Enhancing the Performance of P300-based BCIs by tDCS of the Left VL-PFC

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***Abstract*— It is shown that transcranial direct current stimulation (tDCS), the non-invasive neuromodulation techniques, are positively effective in boosting the performance of various types of BCI systems. The tDCS setups in previous works, however, focus on the stimulation in the locations on the scalp which, because of users' hair, requires electrolyte-soaked sponge electrodes to electrical-conductively bridge the gap between electrodes and scalp. This study proposes a more user-friendly approach by applying tDCS on the left ventrolateral prefrontal cortex (VL-PFC) which locates at the left forehead and investigate its effect on P300-based BCI systems. By comparing the performance of participants between two groups: tDCS stimulation and sham-control, the results suggest that tDCS on the left VL-PFC can increase the amplitude, reduce the latency of P300 and overall boost the classification accuracy of the P300-based BCI system.**

***Keywords*— BCI, EEG, P300, tDCS, VL-PFC**

I. Introduction

Brain-Computer Interfaces (BCI) record neural oscillations from the user's brain, interpret them and give output to the external devices in a form of computer commands [1]. Among techniques that measure the brain's activities, electroencephalography (EEG) is widely used due to its non-invasiveness. There are many types of BCI depending on what methods are used to elicit the specific brain's activities. In active BCIs, the system utilizes EEG that are acquired when users voluntarily perform some specific mental tasks. For example, EEG motor-imagery (MI) and speech-imagery (SI) based BCI utilize EEG when users imagine movements or speech commands without actually performing them [2][3]. In contrast, reactive BCIs utilize EEG that are elicited when users observe some specific stimuli. An example of reactive BCIs includes steady-state visually evoked potential (SSVEP) based BCIs which examine the changes in the frequency of the EEG oscillations that are responded to the frequency of the given visual stimuli [4]. Another well-known reactive BCI is P300-based BCI. P300 refers to an event-related potential (ERP) component that is elicited approximately 300 following the onset of the target stimuli which are presented in an "oddball" paradigm (high ratio of non-target to target stimuli) [5]. The stimuli can be visual, auditory, or even tactile. P300 is typically measured most strongly by the electrodes covering the parietal lobe and its ease of elicitation allowed it to be used in a wide range of applications including keyboard (P300 speller) [6], authentication systems [7], and even lie detection [8].

Neuromodulation is a technique that alters or modulates nerve activity. Transcranial direct current stimulation (tDCS) is one form of neuromodulatory technique. It is a non-invasive and painless brain stimulation treatment that applies a small direct electrical current to the specific area of the user's scalp to stimulate a person's brain [9]. It is believed that the electrical current from the tDCS technique alters the electrical properties of the cortical neurons which increase or decrease the neuron's excitability depending on the polarity of the tDCS electrodes, although the exact mechanism is not yet to be fully comprehensible. The tDCS equipment normally consists of a battery-powered electrical current delivering circuit and two electrodes: anode and cathode. One of the most popular setups of the tDCS technique stimulates the left dorsal lateral prefrontal cortex (DL-PFC) by placing an anodal electrode on the DL-PFC area (i.e., area located at the left eyebrow and above the hairline) and a cathodal electrode at the right forehead, the back of user's neck or the right shoulder. DL-PFC is the brain area that is responsible for human selective attention and plays an important part in human decision-making and working memory. Previous studies show that tDCS on the left DL-PFC can enhance users' vigilance and boost users' performance in many types of tasks that required a high level of selective attention or decision making [10].

The tDCS techniques have also been shown to be positively effective in different types of BCI systems. For instance, previous works have shown that tDCS can improve the performance of the MI-based [11] and SI-based [12] BCI systems in terms of classification accuracy. Some previous works also applied and examined the effect of the tDCS technique on the P300-based BCI experiment as well. Studies show that tDCS can increase P300 amplitude and help reduce the reaction time or latency of the P300 responses which normally get higher as the experiment progress due to users' mental or physical fatigue [13][14].

These studies, however, mostly focus on tDCS that applies to DL-PFC or other areas that lie underneath users' hair, hence the requirement of water or saline-soaked sponge electrodes to ensure the electrically conductive connection between the electrodes and users' scalp. This kind of electrode is inconvenient and not user-friendly, especially in BCI applications that prioritize users' comfort and wearability of the equipment. To solve this problem, we conduct P300-based BCI experiments and examine the effect of tDCS at the left ventrolateral prefrontal cortex (VL-PFC) which is located at the left forehead just above the eyebrow. We also used ready-to-use electrodes instead of the electrolyte-soaked sponge electrodes. Participants in this study were randomly assigned

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to the real tDCS group and sham-stimulation group and the differences between the experimental results of pre-stimulation and post-stimulation sessions were compared between two groups. We hypothesize that the tDCS on the left VL-PFC can improve the performance of the P300-based BCI system similar to the effect of tDCS on the DL-PFC that was shown in previous studies. The methods including the experimental protocol are described in the next section.

II. Method

A. Experimental procedure

The P300 experiments are performed in two sessions: pre-stimulation session and post-stimulation session. Each session of the experiments is intervened by 20 minutes of the tDCS session where each subject either receives the tDCS stimulation or sham stimulation. Each session of the experiments consists of three runs of the P300 experiment where the data from the first run are used as the training data and the data from the other two runs are used as the testing data. The experiments were conducted in a soundproof room without any visual or auditory distraction.

Each run of the P300 experiments consists of ten trials. In each trial. five blocks of visual stimuli were shown consecutively on the computer screen for the subject to observe. A block of stimuli contains eight pictures in which two of them are the target in the training session and only one of them is the target in the testing sessions. The stimuli are displayed in a block-randomized manner. Each visual stimulus lasts 300 ms followed by 200 ms of interstimulus interval. Experiment trials are separated with a black screen with a cross sign at the center of the screen that lasts for 5 seconds. This concludes the total of 4 minutes and 10 seconds per run of the experiments. The visual stimuli are different in each of the three runs of the experiment. In the training sessions, the target picture is a white O sign with a black background and the non-target picture is an X sign with the same background. The testing sessions, however, use random pictures with the same category as the visual stimuli in each experiment and all individual stimuli are distinctive to each other. This allows us to test the BCI performance in a wider range of applications such as the P300 authentication system where only the user knows which one is the target picture (key to unlocking the authentication system). The visual stimuli are pictures of random people, watches, cups, and chairs, in each testing experiment, respectively. Subjects were informed which picture is the target stimulus and given time to get familiar with the target picture before the beginning of each P300 experiment. They were also asked to count whenever the target is shown on the screen and minimize their movements including eye-blinking while observing the visual stimuli to reduce the motion artifacts that might occur in the EEG signal.

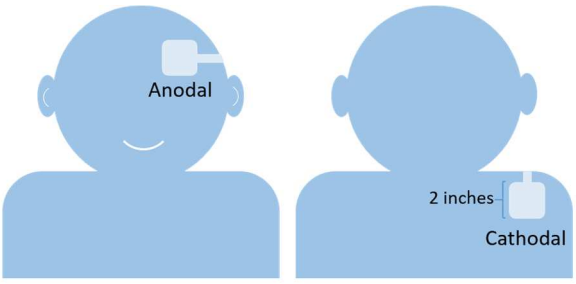


Figure 1. The electrode position for tDCS. The anodal electrode is located on the left forehead and the cathodal electrode is located on the back of the head.

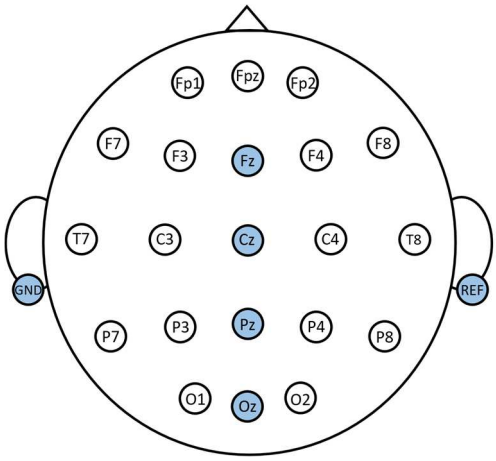


Figure 2. The electrodes positions for the 32-channel EEG acquisition. EEG signals are referenced and grounded to channel Fpz and FCz, respectively.

B. Participants

Eight people (Six male and two female) participated in the experiments of this study. Participants are 23-30 years of age. All participants were healthy and free from any neurological disorders and visual impairments. All subjects have prior experience in BCI but they have never experienced tDCS or any kind of neural stimulations before. All participants gave written informed consent.

C. Transcranial direct current stimulation

The tDCS tool used in this study was custom-made and powered by a 9V battery. The tool was able to deliver an electrical current with amplitude adjustable from 1 mA to 4 mA. The tDCS tool is controlled wirelessly using WeMos D1 mini wifi board and a relay module. Transcutaneous electrical nerve stimulation (TENS) unit pads are used as the electrodes for tDCS stimulation. The TENS unit pads are ready-to-use, reusable, and comfortable. It is also very easy to be attached and detached and does not leave any unpleasant marks or odor on the user's skin. The electrodes are 2×2 inches in size.

In this study, participants were randomly and equally separated into tDCS-stimulation and sham-stimulation groups. In both groups, the anodal electrode is attached to the left side of the participant's forehead (just above the left eyebrow) and the cathodal electrode is attached to the back of the participant's left shoulder (Figure 1). This setup of the tDCS-stimulation aims to neuromodulate the left VL-PFC of the participant's brain. The difference between the tDCS-stimulation group and the sham-stimulation group is the amplitude and the duration of the stimulation. In contrast to the tDCS-group where the amplitude of the electrical current is gradually increased and continuously delivered at 3mA throughout the whole tDCS session (20 minutes), the electrical current in the sham-stimulation group is gradually fade-in and fade-out with the maximum current of 2 mA and the duration of 1 minute. The purpose of the sham stimulation

is to serve as the control trial and to observe the placebo effect.

D. EEG acquisition

We acquired the EEG during the experiments using OpenBCI's Cyton Biosensing Board (ww.openBCI.com) with gold cup electrodes and conductive paste (Ten20). The EEG is recorded in four channels: Fz, Cz, Pz, and Oz according to the 10-20 international system. All EEG signals are referenced and ground at the right and left earlobe, respectively. The location of the EEG channels is shown in Figure 2. The sampling rate of the sensing board was 250 Hz.

E. Data processing and feature extraction

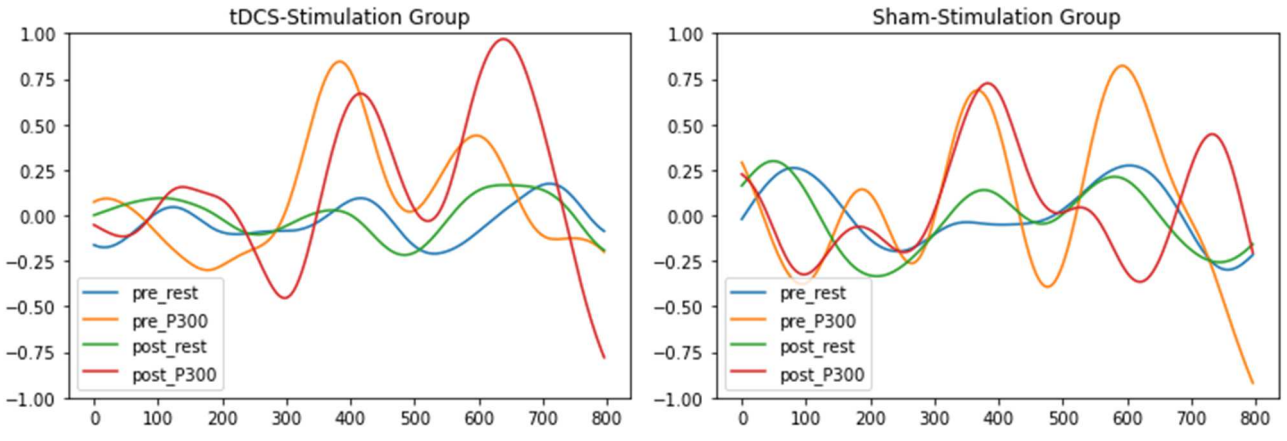
The EEG data from the experiments were first preprocessed by applying a Notch filter at 60 Hz cutoff frequency to remove the line noise and a 4th order Butterworth bandpass filter with a cutoff frequency with a range of 1 to 12 Hz. The filtered EEG data were then segmented into multiple EEG epochs and labeled to their responding class (target or non-target). Since P300 latency can be different in each person and can be delayed up to 800 ms, EEG epoch length was set to 800 ms starting from the onset of each visual stimulus. Each EEG epoch was then decimated with a factor of 10. The decimation process was performed using an 8th order lowpass Chebyshev type 1 filter to prevent the aliasing of the EEG signal and the EEG signal was downsampled by keeping only every 10th sample of the data. Finally, the feature vector that represents each EEG epoch is constructed by concatenating the decimated filtered data from each EEG channel. This concludes the total of 80 features per feature vector.

F. Classification and evaluation

Linear discriminant analysis (LDA) is used as the classification model to classify P300 data in this study. The data from the training sessions were used to train the model. Since the number of target and non-target EEG epochs are imbalanced which could cause the problem when training the classification model, the following methods were applied to fix the imbalance problem. First, the synthetic minority oversampling technique (SMOTE) was used to increase the number of samples of the target class (minority class). SMOTE randomly picks a sample and one of its k nearest neighbors and synthetically creates a sample at a random point between those two samples in the feature space [15]. The oversampling factor was set to 0.8 in this study (i.e., the minority class is oversampled so that its number of samples is 80 percent of the number of the majority class). Second, the non-target samples (majority class) were undersampled by randomly picking samples so that the number of samples of the target class is the same as the number of samples of the non-target class.

To evaluate the performance of the classification models, the trained LDA model is used to get the prediction scores (probability of the EEG epoch being a P300) from all EEG epochs in the testing sessions. We classify each trial of the experiment and calculate the accuracy using the data from one block or multiple consecutive blocks of stimuli. The trial is classified correctly, i.e., the P300 responses are correctly detected, if and only if the mean prediction score of the target epochs is higher than all of the mean prediction scores of the non-target epochs from the same picture. The result shown in the next section will demonstrate that the classification accuracy is increased when more blocks of stimuli are used in the classification. It should be noted that because the SMOTE and the random undersampling method can produce different outcomes in each run, the whole classification process was repeated ten times and the averaged results were used as the final classification result.

After all classification processes for all participants' data are done, the accuracy between the pre-stimulation and post-stimulation sessions is compared. Finally, the differences in the classification result between pre-stimulation and post-stimulation sessions are compared between the tDCS-stimulation and the sham-stimulation group to see the effect of the tDCS-stimulation on the left prefrontal cortex in P300-based BCI system. In addition, the grand averaged P300 EEG epochs between the pre-stimulation and post-stimulation of the two groups are obtained to observe any changes in the ERP including the amplitude and the latency of P300 as well.



(a) (b)

Figure 3. The four type of EEG epochs: rest and P300 EEG epochs in pre-stimulation session (labeled as pre_rest and pre_P300 respectively) and post-stimulation session (labeled as post_rest and post_P300, respectively) grand-averaged across all participants in (a) tDCS-stimulation group and (b) sham-stimulation group. Both group show clear P300 responses at the latency between 300ms to 800 ms.

Table 1. The numerical result (% classification accuracy) of P300-based BCI experiments in both pre-stimulation session and post-stimulation session of all participants in tDCS-stimulation group (S1 to S4) and sham-stimulation group (S5 to S8) Differences between the results from the pre-stimulation and post-stimulation session (Δ) are calculated from the average result of all participants in the same group and shown in the last row.

tDCS-group	Session	Number of block of stimuli					Sham-group	Session	Number of block of stimuli				
		1	2	3	4	5			1	2	3	4	5
S1	pre	61.00	76.00	74.00	76.50	78.50	S5	pre	67.00	81.50	87.00	86.50	87.00
	post	56.50	83.50	82.00	83.00	87.50		post	62.00	72.50	77.50	77.50	86.00
S2	pre	59.50	74.00	72.50	79.00	82.00	S6	pre	59.50	75.00	91.00	90.00	90.00
	post	48.50	69.50	75.50	82.00	84.00		post	52.50	65.00	75.50	79.00	85.00
S3	pre	67.50	71.50	69.00	72.50	78.50	S7	pre	47.00	63.00	82.00	80.50	81.00
	post	61.50	77.00	80.50	87.50	92.00		post	44.50	57.00	69.50	71.00	77.00
S4	pre	70.00	77.50	75.00	81.50	80.50	S8	pre	55.00	66.00	89.00	88.00	92.50
	post	65.50	73.00	75.00	81.50	82.50		post	59.50	65.50	79.50	82.00	89.50
Avg	pre	64.50	74.75	72.63	77.38	79.88	Avg	pre	57.13	71.38	87.25	86.25	87.63
	post	58.00	75.75	78.25	83.50	86.50		post	54.63	65.00	75.50	77.38	84.38
	Δ	-6.50	1.00	5.63	6.13	6.63		Δ	-2.50	-6.38	-11.75	-8.88	-3.25

III. Results and Discussion

A. P300 EEG epochs

Figure 3 shows the grand average of four different types of EEG epochs across all subjects in tDCS-stimulation groups (Figure 3a) and sham-stimulation groups (Figure 3b). The four types of EEG epochs are rest EEG epochs from the pre-stimulation session, P300 EEG epochs from the pre-stimulation session, rest EEG epochs from the post-stimulation session, and P300 EEG epochs from the post-stimulation session. From the figure, we can see that all grand-averaged P300 EEG epochs from both pre-stimulation and post-stimulation sessions in both groups have higher potential than the averaged rest EEG epochs at approximately 300 ms to 800 ms. This proved that the visual stimuli in our experiments were able to evoke the P300 responses in the EEG of the participants. To examine the effect of tDCS stimulation on the amplitude and latency of the P300s, the differences between the averaged maximum amplitude and latency of P300s of the pre-stimulation session and the post-stimulation session of both groups are calculated. In the tDCS-stimulation group, three out of four participants show an increment in the amplitude of P300 (23.83% on average) and a decrement in the latency of P300 (28.13% on average) but the other participant showed a big decrement in the average amplitude of P300 (36.95%) and an increment in the latency of P300s (50.48%). In the sham-stimulation group, however, the differences between amplitude and latency of P300 of the two sessions are random among the participants.

B. P300 experiment

Table 1 shows the classification accuracy (according to the number of the block of stimuli used to calculate the result) of both pre-stimulation and post-stimulation sessions of all participants from both tDCS-stimulation (S1 to S4) and sham-stimulation (S5 to S8) groups. First of all, as we can see from the result table, the classification accuracy increases when more block of stimuli is used in the calculation. When using all five blocks of stimuli, participant S8 shows the highest classification accuracy among all participants (92.50%) and participant S7 shows the poorest result (77.00%). To examine the effect of tDCS on the performance of P300-based BCI experiments, we compare the differences between the results of the pre-stimulation session and post-stimulation session of the two groups. From the results, we can see that when using all blocks of stimuli (which mostly gives the best result in each participant), all participants in the tDCS-stimulation group have higher performance in the post-stimulation session while all participants in the sham-stimulation group have lower performance in the post-stimulation session. Precisely, the average performance in the tDCS-stimulation group increases by 6.63% but the performance in the sham-stimulation group decreases by 3.25% in the post-stimulation session. The reason that the performance in the post-stimulation session is lower than the pre-stimulation in the sham-stimulation group might come might be due to the fatigue from the long experiment sessions. In other words, apart from the possible effect on the amplitude and latency of the P300 discussed in the previous subsection, tDCS stimulation might boost the user's ability to concentrate on a specific task. This theory corresponds to the previous works on the effect of tDCS that enhance the user's vigilance when applied to the left DL-PFC.

The results from this study suggest that applying tDCS stimulation on the left VL-PFC yields a similar effect to when applying tDCS stimulation on the left dlPFC in boosting the performance of the P300-based BCI experiment. This finding benefits the BCI research especially in ones that aim to design wearable BCI systems which prioritize users' comfort. Nevertheless, this current study is only a preliminary study that conducted the experiments on only eight participants (four in each group). A higher number of participants is needed to perform a statistical test and draw any conclusion on the effect of tDCS stimulation to the left VL-PFC in the performance of the P300-based BCI experiments.

IV. Conclusion

This study examined the effect of tDCS stimulation on the performance of P300-based BCI experiments. Unlike previous works that apply the tDCS stimulation on the left DL-PFC, this study applied the stimulation of the left VL-PFC (area on the users' left forehead) which is more comfortable and user-friendly. From the results of the study, not only that the increment and decrement in the amplitude and latency of P300 in the grand-averaged data can be observed, the classification accuracy of the P300-based BCI experiment improves in the post-stimulation session in the participants from the tDCS-stimulation group. The result of this study suggest that tDCS stimulation on the left VL-PFC can boost the performance of P300-based BCI experiment, however, a

higher number of participants and more experiments are needed to make any statistical conclusion.

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