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Transcranial direct current stimulation over the visual cortex facilitates awake consolidation of visual perceptual learning

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Dear Editor

Transcranial direct current stimulation (tDCS) attracts extensive attention from a broad range of research fields, as it can non-invasively and rapidly modulate brain functions such as vision in both healthy and patient populations [1,10]. Meanwhile, vision can also be substantially improved by intensive training, a phenomenon called visual perceptual learning (VPL). VPL has been used to restore and enhance visual functions in neuro-ophthalmological diseases like amblyopia. Moreover, combining VPL and tDCS applied during training can further improve visual skills [2,3]. Since the after-effect of tDCS lasts for tens of minutes after stimulation, persisting during the early period immediately after training, i.e., the early consolidation stage, thus, it is reasonable to speculate that tDCS facilitates VPL by strengthening the early consolidation. Indeed, consolidation is essential in stabilizing and further improving the performance on trained tasks without extra practice (i.e., offline gain) [4]. Therefore, modulating visual performance by tDCS during consolidation will deepen our understanding of mechanisms underlying visual plasticity. To our knowledge, however, whether tDCS can modulate the consolidation of VPL has not been directly investigated yet.

To this end, we adopted a sham-controlled single-blind design and delivered tDCS after training on a texture discrimination task (TDT), a classical task used in many studies on VPL consolidation [5]. Specifically, in TDT, participants need to quickly identify a parafoveal target in a cluttered scene (Fig. 1A). Thirty-three healthy adults (18–28 years old, 20 females) met all the screening criteria and participated in the study (see Supplementary). They were randomly allocated to an active (N = 17) or a sham (N = 16) stimulation group. The sample size was determined by a power analysis in a pilot study (alpha level = 0.05, power = 80%). This study consisted of four sessions – familiarization, training, tDCS stimulation, and test. Participants underwent the familiarization session on the first day, while other sessions took place on the next day. The training session began at 8:30 a.m. and lasted approximately 50 minutes. Immediately after the training session, active or sham tDCS was administrated. The anodal electrode and the cathodal electrode were placed over O2 and Cz (the international 10–20 EEG system), respectively. The O2 position corresponds to the visual cortex of the hemisphere contralateral to the trained visual field. Participants were instructed to stay awake during the daytime and complete the 25-min test session at 8:30 p.m. A Weibull function was used to fit the psychometric curve, i.e., accuracy as a function of stimulus onset asynchrony (SOA). The threshold for each curve was determined as the SOA for 81.6% correct responses.

Our results showed that active tDCS shifted the psychometric curve to the upper left, while there was little change in task performance after the sham stimulation (Fig. 1B). A repeated-measure ANOVA showed a significant interaction between *group* (active vs. sham) and *session* (training vs. test) ($F(1, 31) = 4.49$, $p = 0.04$, $\eta_p^2 = 0.13$), while the main effects of *group* ($F(1, 31) = 0.55$, $p = 0.46$) and *session* ($F(1, 31) = 0.70$, $p = 0.41$) were not significant. For the sham stimulation group, paired *t*-test showed no within-day offline gain ($t(15) = -0.78$, $p = 0.45$), consistent with previous TDT studies where wakefulness alone following training does not result in performance improvement [6]. Conversely, the SOA threshold significantly decreased after the active stimulation ($t(16) = 2.51$, $p = 0.02$, Cohen's $d = 0.61$) (Fig. 1C).

To reduce data variance, the changes in SOA threshold were log-transformed (in decibel (dB), positive value denotes threshold reduction, see Supplementary). The change in SOA threshold was significantly greater than zero after the active stimulation ($t(16) = 3.40$, $p = 0.004$, Cohen's $d = 0.82$) but not after the sham stimulation ($t(15) = -1.44$, $p = 0.17$), indicating that only the active stimulation improved the TDT performance. An independent *t*-test also showed that the threshold change in the active stimulation group was greater than that in the sham stimulation group ($t(31) = 3.35$, $p = 0.002$, Cohen's $d = 1.17$) (Fig. 1D).

Interestingly, we found that sleep interacted with tDCS to influence task performance. We collected sleep quality scores and used a k-means clustering method to classify participants into a better-sleep (BS) cluster (N = 18) and a worse-sleep (WS) cluster (N = 15). In BS, participants' thresholds decreased significantly after the active stimulation, but not after the sham stimulation (change of threshold versus zero, active: $t(6) = 2.72$, $p = 0.035$, Cohen's $d = 1.03$; sham: $t(10) = -1.46$, $p = 0.17$). An independent *t*-test also revealed that the change in SOA threshold of the active stimulation group was greater than that of the sham stimulation group ($t(16) = 2.58$, $p = 0.02$, Cohen's $d = 1.25$). In WS, however, such effects were absent (change of threshold versus zero, active: $t(9) = 1.48$, $p = 0.17$; sham: $t(4) = 0.77$, $p = 0.48$; between-group

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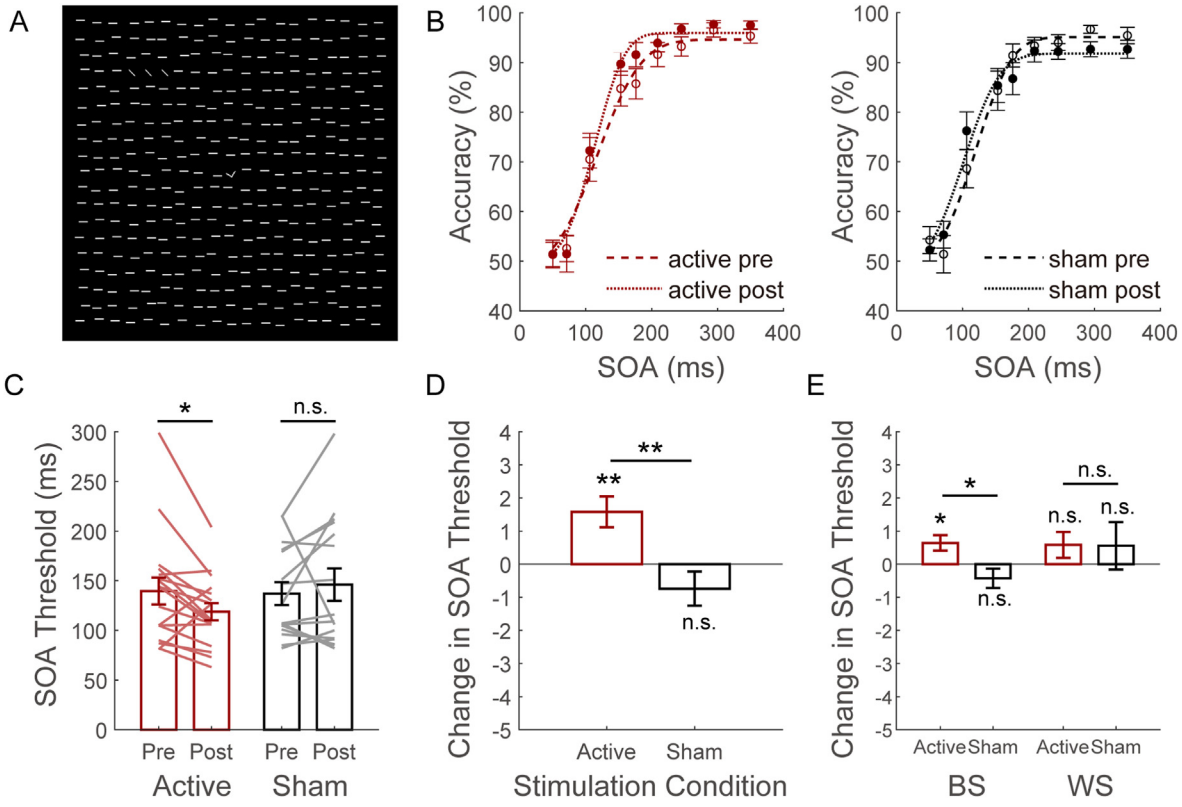

Fig. 1. Graphs depicting (A) the target frame of the TDT task, (B) the psychometric curves before (open) and after (filled) stimulation in the active stimulation group (red) and the sham stimulation group (black), (C) the SOA thresholds before and after stimulation in the active stimulation group (red) and the sham stimulation group (black), (D) the between-group comparison of SOA threshold change, and that (E) tDCS' effects on SOA threshold change were different between the two sleep quality conditions. Two-sided level of significance $*p < 0.05$, $**p < 0.01$.

comparison: $t(13) = -0.04$, $p = 0.97$) (Fig. 1E). Our results suggested that the consolidation of VPL might be modulated by the interplay between sleep and tDCS, consistent with the notion that sleep increases the inducibility of tDCS-induced neural plasticity and benefits learning performance [7].

It should be noted that the exact mechanisms underlying the tDCS-facilitated consolidation of VPL are still unclear. In the present study, tDCS was applied immediately after training, a critical time window wherein the cortical activity level was presumably higher than that before training [8]. Whether and how the excitation of visual cortex during early consolidation was further raised by tDCS and thereby improved task performance should be investigated in the future [2,9].

Here, we found that tDCS could improve performance on the trained task during awake consolidation, and the facilitatory effect was mediated by sleep quality. To the best of our knowledge, this is the first study showing visual skill improvement through awake consolidation facilitated by non-invasive brain stimulation. Our findings extend the scope of tDCS application to the consolidation of visual learning and provide a new way to facilitate human skill training.

Declaration of competing interest

We declare that we have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.brs.2022.01.019.

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