Differential Effects of tDCS on Visuospatial Working Memory Performance under Fatigue

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Introduction

Transcranial direct current stimulation (tDCS) of the left dorsolateral prefrontal cortex (dlPFC) has been shown to promote working memory (WM), however, its efficacy against cognitive fatigue-related performance declines remains uncertain. In this article we report a subset of our observations from a larger study that examined the impact of anodal tDCS of the left DLPFC on visuospatial WM under cognitive fatigue. Specifically, we highlight the differential impact of tDCS on individual WM performance contingent on their baseline WM capacity.

Methods

We employed a repeated-measures design, with participants returning on separate days to perform a WM test under *control*, *anodal tDCS*, and *sham tDCS*. 32 participants completed the study (16 female). The participants were cast into three sex-balanced groups to counterbalance learning between conditions. In each session, participants completed a 60-minute visuospatial two-back test, divided into 12 five-minute blocks, with participants responding to subjective questionnaires between each block. All procedures were approved by Texas A&M University's Institutional Review Board and participants provided written informed consent before the start of experiments.

Participants were instructed to track the position of a circle within a 3x3 grid; If the position of the circle matched the one from two steps prior, they responded with a keypress. The inter-stimulus-interval was 1s with a persistence time of 900ms. The two-back match probability was set to 0.5. Before starting each session, participants were allowed to practice for a minimum of five minutes, under a training mode.

In these experiments, stimulation was provided during the sham and anodal tDCS conditions. A 1x1 tDCS device (Soterix Medical, NY, USA) was used with cathode over the right supra-orbital region (FP2) and the anode over the left dlPFC (F3) in accordance with the 10-10 EEG system. The current intensity was set at 1 mA, and the current density was 0.028 A/m^2 (area = 5x7 cm^2). Under anodal tDCS, the stimulation duration was 10 minutes at set point (1 mA); under sham tDCS, there was a ramp to set point followed by a ramp to 0 mA, lasting a total duration of 20 s. The stimulation onset time was the same for both conditions, i.e., at the start of the fifth block (Karthikeyan & Mehta, 2020).

We rely on performance accuracy to characterize outcomes on the WM test. In addition, participants were stratified on the basis of their baseline WM, i.e., we averaged block 1 accuracy across all sessions and participants; individuals with a mean accuracy greater than or equal to the median at baseline were labeled 'HIGH' performers, while those below the median were labeled 'LOW' performers. For statistical analysis, the data was grouped into five phases: I-V such that phase I-IV consisted of two blocks each, and phase V was made of three blocks, with each block lasting exactly five minutes. We found that the working memory performance measures were not normally distributed, therefore, we relied on the non-parametric Friedman's test to assess the effect of condition on the stratified measures.

Results

On performance-baseline based stratification, under anodal tDCS, we found a significant effect of time in both 'HIGH' and 'LOW' performers (all $p<0.0001$; $k_w \in [0.124, 0.212]$). Notably, we observed improvements in performance accuracy during stimulation (all $p < 0.0017$). This improvement, relative to baseline, persisted until the terminal phase, when accuracy returned to baseline levels in 'LOW' performers and dropped to a level below baseline in 'HIGH' performers. The improvement in performance accuracy from phase II-III displayed a larger magnitude change in 'LOW' performers than in 'HIGH' performers, although both were found to be statistically significant going from phase II-III (all $p < 0.0001$). Under sham tDCS, we note that 'LOW' performers do not exhibit a significant effect of time ($p > 0.53$), however they continue to perform substantially worse than their 'HIGH' performing counterparts at all time points (all $p < 0.032$). The 'HIGH' performers exhibited a statistically significant decrease in performance accuracy from phase II to V, with substantial decreases in magnitude concomitant with the stimulation onset interval i.e. phase III. Under the control condition, 'LOW' performers continued to perform poorly with respect to their 'HIGH" performing counterparts, however, from phase I to II they displayed an improvement in accuracy ($p=0.0017$). The 'HIGH' performers showed a gradual decrease in performance level from phase I to V, with a significant decrease in accuracy across phase pairs I-II, II-III, and IV-V (all $p<0.0001$; $k_w \in [0.124, 0.212]$).

Discussion

We found that both 'HIGH' performers and 'LOW' performers were tangibly aided by anodal tDCS. These improvements were seen to last beyond the stimulation interval for both groups, however, the magnitude change in accuracy was greater for 'LOW' performers. Prior evidence points to a preferential effect of tDCS in novices compared to experts, with experts not shown to benefit from tDCS under some conditions (Toth, Ramsbottom, Constantin, Milliet, & Campbell, 2021). Researchers reason that this is likely the effect of learning, where tDCS is known to play a facilitatory role (Krause, et al., 2017). Although participants were provided the opportunity to practice the WM task before the experiments, they came in with varying levels of preparedness and comprehension. Studies have shown that as individuals gain experience on a cognitive task, the brain networks associated with task performance change (e.g. (Hill & Schneider, 2006)), and so does the efficacy of neuromodulation (Toth, Ramsbottom, Constantin, Milliet, & Campbell, 2021). Therefore, it is likely that the differences we note here are associated with the effect of participant learning enhanced under anodal tDCS, in addition to region-wide cortical excitability and plasticity changes enabled via stimulation (Hill, Fitzgerald, & Hoy, 2016). Furthermore, the 'HIGH' performers were able to maintain their performance levels for longer than the 'LOW' performers, despite increasing perceptions of fatigue in both groups. We hypothesize that this disparity is associated with the time scales at which fatigue, learning, and task expertise occur, where 'HIGH' performers may have reached a ceiling sooner. Longer durations of stimulation may elicit similar outcomes in the latter group, implicating the need of future examinations on dosage and personalized neuromodulation.

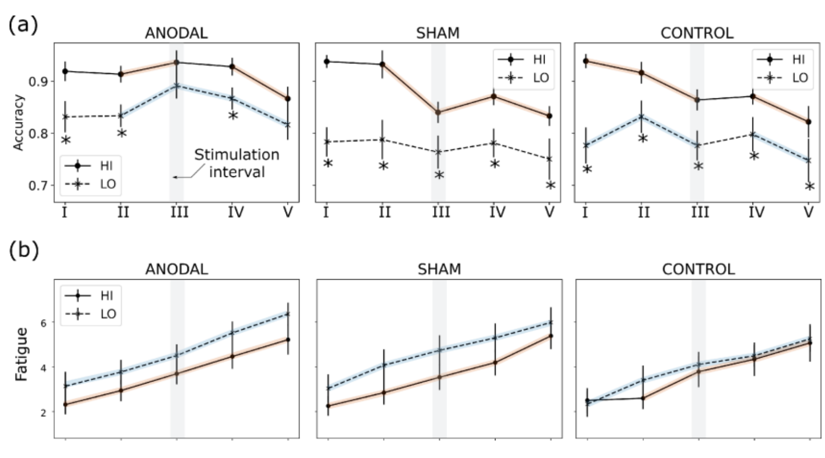

Fig. 1: (a) Performance measures stratified based on baseline (block 1) accuracy values for each condition. The shaded segments represent consecutive time points at which the measures were significantly different from one another and the asterisk represents stratification differences that are significant at each time point. (b) Subjective fatigue trends between high and low performers across each condition.

References

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