation group (RS) and right hemisphere anodal stimulation group (RA). The short term impact of the tDCS on phase synchronization was measured by the PLV difference in left hand MI task between the two successive sessions.

II. Proposed Methods

A. EEG Acquisition and Online Experimental Paradigm

Ten male right-handed-dominant healthy subjects were randomly assigned into the RA group and RS group. All participants were naïve to BCI control. Each group contains five subjects who are free of medication and mental problem. Informed consent form were read and filled up by all participants before their participation of experiment. Twenty-one Ag/AgCl electrodes involving M1 and the SMA were selected. The reference electrode was mounted between the Cz and CPz. The EEG signal was acquired using a NeuroScan SynAmps^2 amplifier with the sampling rate at 1000 Hz (see Fig. 1(a)). The EEG signal was fed into BCI2000 for online processing and analysis [17]. The

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standard cursor control paradigm of BCI2000 was used in the experiment. Subject-specific control signal electrodes and frequency were initialized using method as [18]. The online BCI paradigm with feedback was shown in Fig. 1(b). The imagination of left and right hand movement was designated to control the cursor up and down, respectively. The duration of each trial was 8 seconds with 4 seconds feedback period. During the first second, the screen was black and the subjects were in relax state. At second 1, a rectangle presented indicating the start of the task. The top right rectangle indicated the imagination of the right hand movement and the bottom right rectangle indicated the imagination of the left hand movement. At second 3, a ball appeared and the subjects were instructed to perform the MI task according the position of the rectangle. The ball moved from the left to the right at a constant speed. The vertical position of the ball was determined by the power difference between two pre-selected electrodes in subject-specific frequency band. Each session consisted of 140 trials and 70 trials per task.

B. Transcranial Direct Current Stimulation

The tDCS was administered by the Phoresor II Auto (Modal PM850, IOMED, Salt Lake City Utah, USA) for 15 minutes through rectangular saline-soaked sponge electrodes (35 cm^2). The current intensity was 1mA and the ramp time was 10 seconds. The anodal electrode was placed over the right side of the M1 and the cathodal electrode was placed over the contra-lateral supraorbital area. For the RA group, the current kept at 1mA during the stimulation period. For the RS group, the anodal electrode was turned on 30 seconds and then turned off. All the subjects were blinded to the kind of stimulation.

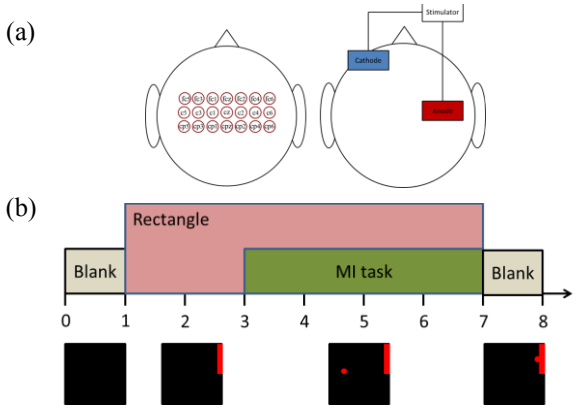

Figure 1. Experimental paradigm. (a) Arrangement of the recording and tDCS electrodes placement.(b) Structure of the online paradigm.

C. Empirical Mode Decomposition Algorithm

Because the PLV calculation requires extracting the instantaneous phase within a narrow band, we employ the empirical mode decomposition (EMD) [19] to satisfy the requirement. EMD method has been demonstrated as a useful method for phase synchrony measurement compared with Fourier analysis [20]. The EMD decomposed (intrinsic mode functions) IMFs and the residual can be expressed as:

$$s(t) = \sum_{i=1}^{n} c_i(t) + r(t) \tag{1}$$

where $s(t)$ is the recorded EEG signal, $c_i(t),\ i = 1, 2, \ldots n$ is the decomposed IMFs and $r(t)$ is the residual.

D. Phase Locking Value Calculation

All IMFs obtained from the EMD have a well-behaved Hilbert transformation. The instantaneous phase of a given signal $c(t)$ is calculated as:

$$\hat{c}(t) = \frac{1}{\pi} p.v \int_{-\infty}^{+\infty} \frac{c(\tau)}{t-\tau} d\tau \tag{2}$$

$$\theta(t) = \arctan \frac{\hat{c}(t)}{c(t)} \tag{3}$$

where the $\hat{c}(t)$ is the Hilbert transform of $c(t)$ and $p.v$ indicated the Cauchy principal value. $\theta(t)$ is the instantaneous phase.

Given two signal $s_1(t)$ and $s_2(t)$ over two electrodes, and $\theta_1(t)$ and $\theta_2(t)$ their corresponding instantaneous phases, the difference of the instantaneous phases is calculated $\Delta\theta(t) = \theta_1(t) - \theta_2(t)$. The phase difference between two electrodes is fluctuated around a value and a statistical criterion is utilized to quantify the degree of phase synchronization. Then single trial PLV is defined as:

$$PLV(t) = \left| \left\langle e^{j\Delta\theta(t)} \right\rangle_t \right| \tag{4}$$

where $\langle \cdot \rangle_t$ is the operator of moving average over a time window. In the case of two signal are completed synchronized, $\Delta\theta(t)$ is a constant value and $PLV(t)$ equal 1. If the two signals are unsynchronized, $\Delta\theta(t)$ follows a uniform distribution and $PLV(t)$ equal zero. In this study, PLV calculation was applied to the IMF2 which contains the mu rhythm. Because the anodal electrode was placed over the right side of the M1, the modulation effect of tDCS on phase synchronization in MI is evaluated by the PLV over C4-FCz in left hand MI task. A time window of 1 s was adopted for calculating the PLV and the PLV was normalized in relation to a reference period in the relax state.

III. Result

A. PLV over C4-FCz during Left and Right Hand MI Task

Fig. 2(a) shows the normalized PLV curves over C4-FCz of RA group during the left and right hand MI task. The mean normalized PLV of each subject performing MI task was illustrated in right bottom of Fig. 2(a). Each symbol represented one subject. Except the subject RA4, the normalized PLV over C4-FCz had a higher value in left hand MI task than in right hand MI task. The reason for the undistinguished normalized PLV in the left hand MI task for subject RA4 might be that he was naïve to the BCI control or he has lower right handedness than other subjects. Fig. 2 (b) showed the normalized PLV curves of RS group. The mean normalized PLV of each subject over C4-FCz had a higher value during left hand MI task than right hand MI task.

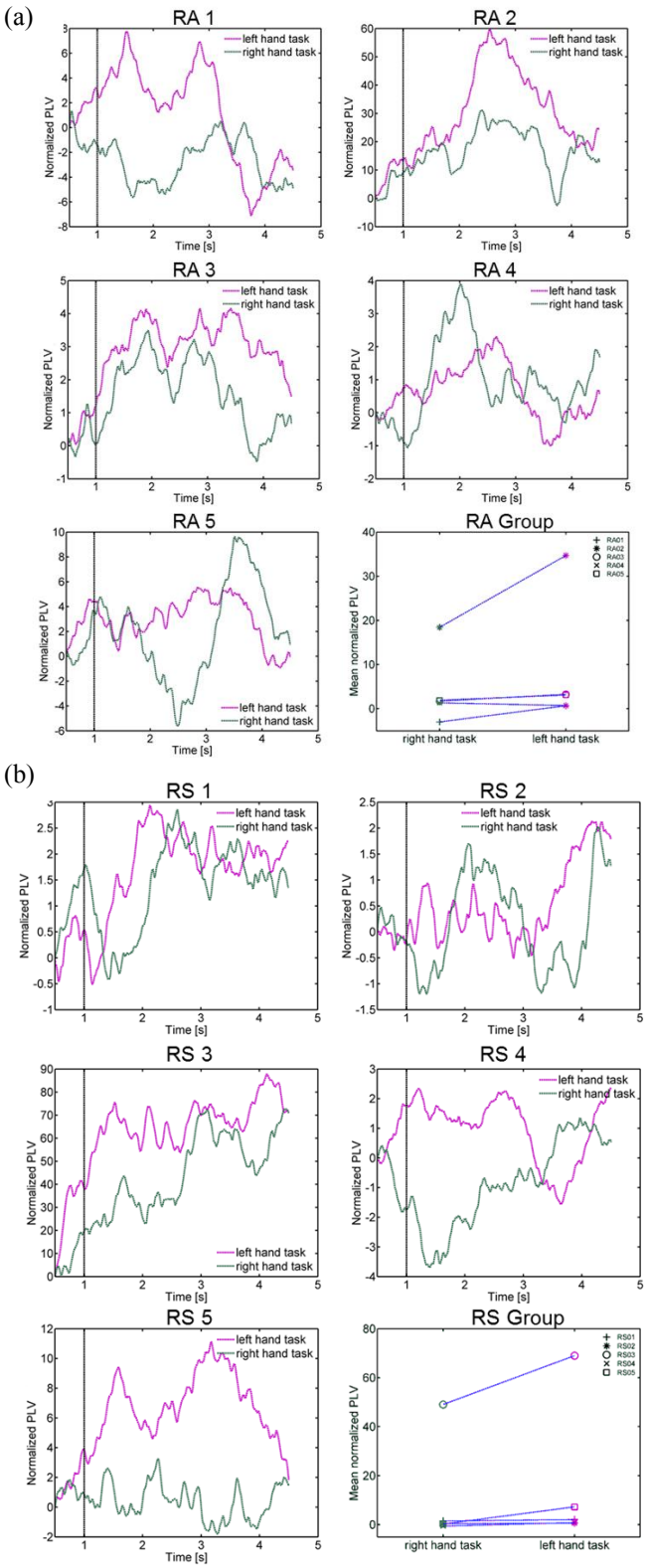

Figure 2. Normalized PLV curves over C4-FCz for RA (a) and RS (b) group. The line indicated the beginning of the MI task. The mean normalized PLV of each subject performing MI task was plotted (right bottom). Each symbol represented one subject.

B. Effect of Anodal tDCS on PLV over C4-FCz during Left Hand MI Task and right Hand MI Task

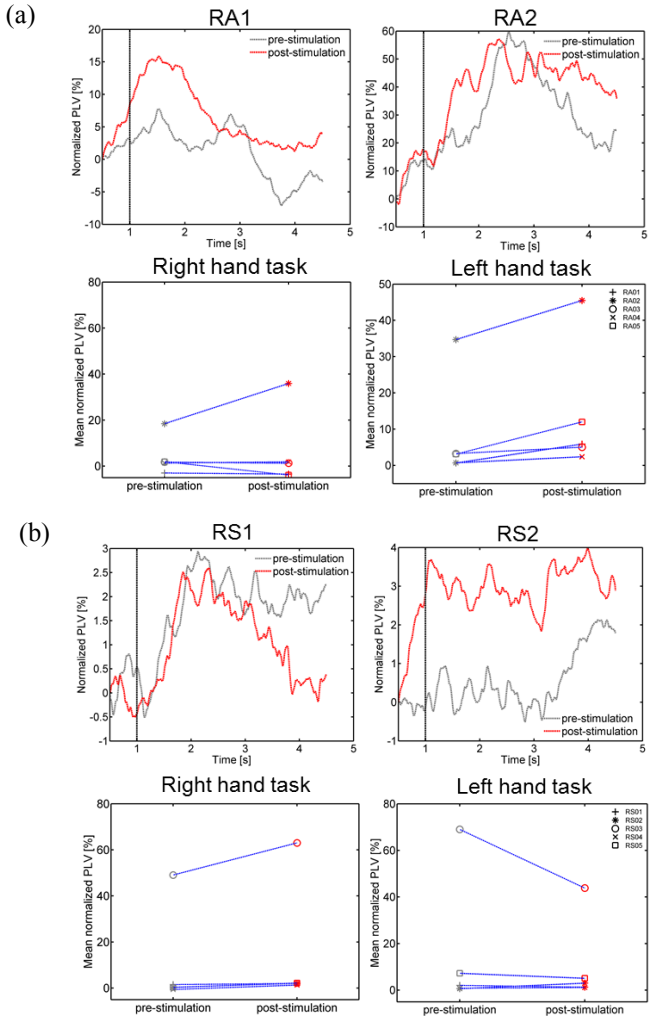

Figure 3. Normalized PLV curves over C4-FCz for RA (a) and RS (b) group pre and post-stimulation. Two representative subjects of each group are shown.

Fig. 3 shows the normalized PLV curves in left and right hand MI task for RA group. During the left hand MI task, the normalized PLV over C4-FCz of each subject showed a clear increment after the anodal tDCS stimulation, but not the right hand task. The right bottom of Fig. 3(a) displays the mean normalized PLV of each subject during left hand MI task. Each symbol represented one of the subjects in RA group. The mean increment of the normalized PLV after the anodal stimulation was 5.67% ± 1.84% (mean ± s.e.m.).

Fig. 3(b) shows the normalized PLV curves in left and right hand MI task for RS group. The mean normalized PLV of each subject in RS group were shown in the right bottom of Fig. 3(b). It presented that only subject RS2 manifested a clear PLV increment after the sham tDCS stimulation. The reason could be that the subject has learned to self-regulate the EEG pattern after the first session in order to successfully control the BCI system. The mean increment of the normalized PLV after sham stimulation was -5.07% ± 5.08% (mean ± s.e.m.).

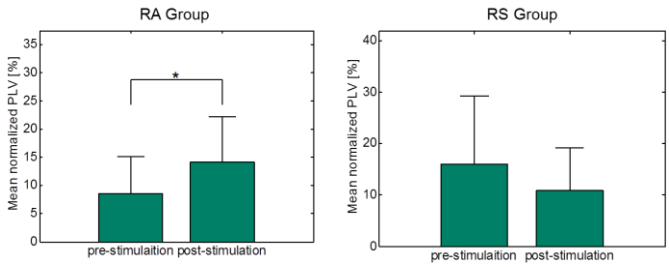

Figure 4. Comparision of the normalized PLV (mean ± s.e.m.) between pre-stimulation and post-stimulation duiring left hand task

The mean normalized PLV pre and post-stimulation in left hand MI task was presented in Fig. 4. It manifested that the normalized PLV in left hand MI task was significantly increase after the anodal tDCS stimulation (paired t-test, $p = 0.0371$, $n = 5$), but for the right hand task (paired t-test, $p = 0.621$, $n = 5$). The value has not shown a significant difference after the sham stimulation in left hand MI task (paired t-test, $p = 0.374$, $n = 5$) and right hand MI task (paired t-test, $p = 0.181$, $n = 5$)

IV. Conclusion

In this study, we investigated the modulation effect of tDCS on phase synchronization in MI. The normalized PLV between the right M1 and SMA significantly increased in left hand MI task after the anodal tDCS stimulation. It manifests that anodal tDCS can impact the coupling of the brain activities and enhance the phase synchronization in MI. The phenomenon of phase synchronization is a distinct EEG pattern during motor imagery tasks [11]. It has been adopted as an important feature for classify the different mental tasks. Therefore, a more prominent PLV feature will potentially facilitate the MI BCI classification. The increase of the phase synchronization induced by the tDCS indicates that external stimulation has effect on the brain activity in MI and might contribute to the BCI control. Moreover, the phase synchronization reflects the neural ensembles and is involved in a variety of cognitive functions. The tDCS impact on the phase synchronization could be helpful to understand the brain mechanism and explain the tDCS effect on various cognitive and motor tasks [5-8].

There are also two questions we concerned for further investigation. The first question is that whether the tDCS improvement effect on various mental tasks benefits from the neural synchrony changes. The second question is the enhancement effect on various cognitive functions caused by the long-term tDCS induced neuroplasticity changes.

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