Article

PERCEPTION

Perception
2022, Vol. 51(4) 263–275

DOI: 10.1177/03010066221086446
journals.sagepub.com/home/pec
SAGE

Anodal tDCS Over the Left Frontal Eye Field Improves Sustained Visual Search Performance

Tian Gan, Yanyan Huang, Xin Hao, Lina Hu, Yan Zheng, and Zhen Yang
Department of Psychology, Zhejiang Sci-Tech University, Hangzhou, China

Abstract

Monotonous and repetitive tasks cause vigilance, or sustained attention decrement, which possibly leads to irreparable accident consequences in the aerospace and nuclear industry. Buffering the decrement of vigilance in visual search tasks is essential for cognitive enhancement and ergonomic research. This study aimed to evaluate the efficacy of anodal transcranial direct current stimulation (tDCS) applied to the left frontal eye field (FEF) to improve the performance of the sustained visual search. Twenty-seven healthy participants received anodal and sham tDCS of 2 mA for 28.8 min and completed a visual search task lasting for approximately 40 min without any break. For the online effect, results showed that the d' hit rate and accuracy under anodal tDCS were significantly higher than those under sham conditions during 0–19.2 min time intervals. For the after-effect, compared with sham, anodal tDCS caused significantly higher d' in the 10 min after completing the tDCS. Our findings suggest that anodal tDCS over the left FEF could effectively mitigate the decline of visual vigilance performance by buffering cognitive resource depletion.

Keywords

cognitive enhancement, sustained visual attention, vigilance, frontal eye field, transcranial direct current stimulation

Date Received: 28 October 2021; accepted: 22 February 2022

Corresponding author:
Tian Gan, Department of Psychology, Zhejiang Sci-Tech University, 5 Second Avenue, Xiasha Higher Education Zone, Hangzhou 310018, China.
Email: gantian@zstu.edu.cn

Introduction

Sustained attention, often referred to as vigilance in humans, denotes the ability to sustain attention to a task for a period of time to detect and respond to infrequent critical events (Davies & Parasuraman, 1982; Nelson et al., 2013). However, as time on the task increases, the operator's performance becomes impaired or degrades. This impairment is known as a "vigilance decrement" (Verster & Roth, 2013). Specifically, the vigilance decrement in sustained visual search is a focus of widespread concern in many areas such as enemy aircraft detection, high-speed rail driving, and motor vehicle driving, among others. Such interest is explained by the fact that during task execution, misjudgment (i.e., target detection rate decreases) or failure to detect dangerous information in time (i.e., reaction time slows down) due to the decrement of visual sustained attention may result in irreparable accident consequences (Helton & Russell, 2011). Therefore, maintaining visual sustained attention is an important guarantee for an individual's performance in the course of long-term monotonous task execution. How to buffer the decrement of visual sustained attention is one of the critical contents of cognitive enhancement and ergonomic research.

At present, the enhancement approaches which can improve sustained attention include biochemical intervention, behavioral training, and physical stimulation intervention (Dresler et al., 2018). However, the effect of long-term consumption of biochemical agents (e.g., caffeine) will decline over time, and some side effects occur, such as interference in sleep and withdrawal difficulties (Ning et al., 2019; Vera et al., 2020). For behavioral training, the intervention cycles required are excessively long, and determining a causal relationship between behavioral training and improved attention is difficult (Wang & He, 2020). With cognitive neuroscience and technology development, increasing studies have begun to pay attention to the enhancement of cognitive performance by physical stimulation, such as transcranial direct current stimulation (tDCS). Many studies have found that tDCS has a significant enhancement effect on cognitive functions such as perception and attention (Martin et al., 2019; Roy et al., 2015; Silva et al., 2017). In addition, tDCS can be used as an effective way to explore the causal relationship between the cerebral cortex and specific cognitive function (Coffman et al., 2014). Therefore, tDCS might be an ideal tool to modulate the decrement of visual sustained attention.

Two existing psychological theories attempt to explain the reason for sustained attention decrement: arousal theory and resource theory. The first one holds that a higher degree of arousal is a prerequisite for an individual to complete a task successfully (Hebb, 2015). In long-term tasks, maintaining a high level of activation is difficult for an individual's central nervous system. Thus, with the passage of time, the vigilance decreases with the decline in physical arousal. By contrast, when the physiological arousal increases, the improvement of individual arousal level will be apparent by the increase in hit rate and false alarm rate, as well as significant changes in response bias (Posner, 1978). The second theory argues that cognitive processing relies on a limited pool of resources (Kahneman, 1973). According to this theory, when the individual consumes resources too fast to maintain attention, and cannot promptly replenish the attention resources, the performance will decline (Parasuraman et al., 1987). Correspondingly, when the attention resources are promptly replenished, the individual's sensitivity will improve, which is characterized by the increase in the hit rate and the decrease in the false alarm rate (Nelson et al., 2013). By using tDCS and signal detection theory metrics (Craig, 1987), Nelson (2013) found that the improvement in visual sustained attention was manifested by the increase in perceptual sensitivity (d') rather than the change in response bias (β), which fit well within resources theory. They further found that tDCS over the prefrontal cortex (PFC) could slow the decline of vigilance by increasing cognitive resources, which provides evidence for using tDCS to modulate sustained attention.

Apart from PFC, as the main brain areas in the dorsal attention network (DAN), the frontal eye field (FEF), intraparietal sulcus (IPS), and inferior parietal cortex (IPC) also play important roles in sustained attention (Hopfinger et al., 2000). Previous studies have earlier verified the causal relationship between PFC, parietal cortex, and sustained attention (Fiene et al., 2018; Nelson et al., 2013). However, few studies have examined whether increasing the excitability of FEF can enhance sustained attention. As far as we know, only one study used tDCS to modulate the excitability of FEF to affect visual sustained attention. The results showed that compared with sham stimulation, on-line anodal tDCS over the left FEF could improve the performance of visual sustained attention. Specifically, the accuracy in complex visual search tasks was improved, and the decrement of vigilance was mitigated (Nelson et al., 2015). However, the number of subjects in this study is relatively small, only 11. Additionally, the effect size was not reported. Consequently, estimating the statistical effectiveness of the results is difficult (Cohen, 1973). In addition, this study only took the accuracy as the indicator of vigilance. Whether tDCS over the left FEF to enhance sustained attention is related to the changes in cognitive resources is unclear. Therefore, the present study will use more sensitive and representative dependent variable indexes (*d'*, β, hit rate, and false alarm rate) to investigate the impact of anodal tDCS over the left FEF on visual sustained attention.

The changes in the excitability of brain regions stimulated by tDCS do not disappear immediately after stimulation but may last for a period of time. It has been found that 20–30 min tDCS could lead to subsequent behavioral and cortical changes lasting for 90 min or longer (Nitsche & Paulus, 2001). However, for complex cognitive tasks, whether the effects can be maintained after stimulation remains unclear (Hanken et al., 2016). From the viewpoints of practical implication, exploring the long-term potentiation effect of tDCS stimulation on complex cognitive tasks is also meaningful in the real world.

To sum up, this study aimed to explore the online effect and after-effect of tDCS over the left FEF on the performance in a long-term visual sustained attention task. We hypothesized that using tDCS to increase the excitability of the left FEF could buffer the decrement of visual sustained attention, and this enhancement effect could be maintained after the stimulation. Compared with the sham conditions, during and after tDCS stimulation, anodal tDCS over the left FEF is expected to improve the *d'*, hit rate, and accuracy, and reduce the false alarm rate.

Method

Participants

The study was powered to detect a medium effect size of $f = 0.25$ for the interaction between stimulation and block at a power (β) of .80 using G*Power (Version 3.1) (Faul et al., 2007; Ferguson, 2009). The result indicated 16 participants were needed. Twenty-eight healthy college students took part in this study. They are all right-handed and have normal vision. Participants were excluded from the study if they had any neurological or psychological disorders, epilepsy, drug, or alcohol abuse or dependence, head trauma, or color deficiency. One participant's data were excluded from analysis due to the tDCS device failure, and the final sample included 27 participants (15 females). The age for the participants ranged from 18 to 24 years old (mean age of 19.19 ± 1.52). This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Human Research Ethics Committee of Zhejiang Sci-Tech University.

Vigilance Task (Visual Search Task)

The experiment was programmed using E-prime2.0 (Psychology Software Tools Inc., Pittsburgh, PA, USA). The vigilance task was adapted from the visual search detection paradigm in the study of

Nelson et al. (2015). The search arrays consisted of 80 blue circles and 80 red squares on a white background; 25% of the trails displayed a red circle which was the objective target.

At the beginning of each trial, a black fixation cross was presented centrally for a variable duration (from 800 to 1200 ms). This was followed immediately by the presentation of a search array for 7 s (see Figure 1). The participants were instructed to detect the target stimuli as quickly and accurately as possible. If the participants detected the red circle, they responded by pressing the "F" key on the keyboard. If they did not detect the target, they responded by pressing the "J" key on the keyboard. The key assignment was counterbalanced across the participants.

Study Protocol

A randomized single-blind design was used. Participants attended the lab for the two sessions (anodal and sham), completed at least one week apart, with session order randomly counterbalanced across participants. All participants signed informed consent documents and filled out an Initial Screening Questionnaire prior to their first tDCS session. Following completion of the information, the practices of the visual search task would begin. Participants would be provided with automatic feedback on their responses immediately following each trial. After the correct rate reaches 80%, they would be provided a short break before completing the main task.

All participants performed four consecutive blocks of visual search trials (eight target stimulus-present and 28 target stimulus-absent trails randomly presented in each block). Each block took approximately 9.6 min to complete, and there was no feedback on their response. In the first three blocks of the task (28.8 min), participants received either anodal tDCS or sham tDCS. In the last block, the intervention stopped automatically, and the visual search task was continued without stimulation.

Transcranial Direct Current Stimulation

The constant current was delivered by a battery-driven stimulator (Multichannel, non-invasive wireless tDCS neurostimulator, Starlab, Barcelona, Spain) controlled by a Bluetooth system. Two 25 cm^2 saline-soaked sponge electrodes were used for current delivery. The anode electrode was placed over the left FEF, which was located 5 cm lateral toward the left and 4 cm anterior from the vertex, corresponding with the left pre-central and superior frontal gyrus (Ball et al., 2013; Paus, 1996).

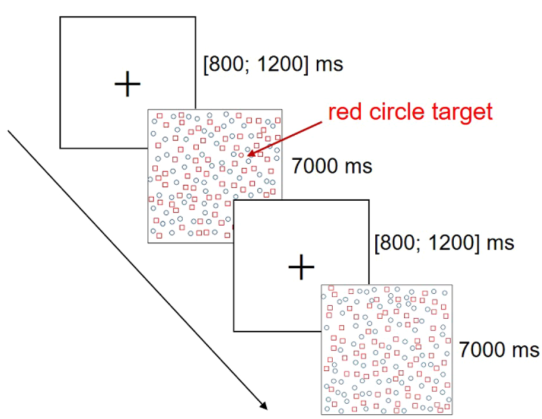

Figure 1. Experimental paradigms of the visual search task.

The cathodal electrode was placed over the right orbitofrontal cortex (OFC: equivalent to location FP2, according to the international 10–20 EEG system) (Willis et al., 2015). In our study, we applied a 2 mA current for 28.8 min. The current was ramped up over 15 s, and back down over 15 s at the cessation of stimulation during the anodal condition. For the sham condition, the simulation was gradually ramped up over 15 s to 2 mA, then ramped down over 15 s and the machine switched off.

Statistical Analyses

Statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS) for Windows (version 26.0; IBM Corp., Armonk, NY, USA). Accuracy data outside the range of three standard deviations from the study mean for that task were removed before analysis. Separate mixed-effects models for repeated measures (MMRM) were conducted for outcome measure using stimulation and block as fixed factors, subject as a random factor, and session number (visit) as a covariate. The stimulation variable had two levels (anodal, sham). The block variable had four levels (block 1–block 4). Multiple comparisons were made for the main effect of stimulation on the respective outcome measures using a Bonferroni correction. Post-hoc pairwise comparisons were conducted to interpret significant main effects. A p-value < .05 was considered statistically significant. Paired t-test was used to examine performance differences between anodal and sham stimulation if the main effect was significant. Furthermore, to explore whether an individual's baseline performance was predictive of anodal tDCS-related improvements in visual sustained attention, Pearson's correlations were conducted between the performance during baseline and the change in performance during anodal tDCS ($\Delta\text{Performance} = d'_{\text{Anodal}} - d'_{\text{Sham}}$) (Brosnan et al., 2018).

Results

Baseline Data

Recent research has reported that the excitability of the motor cortex began to change after 5–13 min of tDCS (Nitsche & Paulus, 2001), so the first 4.8 min of data were taken as the baseline. As shown in Table 1, the paired-sample t-test showed no significant difference in visual search performance at d', β, hit rate, false alarm rate, and accuracy between anodal and sham stimulation during the baseline.

Perceptual Sensitivity (d')

MMRM analysis showed that the main effect of block was failed to reach significance ($F_{(3,\ 182)} = 1.878$, $p > .05$, $\eta^2_p = 0.030$). However, there was a significant main effect of stimulation ($F_{(1,\ 182)} = 32.276$,

Table 1. Visual search performance for the anodal and sham stimulation during baseline.

	Mean (standard deviation)				
Measure	Anodal	Sham	t	df	p-value
d'	1.854 (0.899)	1.607 (0.805)	1.292	26	.208
β	2.475 (1.381)	2.610 (1.375)	−0.399	26	.693
Hit rate	0.656 (0.218)	0.631 (0.155)	0.585	26	.564
False alarm rate	0.112 (0.095)	0.138 (0.139)	−0.931	26	.360
Accuracy	0.853 (0.117)	0.813 (0.123)	1.562	26	.130

$p < .001$, $\eta_p^2 = 0.151$). Pairwise comparisons showed that d' in anodal stimulation (1.983 ± 0.143) was significantly higher than that in sham condition (1.626 ± 0.134). Most importantly, there was a significant interaction between stimulation and block ($F_{(3,\ 182)} = 3.049$, $p < .05$, $\eta_p^2 = 0.048$). Simple effect analysis showed that the d' under anodal condition was significantly higher than that under the sham conditions in block 1 (Cohen's $d = 2.195$, $p < .01$), block 2 (Cohen's $d = 4.222$, $p < .001$) and block 4 (Cohen's $d = 1.766$, $p < .05$), except in block 3 (Cohen's $d = 1.022$, $p > .05$) (see Figure 2A). What's more, the Pearson' correlation analysis showed that the d' under baseline was significantly correlated to the tDCS-related improvements in performance (ΔPerformance $= d'_{\text{Anodal}} - d'_{\text{Sham}}$), such that worse performance during baseline (x-axis) was predictive of larger tDCS-related improvements in sustained attention performance in block 2 and block 4 (y-axis) (block 2: $R^2 = 0.266$, $p < .05$; see Figure 3A; block 4: $R^2 = 0.228$, $p < .05$; see Figure 3B).

Response Bias (β)

MMRM analysis revealed a significant main effect of block ($F_{(3,\ 182)} = 2.999$, $p < .05$, $\eta_p^2 = 0.047$). Pairwise comparisons showed that β in block1 (4.414 ± 0.504) was significantly lower than that in block 4 (0.502 ± 0.480). However, the main effect of stimulation ($F_{(1,\ 182)} = 2.620$, $p > .05$, η_p^2

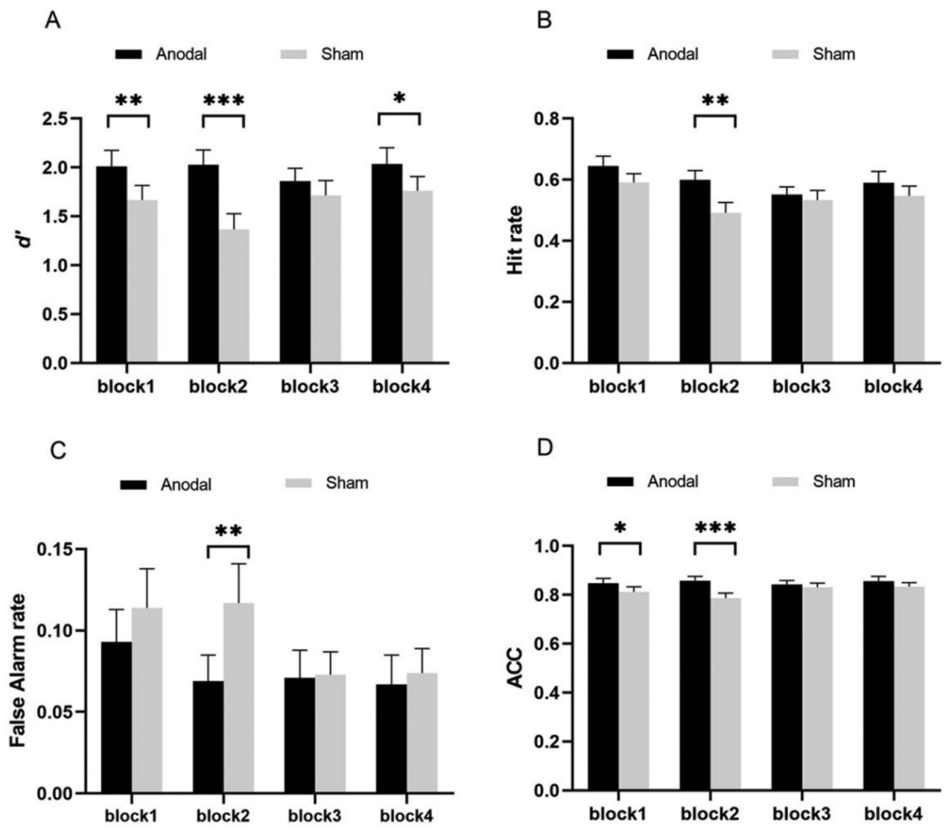

Figure 2. Mean d' (A), hit rate (B), false alarm rate (C), and ACC (D) of the anodal and sham stimulation from block 1 to block 4. * indicates $p < .05$; ** indicates $p < .01$; *** indicates $p < .001$; error bars reflect standard error of the mean (SEM).

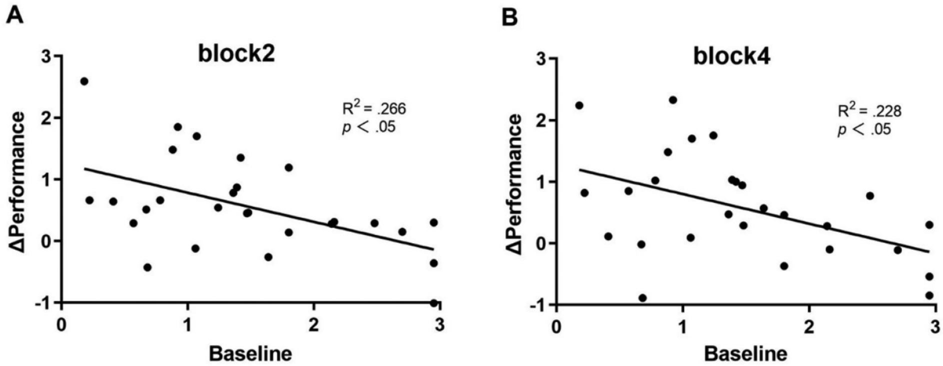

Figure 3. The correlations between baseline performance and tDCS-related improvements in block 2 (left) and block 4 (right). Baseline performance denotes the mean of d' during the first 4.8 min. ΔPerformance = $d'_{\text{Anodal}}-d'_{\text{Sham}}$.

= 0.014) and the interaction between stimulation and block ($F_{(3,\ 182)} = 0.677$, $p > .05$, $\eta_p^2 = 0.011$) were not significant.

Hit Rate

MMRM analysis revealed a significant main effect of stimulation ($F_{(1,\ 182)} = 12.013$, $p < .01$, $\eta_p^2 =$ 0.062). Pairwise comparison showed that the hit rate in anodal stimulation (0.596 ± 0.026) was significantly higher than that in sham stimulation (0.541 ± 0.026). In addition, there was a significant main effect of block ($F_{(3,\ 182)} = 4.865$, $p < .01$, $\eta_p^2 = 0.074$). Pairwise comparisons showed that the hit rate in block 1 (0.618 ± 0.026) was significantly higher than that in block 2 (0.546 ± 0.028) and block 3 (0.542 ± 0.025). The interaction between stimulation and block was not significant ($F_{(3,\ 182)}$ = 1.394, $p > .05$, $\eta_p^2 = 0.023$). A series of paired t-tests were conducted to examine the differences in hit rate between the two tDCS conditions at each block. The results noted that in block 2, the hit rate under anodal condition was significantly higher than that under sham condition (Cohen's $d = 3.342$, $p < 0.01$). However, in block 1 (Cohen's $d = 1.768$, $p > .05$), block 3 (Cohen's $d = 0.583$, $p > .05$) and block 4 (Cohen's $d = 1.243$, $p > .05$), the differences between anodal and sham condition were not significant (see Figure 2B).

False Alarm Rate

MMRM analysis revealed a significant main effect of stimulation ($F_{(1,\ 182)} = 5.702$, $p < .05$, $\eta_p^2 =$ 0.030). Pairwise comparison showed that the false alarm rate in anodal stimulation (0.075 ± 0.016) was significantly lower than that in sham stimulation (0.095 ± 0.017). In addition, there was a significant main effect of block ($F_{(3,\ 182)} = 3.895$, $p < .05$, $\eta_p^2 = 0.060$). Pairwise comparisons showed that the false alarm rate in block 1 (0.104 ± 0.019) was significantly higher than that in block 3 (0.072 ± 0.015) and block 4 (0.070 ± 0.015). The interaction between stimulation and block was not significant ($F_{(3,\ 182)} = 1.551$, $p > .05$, $\eta_p^2 = 0.025$). A series of paired t-tests were conducted to examine the differences in false alarm rates between different tDCS conditions at each block. The results noted that in block 2, the false alarm rate under anodal condition was significantly lower than that under sham condition (Cohen's $d = -2.353$, $p < .01$). However, in block1 (Cohen's $d = -0.951$, $p > .05$), block 3 (Cohen's $d = -0.128$, $p > .05$), and block 4

(Cohen's $d = -0.423$, $p > .05$), there was no significant difference in hit rate between anodal and sham conditions (see Figure 2C).

Accuracy (ACC)

MMRM analysis showed that the main effect of block was not significant ($F_{(3,\ 182)} = 1.855, p > .05, \eta_p^2 = 0.030$). However, there was a significant main effect of stimulation ($F_{(1,\ 182)} = 22.599$, $p < .001$, $\eta_p^2 = 0.111$). Pairwise comparison showed that ACC in anodal stimulation (0.851 ± 0.017) was significantly higher than that in sham stimulation (0.816 ± 0.016). It is important to point out that there was a significant interaction between stimulation and block ($F_{(3,\ 182)} = 3.140$, $p < .05$, $\eta_p^2 = 0.049$). Further analysis revealed that the ACC in anodal stimulation was significantly higher than that in sham stimulation only in block 1 (Cohen's $d = 1.707$, $p < .05$) and block 2 (Cohen's $d = 3.769$, $p < .001$). In block 3 (Cohen's $d = 0.727$, $p > .05$) and block 4 (Cohen's $d = 1.253$, $p > .05$), the differences between ACC under anodal and sham condition were not significant (see Figure 2D).

Discussion

This study explored the online and after stimulation effects of anodal tDCS over the left FEF on the performance in a long-term visual vigilance task. The results indicated that during anodal tDCS over the left FEF, the performance was improved, in terms of perceptual sensitivity (d'), hit rate, false alarm rate, and ACC rather than response bias (β). In particular, the improvement of d' lasted at least 10 min after the completion of stimulation. These findings are in line with our expectations and provide support for resource theory and further suggested that anodal tDCS over the left FEF might be an effective approach to mitigate the decline of cognitive resources and improve performance in a visual sustained attention task.

Two reasons may explain the enhanced effects of tDCS on performance in a visual vigilance task. The first one is that tDCS over the left FEF could increase the attention resources needed to complete the long-term task. According to resource theory, the vigilance decrement is commonly caused by individuals expending resources to maintain attention at a rate faster than they can be replenished, thus resulting in the cognitive or mental demand overload (Finomore et al., 2013). Our findings fit well within this theory, which suggests that anodal tDCS has increased the speed of cognitive resource replenishment, which was characterized by the increase in hit rate and the decrease in false alarm rate, leading to a significant improvement in perceptual sensitivity but not response bias. Notably, some studies have found that improving the subjects' arousal through drugs or music can also enhance the subjects' performance in sustained attention. According to arousal theory, if the enhanced effect of tDCS over the left FEF on performance is related to the improvement of arousal level, then, under anodal tDCS, not only the hit rate will increase. Instead, the false alarm rate may also increase, and the response bias will change (Dong, 2007). However, our findings do not support these inferences. Thus, tDCS over the left FEF is related to the change in cognitive resources rather than arousal level. The second possible explanation is that anodal tDCS over the left FEF improves the accuracy of visual search. FEF is an indispensable brain region in the process of visual search (Hung et al., 2011; Kanai et al., 2012). The primary function of this area is to detect task-related stimuli and inhibit irrelevant stimuli to promote the processing of new presentation stimuli (Tian & Yao, 2009). As found in the neurophysiological studies of Buschman and Miller (2007), in the visual search tasks requiring identification of target stimuli and interference stimuli, the nerve cells of FEF are the most sensitive to target stimuli. Therefore, tDCS over the left FEF may promote individual recognition and orientation of target stimuli, improve their search efficiency, and thus improve individual task performance.

The results of this study suggest that the left FEF may be a critical region of visual sustained attention, and improving the excitability of this region can effectively improve the performance of individuals in a visual search task lasting for over 40 min. Consistent with our finding, by using repeated TMS, Esterman et al. (2015) found that inhibiting the activity of FEF could affect the sustained attention performance of participants, characterized by the slower response and a higher error rate of participants' response to the low-probability stimulus. In addition, previous fMRI studies and a recent meta-analysis have found that the dorsal attention network (DAN), including the FEF, were associated with sustained attention over periods of several seconds to several minutes (Hopfinger et al., 2000; Langner & Eickhoff, 2013). On the bases of these findings, we speculate that anodal tDCS over FEF may not only influence the individual's visual sustained attention directly by regulating the excitability of this region but also influence the individual's performance in visual search tasks by promoting the activation of the whole DAN and triggering network oscillations, and ultimately improve individual performance under the synergistic action. Although this assumption requires further validation by neuroimaging techniques, it still enhances our understanding of the function of FEF in visual sustained attention.

Specifically, our findings revealed that during block 1 (0–9.6 min) and block 2 (9.6–19.2 min), the *d'*, hit rate, and ACC under anodal conditions were significantly higher than those under sham conditions. However, these differences were insignificant in block 3 (during 19.2–28.8 min time interval). These results were consistent with previous findings. For example, in the study of Nelson et al. (2015), 30 min tDCS over the left FEF was applied on 11 active-duty military participants while they were completing a visual search task. During the 0–20 min time interval, the ACC under anodal tDCS condition was significantly higher than that under sham condition. Furthermore, during the 20–30 min time interval, the ACC in anodal stimulation has declined, which is similar to the results of this study. Notably, from the data in Figure 2, the performance of anodal condition seemed to be at a consistently high level, and the performance trend might increase under the sham conditions in blocks 3 and 4. We suggest that this phenomenon may be due to participants being more uncertain about the appearance of the target stimulus during the initial stage of the task. Thus, more misses or false alarms would occur. With the increase in the number of trials, participants gradually became familiar with the task and learned how to detect the target quickly, thus resulting in the practicing and learning effects (Hanken et al., 2016), which were shown in the results of the sham condition. However, under the anodal condition, not only the learning effect occurred, but also the enhancement effect of tDCS. Therefore, the vigilance performance was constantly at a high level in all of the blocks.

Another interesting finding is that both the online (block 2) and offline (block 4) tDCS-related benefits on d' were negatively correlated with participants' baseline performance. That is, participants with worse sustained attention capacity at baseline might benefit more from anodal tDCS. This finding indicated that the FEF might be a viable target region for cognitive enhancement to promote visual sustained attention in individuals with worse performance. Consistent with this result, an increasing number of literatures have reported that individual differences in baseline cognitive ability can modulate the tDCS effects in healthy adults. For example, Brosnan (2018) found that poorer performance at baseline was associated with greater tDCS-related benefits to sustained attention performance in older adults. Tseng et al. (2012) reported that the performance in a visual short-term memory task was enhanced with anodal tDCS only in participants who did not initially perform well. Together, these findings highlight the important variable of interindividual differences in the cognitive enhancement study of tDCS.

Apart from the online enhanced effects, the results of this study found that d' under anodal stimulation was significantly higher than that under the sham condition in 10 min after the completion of stimulation (block 4), which indicated the improvement impact of anodal tDCS on cognitive performance after the stimulation. However, no significant difference existed in hit rate and ACC. A possible explanation for these findings may be that d' could more accurately reflect the changes in the sensitivity of participants (Craig, 1987). These results further support the necessity to take the subject's sensitivity (d') as the dependent variable index when exploring the vigilance performance (Macmillan & Creelman, 2009; Nelson et al., 2013). For the first time, this study found that 30 min tDCS over FEF had a significant impact on sustained attention even when the tDCS had finished, which provides inspiration for the application of tDCS in the cognitive enhancement of military and aviation practitioners. The long-lasting after-effects of tDCS may be due to the enhanced efficacy of N-methyl-D-aspartate receptors in the case of anodal stimulation. These efficacy changes may be induced by an intrastimulation polarity-specific neuronal depolarization or hyper-polarization (Ai et al., 2021; Fritsch et al., 2010; Nitsche et al., 2003). Additional work is necessary to be done to explore the longer enhancement after-effects of tDCS.

Several limitations to this study need to be acknowledged. First, existing studies have found that tDCS lasting for 5 min would not change the cortical excitability or significantly impact the participants' performance (Hanken et al., 2016; Nitsche & Paulus, 2001). Thus, using pre-4.8 min data as the baseline in this study is theoretically feasible. Nonetheless, the experimental results would be more convincing if the baseline level could be evaluated separately before the start of stimulation, which should be considered in future studies. Second, based on the purpose of our research and referring to the previous study (Nelson et al., 2015), this study only selected the left FEF for stimulation. Considering the importance of the right FEF in spatial attention (Hung et al., 2011; Langner & Eickhoff, 2013), the right FEF should be added to the experiment in future studies, which can provide more comprehensive evidence for revealing the specific function of the FEF in visual sustained attention. Thirdly, although the effect sizes of paired t-tests for the differences in d', ACC, hit rate and false alarm rates between anodal and sham tDCS conditions at block 2 were large or medium (Cohen's $d > 1.7$), it is worth noting that the effect size of the interaction between stimulation and block was small ($0.04 < \eta_p^2 < 0.25$) (Ferguson, 2009). Future research could therefore concentrate on improving the effect size of tDCS enhancement by improving spatial resolution and changing stimulus parameters. Last but not the least, the spatial resolution of tDCS technology is not high. Although this study refers to the placement of electrodes in previous studies (Ball et al., 2013; Paus, 1996), the effectiveness of cortical stimulation can undergo further testing by using brain localization and brain imaging techniques to improve the accuracy of stimulating the FEF.

Conclusion

The present study was designed to determine the online and after-effects of anodal tDCS over the left FEF on the performance in a visual sustained attention task. The most apparent finding emerging from this study is that anodal tDCS over the left FEF could significantly improve performance in terms of perceptual sensitivity (d'), hit rate, false alarm rate, and ACC (Cohen's $d > 1.7$). And the improvement of d' remained effective for at least 10 min after the completion of the stimulation (Cohen's $d = 1.766$). The current findings add substantially to our understanding of the mechanism of vigilance decrement and to the evidence that tDCS over the left FEF can be used as an effective measure to buffer the decline of vigilance performance in monotonous and tedious tasks in real life.

Acknowledgments

The authors thank Xinkui Hu, Wei Gao, and Zhe Wang for their assistance with tDCS stimulation.

Ethical Approval

All study procedures were conducted regarding ethical standards. The study was performed by the Declaration of Helsinki and its later amendments or comparable ethical standards; this study was approved by the Human Research Ethics Committee of Zhejiang Sci-Tech University.

Consent to Participate

Informed consent was obtained from all participants included in the study. All data generated or analyzed during this study are included in this published article.

Consent to Publication

All participants and authors of the present study consented to publish this paper.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Annual Project of Philosophy and Social Science in Zhejiang Province, the Fundamental Research Funds of Zhejiang Sci-Tech University (grant nos. 22NDJC073YB, 2021Q055).

Data Availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

Statements and Declarations

There are no conflicts of interest directly or indirectly related to the work submitted for publication and there has been no significant financial support for this work that could have influenced its outcome.

ORCID iD

Tian Gan https://orcid.org/0000-0002-8661-4841

References

Ai, Y., Li, L., & Yin, M. (2021). Effects of different timing of transcranial direct current stimulation on post-stroke cognitive impairment. *Chinese Journal of Rehabilitation Medicine*, *36*(3), 315–321. https://doi.org/10.3969/j.issn.1001-1242.2021.03.011

Ball, K., Lane, A. R., Smith, D. T., & Ellison, A. (2013). Site-dependent effects of tDCS uncover dissociations in the communication network underlying the processing of visual search. *Brain Stimulation*, *6*(6), 959–965. https://doi.org/10.1016/j.brs.2013.06.001

Brosnan, M. B., Arvaneh, M., Harty, S., Maguire, T., O'Connell, R., Robertson, I. H., & Dockree, P. M. (2018). Prefrontal modulation of visual processing and sustained attention in aging, a tDCS-EEG coregistration approach. *Journal of Cognitive Neuroscience*, *30*(11), 1630–1645. https://10.1162/jocn_a_01307

Buschman, T. J., & Miller, E. K. (2007). Top-down versus bottom-up control of attention in the prefrontal and posterior parietal cortices. *Science (New York, N.Y.)*, *315*(5820), 1860–1862. https://doi.org/10.1126/science.1138071

Coffman, B. A., Clark, V. P., & Parasuraman, R. (2014). Battery powered thought: Enhancement of attention, learning, and memory in healthy adults using transcranial direct current stimulation. *Neuroimage*, *85*, 895–908. https://doi.org/10.1016/j.neuroimage.2013.07.083

Cohen, J. (1973). Statistical power analysis and research results. *American Educational Research Journal*, *10*(3), 225–229. https://doi.org/10.2307/1161884

Craig, A. (1987). Signal detection theory and probability matching apply to vigilance. *Human Factors*, *29*(6), 645–652. https://doi.org/10.1177/001872088702900604

Davies, D. R., & Parasuraman, R. (1982). *The psychology of vigilance*. Academic Press.

Dong, Y. (2007). The effect of emotions on selective and sustained attention in adolescents with learning disabilities. *Acta Psychologica Sinica*, *39*(4), 679–687. https://doi.org/CNKI:SUN:XLXB.0.2007-04-015
Dresler, M., Sandberg, A., Bublitz, C., Ohla, K., Trenado, C., Mroczko-Wasowicz, A., & Repantis, D. (2018). Hacking the brain: Dimensions of cognitive enhancement. *ACS Chemical Neuroscience*, *10*(3), 1137–1148. https://doi.org/10.1021/acschemneuro.8b00571
Esterman, M., Liu, G., Okabe, H., & Reagan, A. (2015). Frontal eye field involvement in sustaining visual attention: Evidence from transcranial magnetic stimulation. *Neuroimage*, *111*, 542–548. https://doi.org/10.1016/j.neuroimage.2015.01.044
Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/bf03193146
Ferguson, C. J. (2009). An effect size primer: A guide for clinicians and researchers. *Professional Psychology-Research and Practice*, *40*(5), 532–538. https://doi.org/10.1037/a0015808
Fiene, M., Rufener, K. S., Kuehne, M., Matzke, M., Heinze, H. J., & Zaehle, T. (2018). Electrophysiological and behavioral effects of frontal transcranial direct current stimulation on cognitive fatigue in multiple sclerosis. *Journal of Neurology*, *265*(3), 607–617. https://doi.org/10.1007/s00415-018-8754-6
Finomore, V. S., Shaw, T. H., Warm, J. S., Matthews, G., & Boles, D. B. (2013). Viewing the workload of vigilance through the lenses of the NASA-TLX and the MRQ. *Human Factors*, *55*(6), 1044–1063. https://doi.org/10.1177/0018720813484498
Fritsch, B., Reis, J., Martinowich, K., Schambra, H. M., Ji, Y., Cohen, L. G., & Lu, B. (2010). Direct current stimulation promotes BDNF-dependent synaptic plasticity: Potential implications for motor learning. *Neuron*, *66*(2), 198–204. https://doi.org/10.1016/j.neuron.2010.03.035
Hanken, K., Bosse, M., Mohrke, K., Eling, P., Kastrup, A., Antal, A., & Hildebrandt, H. (2016). Counteracting fatigue in multiple sclerosis with right parietal anodal transcranial direct current stimulation. *Frontiers in Neurology*, *7*, 154. https://doi.org/10.3389/fneur.2016.00154
Hebb, D. O. (2005). *The organization of behavior: A neuropsychological theory*. Psychology Press.
Helton, W. S., & Russell, P. N. (2011). Working memory load and the vigilance decrement. *Experimental Brain Research*, *212*(3), 429–437. https://doi.org/10.1007/s00221-011-2749-1
Hopfinger, J. B., Buonocore, M. H., & Mangun, G. R. (2000). The neural mechanisms of topdown attentional control. *Nature Neuroscience*, *3*(3), 284–291. https://doi.org/10.1038/72999
Hung, J., Driver, J., & Walsh, V. (2011). Visual selection and the human frontal eye fields: Effects of frontal transcranial magnetic stimulation on partial report analyzed by Bundesen's theory of visual attention. *Journal of Neuroscience*, *31*(44), 15904–15913. https://doi.org/10.1523/JNEUROSCI.2626-11.2011
Kahneman, D. (1973). *Attention and effort (Vol. 1063, pp. 218-226)*. Prentice-Hall.
Kanai, R., Muggleton, N., & Walsh, V. (2012). Transcranial direct current stimulation of the frontal eye fields during pro- and antisaccade tasks. *Frontiers in Psychiatry*, *3*, 45. https://doi.org/10.3389/fpsyt.2012.00045
Langner, R., & Eickhoff, S. B. (2013). Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychological Bulletin*, *139*(4), 870–900. https://doi.org/10.1037/a0030694.supp
Macmillan, N. A., & Creelman, C. D. (2009). *Detection theory: A user's guide*. Taylor and Francis.
Martin, D. M., Mohan, A., Alonzo, A., Gates, N., & Gbadeyan, O. (2019). A pilot double-blind randomized controlled trial of cognitive training combined with transcranial direct current stimulation for amnestic mild cognitive impairment. *Journal of Alzheimer's Disease*, *71*(2), 503–512. https://doi.org/10.3233/JAD-190306
Nelson, J. M., Mcintire, L. K., Goodyear, C., Walters, C., & Mckinley, R. A. (2015). Augmenting visual search performance with transcranial direct current stimulation (tDCS). *Military Psychology*, *27*(6), 335–347. https://doi.org/10.1037/mil0000085
Nelson, J. T., McKinley, R. A., Golob, E. J., Warm, J. S., & Parasuraman, R. (2013). Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). *Neuroimage*, *85*, 909–917. https://doi.org/10.1016/j.neuroimage.2012.11.061
Ning, Y., Tian, H., & Zhou, Y. (2019). Research progress in cognitive enhancing pharmacological products in the army. *Military Medical Sciences*, *43*(5), 380–385. https://doi.org/10.7644/j.issn.1674-9960.2019.05.013

Nitsche, M. A., Fricke, K., Henschke, U., Schlitterlau, A., Liebetanz, D., & Paulus, W. (2003). Pharmacological modulation of cortical excitability shifts induced by transcranial direct current stimulation in humans. *The Journal of Physiology*, *553*(1), 293–301. https://doi.org/10.1113/jphysiol.2003.049916

Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, *57*(10), 1899–1901. https://doi.org/10.1212/wnl.57.10.1899

Parasuraman, R., Warm, J. S., & Dember, W. N. (1987). *Vigilance: Taxonomy and utility*. Springer.

Paus, T. (1996). Location and function of the human frontal eye-field: A selective review. *Neuropsychologia*, *34*(6). https://doi.org/10.1016/0028-3932(95)00134-4

Posner, M. I. (1978). *Chronometric explorations of mind*. Lawrence Erlbaum.

Roy, L. B., Sparing, R., Fink, G. R., & Hesse, M. D. (2015). Modulation of attention functions by anodal tDCS on right PPC. *Neuropsychologia*, *74*, 96–107. https://doi.org/10.1016/j.neuropsychologia.2015.02.028

Silva, A. F., Zortea, M., Carvalho, S., Leite, J., Torres, I. L., Fregni, F., & Caumo, W. (2017). Anodal transcranial direct current stimulation over the left dorsolateral prefrontal cortex modulates attention and pain in fibromyalgia: Randomized clinical trial. *Scientific Reports*, *7*(1), 135–146. https://doi.org/10.1038/s41598-017-00185-w

Tian, Y., & Yao, D. Z. (2009). Brain mechanism for exogenous facilitation and inhibition of return in visual search. *Acta Biophysica Sinica*, *24*(3), 203–208. https://doi.org/CNKI:SUN:SWWL.0.2009-03-008

Tseng, P., Hsu, T. Y., Chang, C. F., Tzeng, O. J., Hung, D. L., & Juan, C. H. (2012). Unleashing potential: Transcranial direct current stimulation over the right posterior parietal cortex improves change detection in low-performing individuals. *Journal of Neuroscience*, *32*(31), 10554–10561. https://doi.org/10.1523/JNEUROSCI.0362-12.2012

Vera, J., Redondo, B., Bardon, A., Perez-Castilla, A., Garcia-Ramos, A., & Jimenez, R. (2020). Effects of caffeine consumption on intraocular pressure during low-intensity endurance exercise: A placebo-controlled, double-blind, balanced crossover study. *Clinical Science*, *48*(5), 602–609. https://doi.org/10.1111/ceo.13755

Verster, J. C., & Roth, T. (2013). Vigilance decrement during the on-the-road driving tests: The importance of time-on-task in psychopharmaco-logical research. *Accident Analysis and Prevention*, *58*, 244–248. https://doi.org/10.1016/j.aap.2012.10.005

Wang, H., & He, Q. (2020). The effects of meditation on attention. *Advances in Psychological Science*, *28*(2), 284–293. https://doi.org/10.3724/sp.J.1042.2020.00284

Willis, M. L., Murphy, J. M., Ridley, N. J., & Vercammen, A. (2015). Anodal tDCS targeting the right orbitofrontal cortex enhances facial expression recognition. *Social Cognitive and Affective Neuroscience*, *10*(12), 1677–1683. https://doi.org/10.1093/scan/nsv057