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Can SSVEP be modulated by tDCS?

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Introduction: Steady-state visual evoked potential (SSVEP)-based brain-computer interface (BCI) is one of the representative reactive BCI paradigms [1]; however, it has been frequently reported that non-negligible numbers of individuals have difficulty in using SSVEP-based BCI systems due to the low signal-to-noise-ratio (SNR) of SSVEP responses for specific stimulation frequencies. Many studies have strived to overcome the so-called "BCI illiteracy" issue by introducing new visual stimuli or classification algorithms, but it still remains a challenging issue to be addressed for the commercialization of SSVEP-based BCI. In this study, inspired by a recent report that transcranial direct current stimulation (tDCS) can modulate visual evoked potentials [2], we investigated whether the representative features of SSVEP-based BCIs such as SNR, amplitude, and canonical correlation analysis (CCA) coefficient can be modulated by tDCS, especially for individuals with low-SNR SSVEP.

Materials, Methods and Results: Twenty healthy subjects volunteered to participate in our study, three of whom were excluded due to severe noises and artifacts included in the recorded EEG data. Each participant participated in two double-blinded experiments - an actual tDCS experiment (2-mA anodal stimulation for 20 min, anode: Iz, cathode: Cz) and a sham tDCS experiment (2-mA anodal stimulation for 1 min) - conducted on different days. The second experiment was conducted at least one month after the first experiment in order to avoid any possible training effect and post-tDCS effect. On each day, SSVEP responses were recorded right before and after the randomly assigned actual or sham tDCS session, using six EEG electrodes (Oz, O1, O2, POz, PO3 and PO4). In each SSVEP session, one trial consisted of 2-s fixation, 10-s SSVEP stimulation, and 7-s resting periods. Checkerboard pattern-reversal visual stimuli with frequencies of 5, 6, and 7.5 Hz were presented 15 times in a randomized order for each frequency. After high-pass filtering at 1 Hz, amplitudes, SNR values, and CCA coefficients for three stimulation frequencies were evaluated, and then each feature was averaged over channels.

Total 204 datasets (17 subjects x 3 frequencies x 2 sessions (pre- and post-tDCS) x 2 conditions (actual and sham tDCS)) were processed according to the procedure explained below. First, we gathered pairs of pre-tDCS and post-tDCS SSVEP datasets of which the initial SNR (i.e., SNR of pre-tDCS SSVEP) was lower than a certain threshold (e.g., SNR < 1.6). We then evaluated the statistical differences in the amplitudes, SNR values, and CCA coefficients of the SSVEP datasets recorded before and after the actual/sham tDCS using the paired t-test. We repeated this procedure while varying the threshold value from 1.5 to 2.5.

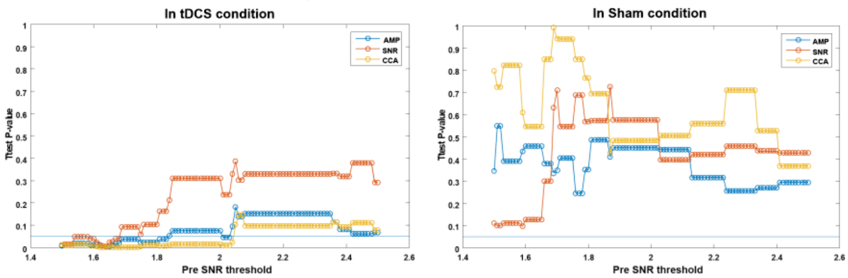

Figure 1. *Changes in p-values with respect to the pre-SNR threshold: (Left) actual tDCS; (right) sham tDCS*

Results: Experimental results showed that 20-min anodal tDCS can significantly enhance not only the spectral power, but also SNR and CCA coefficient of SSVEP responses especially when the SNR of the initial SSVEP is low (Figure 1). The difference in the CCA coefficients remained statistically significant even for SNRs as high as 2. No SSVEP features showed statistically significant changes after sham tDCS.

Discussion: tDCS has the potential to be used to enhance the overall performance of SSVEP-based BCI systems, especially for individuals who do not respond to specific visual stimulation frequencies.

Significance: To the best of our knowledge, this is the first study that reported the enhancement of SSVEP responses after tDCS.

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