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RESEARCH ARTICLE

Effects of transcranial direct current stimulation on inhibition-related oscillatory brain activity during an emotional antisaccade task

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ABSTRACT

Objective: Previous studies have shown that transcranial direct current stimulation (tDCS) applied to the dorsolateral prefrontal cortex (dlPFC) can enhance attentional performance and influence emotional processing. However, the neural mechanisms underlying these effects are not fully understood. This study aimed to investigate oscillatory changes following tDCS over the dlPFC, with the hypothesis that anodal stimulation of the right dlPFC would modulate inhibition-related oscillations in the presence of threatening faces compared with left dlPFC stimulation.

Method: Thirty-six healthy participants underwent bilateral tDCS to the dlPFC. One group received anodal tDCS to the right dlPFC and cathodal to the left dlPFC, while the second group received the opposite montage. A control group received sham stimulation. Before and after stimulation, behavioral performance and event-related theta oscillations were recorded during an antisaccade task involving neutral and angry faces.

Results: Compared to the left-dlPFC group, the right-dlPFC group showed lower theta responses at F3 after anodal stimulation, particularly during antisaccade trials with angry faces, which are known to impose higher inhibitory demands due to threat salience. No group differences were found in saccade latencies. These findings suggest that anodal right dlPFC stimulation modulates oscillatory activity related to inhibitory control under emotionally salient conditions.

Conclusion: A decrease in theta oscillations following anodal tDCS over the right dlPFC may indicate enhanced inhibitory control during the processing of threatening stimuli. These results point to a potential role of dlPFC-targeted tDCS in regulating cognitive control and emotional processing, particularly in individuals with difficulties in these domains. However, the directionality and causality of these effects cannot be conclusively established due to limitations of the current study design.

Keywords: Antisaccade, event-related oscillations, theta band, transcranial direct current stimulation

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INTRODUCTION

The antisaccade task is a cognitive task used to assess inhibitory control by suppressing reflexive eye movements and initiating voluntary movements in the opposite direction (1). This process engages brain regions such as the frontal eye fields (FEF), the dorsolateral prefrontal cortex (dlPFC), the superior colliculus, and the basal ganglia (2, 3). Modified versions, such as the emotional antisaccade task, use emotionally valenced stimuli (e.g., angry faces), which reduce reaction times compared to neutral faces, suggesting heightened arousal and attentional engagement (4). Angry faces were selected in this study due to their well-documented capacity to rapidly capture and sustain attention and their increased salience in peripheral vision, which imposes greater demands on inhibitory control mechanisms in antisaccade tasks (5–7).

This study investigated whether transcranial direct current stimulation (tDCS) targets and modulates dlPFC excitability, a critical region for inhibitory control and cognitive functions. The dlPFC plays a key role in inhibiting reflexive saccades toward visual stimuli and facilitating antisaccade execution. Lesions or disruptions to the dlPFC impair antisaccade performance, highlighting its essential inhibitory role (8). The dlPFC directly inhibits saccade initiation via modulation of the superior colliculus and is crucial for suppressing reflexive saccades. While the basal ganglia and thalamus contribute to this control, their roles are considered secondary. Notably, the right dlPFC is particularly implicated in emotion-related cognitive control, exerting top-down regulation over limbic regions such as the amygdala during threat processing (e.g., angry faces) and facilitating attentional disengagement from emotionally salient stimuli (9, 10). A systematic review summarizing 26 studies combining tDCS and eye-tracking demonstrated that tDCS, particularly when targeting prefrontal regions, can modulate oculomotor behaviors and related cognitive and emotional processes across both healthy and clinical populations (11). Despite growing interest in tDCS, studies specifically examining its effects on inhibitory control at the neural and behavioral levels while considering emotional valence remain scarce in the literature. By addressing this gap, the current study has the potential to offer novel insights into the neurocognitive underpinnings of executive function and inform the development of more targeted, evidence-based interventions for both clinical and non-clinical populations.

A growing body of literature investigates correlates of inhibitory control during the antisaccade task, with particular focus on event-related potentials (ERPs) (12, 13). Components such as the N200 and P300 are linked to cognitive mechanisms underlying response inhibition and error detection (14), both critical for antisaccade performance. Research suggests that tDCS targeting the left dlPFC can enhance reaction times and modulate ERP responses, with studies showing that tDCS increases P300 amplitude, an ERP marker associated with selective attention, conflict monitoring, and response inhibition, particularly in cognitive control tasks such as the Flanker task (15).

Beyond ERPs, oscillatory dynamics—particularly in the theta range (4–7 Hz)—play a crucial role in cognitive control, including antisaccade inhibition mechanisms. Frontal midline theta activity, associated with top-down executive control, increases during response inhibition, error monitoring, and conflict resolution (16, 17). While beta and alpha oscillations have also been linked to antisaccade performance (18), van Noordt et al. (19) showed that medial frontal theta activity increases during response preparation and enhances post-error, suggesting theta's role in both proactive and reactive control. Although tDCS modulates theta activity in cognitive control paradigms (20, 21), its role in antisaccade inhibition remains underexplored. Examining theta activity in emotional antisaccade tasks may reveal neural mechanisms of inhibition and cognitive-emotion interactions, complementing ERP research.

In summary, the antisaccade task is a robust measure of dlPFC function, with event-related oscillations (EROs) providing insights into its electrophysiological underpinnings. tDCS over the dlPFC can enhance inhibitory control by modulating neural circuits. This study explores oscillatory brain activity changes during an emotional antisaccade task following tDCS to the dlPFC, particularly examining the influence of emotional valence (angry faces) on inhibitory control. It builds on existing research linking the dlPFC to cognitive control and its interaction with emotion (3, 8). By analyzing theta oscillations, this study aims to deepen understanding of inhibitory control (16, 17, 19) and contribute to targeted interventions for inhibitory dysfunction. We hypothesize that anodal tDCS over the right dlPFC will more effectively modulate inhibition-related theta oscillatory activity, particularly in response to threatening (angry) faces, compared to neutral faces and to anodal tDCS over the left dlPFC or the sham condition.

METHODS

Participants

This study employed a randomized, placebo-controlled design in which 36 healthy individuals aged between 20 and 40 years (23 women; mean age=23.3, standard deviation [SD]=4.4 years) were assigned to one of three groups using a computer-generated, permutation-based randomization procedure: (1) right anodal/left cathodal tDCS targeting the right dlPFC (n=11; four women, mean age=24, SD=1.7 years), (2) left anodal/right cathodal tDCS targeting the left dlPFC (n=10; eight women, mean age=22, SD=0.3 years), or (3) sham stimulation (n=15; 11 women, mean age=23.6, SD=1.2 years). All participants were recruited through online advertisements and university bulletin boards. Exclusion criteria included a history of psychiatric or neurological disorders, self-reported current psychiatric or neurological conditions, use of medications (e.g., psychotropic drugs), left-handedness, and the presence of implanted medical devices (e.g., brain stimulators, pacemakers, shrapnel, or surgical clips) (22).

Emotional Antisaccade Task

Immediately before and after tDCS, participants completed an emotional antisaccade task. The task followed Ansari and Derakshan's design (23), using angry and neutral facial expressions as targets (24). The face images were selected from the Karolinska Directed Emotional Faces (KDEF) (24) database, with an equal number of five male and five female identities (cf. (25)). The task consisted of eight blocks, each with 40 trials, including two blocks per condition: angry antisaccade, neutral antisaccade, angry prosaccade, and neutral prosaccade. Following a practice session, the experiment began with one of the four block types and alternated throughout the session. The order of these blocks varied across participants to minimize order effects. Each trial began with a fixation cross presented for an intertrial interval (ITI) that was continuously jittered between 2600 and 3600 ms, with values randomly drawn from a uniform distribution on each trial. Participants were instructed to maintain their gaze on the fixation cross. After the fixation cross disappeared (with a 200 ms gap), a face (3.3°×6°) appeared 11° to the left or right of the center of the screen. On prosaccade blocks, participants were instructed to look at the face, while on antisaccade blocks, they were instructed to look away from the face to its mirror position on the screen as quickly as possible without directly gazing at it. The faces remained on the screen for 600 ms (Fig. 1).

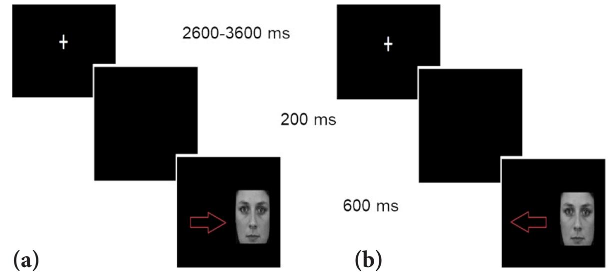

Figure 1. A schematic example of a prosaccade trial **(a)** and an antisaccade trial **(b)**.

tDCS Protocol

Thirty-six healthy participants received either 20 minutes of 2 mA active stimulation (11 with right anodal/left cathodal dlPFC stimulation and 10 with left anodal/right cathodal dlPFC stimulation) or sham stimulation (15 participants) using a bilateral montage. During stimulation, participants were instructed to sit quietly with their eyes open without performing any tasks. tDCS was delivered using a battery-powered direct current (DC) stimulator (NeuroConn, Ilmenau, Germany) and two saline-soaked rubber electrodes (5×7 cm), each covered with a 35 cm^2 sponge. Approximately 6 mL of saline solution was applied to each side of the sponge (front and back), totaling 12 mL per sponge. Electrode placement was determined using the BeamF3 online calculator (26), which incorporated individual head measurements (head circumference, nasion-inion distance, and tragus-tragus distance) based on the 10/20 electroencephalography (EEG) system. For active stimulation, the anode was placed over either the left dlPFC (F3) or the right dlPFC (F4), while the cathode was positioned over the corresponding region in the contralateral hemisphere, following a consistent montage across participants. The 5 cm edge of the sponge was oriented parallel to the ear, while the 7 cm edge was oriented parallel to the forehead. Before placement, hair at the electrode sites was parted to ensure optimal electrode-scalp contact. Two elastic straps secured the electrodes, maintaining impedance below 5 kΩ throughout the session. In the sham condition, electrodes were placed identically (F3 for half of the participants and F4 for the other half), but the current was ramped up to 2.0 mA and then ramped down at the beginning and end of the stimulation period to maintain participant blinding. The antisaccade task was administered both before and after tDCS while the EEG cap remained in place, with a consistent interval of no more than five minutes between tDCS completion and post-stimulation testing.

EEG Data Acquisition and Preprocessing

The EEG recordings were conducted in a quiet, dark room at the Neurotechnology and Bioinformatics Laboratory, Uskudar University. Data were recorded using the international 10–20 system with 30 Ag–AgCl active electrodes fixed to an elastic cap (Brain Products, Munich, Germany). The left mastoid served as the offline reference, and the ground electrode was placed at the medial frontal site. Eye movements were tracked using two electrodes placed around the right eye. Signals were amplified using the actiCHamp Plus system (0.1–250 Hz bandpass filter, 500 Hz sampling rate). Stimuli were displayed on a monitor positioned 50 cm from participants, with one computer controlling presentation and another dedicated to EEG recording.

Saccade latencies (SLs) were computed from the difference between the left and right horizontal electrooculogram (HEOG) signals. Saccades were identified as peaks, with those exceeding 50 μV in the expected direction (polarity) classified as valid. SLs with durations shorter than 80 ms or longer than 500 ms were excluded (23).

EEG preprocessing and oscillatory analysis were performed using BrainVision Analyzer (v2.2.2.8298, available at https://www.brainproducts.com). Raw data were filtered with a 0.5–60 Hz bandpass and a 50 Hz notch filter. Data were re-referenced to the averaged mastoid electrodes. Segments with prolonged artifacts were interpolated, and ocular artifacts were corrected using an ocular correction (classical regression-based algorithm, (27). Ocular correction was applied without time-range restrictions and conducted prior to segmentation. Data were segmented from -100 to+700 ms relative to each experimental condition. Fast muscle artifacts were removed using a semi-automated procedure; segments exceeding 50 μV/ms, 200 μV/200 ms, or showing <0.5 μV activity were excluded. Baseline correction was applied using a −100 ms pre-stimulus interval. Cleaned segments were averaged across the four conditions and extracted from nine electrodes (C3, C4, Cz, F3, F4, Fz, P3, P4, and Pz). Each participant's condition-specific averaged data was filtered in the theta band (4–7 Hz). The largest peak-to-peak difference (in microvolts) between 0 and 500 ms after the presentation of the faces was identified using the peak detection feature in BrainVision, and all detected peaks were then visually verified for accuracy. Finally, the event-related theta oscillatory responses for each experimental condition were analyzed and compared.

Questionnaires

The trait subscale of the State-Trait Anxiety Inventory (STAI-T) (28) was used to assess individual differences in baseline anxiety, which are known to influence cognitive control and emotional processing, both relevant to antisaccade task performance and potentially modulated by tDCS. The STAI-T comprises 20 self-report items rated on a four-point Likert scale (total scores 20-80), with seven reverse-scored items; higher scores indicate greater trait anxiety. The scale demonstrates strong internal consistency (α=0.89), and its Turkish adaptation (29) shows high psychometric quality (test-retest r=0.73). In this study, internal consistency was α=0.85.

The Attentional Control Scale (ACS) (30) includes 20 items assessing voluntary attentional control on a four-point scale, where higher scores reflect better control. The original version shows good reliability (α=0.88; test-retest r=0.61), and the Turkish adaptation (31) maintains acceptable consistency (α=0.78; item-total correlations 0.28-0.45). In the current study, reliability was α=0.80.

Procedure

Before the experiment, all participants were fully informed about the procedures and potential tDCS side effects before providing written consent. They performed the antisaccade task both before and immediately after tDCS, with reaction time, accuracy, and EEG data recorded to assess stimulation effects. After the session, participants were asked verbatim: "Do you think you received real tDCS stimulation?" All procedures were conducted at Uskudar University's Neurotechnology and Bioinformatics Laboratory in compliance with the Declaration of Helsinki ethical guidelines and were approved by the Uskudar University Clinical Research Ethics Committee (Approval No: 61351342/2017/04).

Statistical Analyses

Age, STAI-T, and ACS scores were compared among the three groups using one-way analysis of variance (ANOVA), while gender distribution was analyzed using a chi-square test. SLs and peak-to-peak amplitudes of event-related theta oscillations were calculated during the antisaccade task, which included neutral and angry face conditions. One participant from the right tDCS group was excluded from the behavioral analysis due to abnormally high SLs, identified as outliers relative to the group distribution. After excluding this participant from the right tDCS group, SLs were confirmed to be normally distributed across all conditions (Shapiro–

Table 1: Descriptives for the ACS and the Trait Subscale of The State-Trait Anxiety Inventory across groups

	Age		ACS		STAI-T	
	Mean	SD	Mean	SD	Mean	SD
Left tDCS	22	0.3	50.78	2.95	43	2.74
Right tDCS	24	1.7	52.75	2.86	38.88	1.86
Sham	23.6	1.2	55.67	1.48	41.93	2.05

ACS: Attentional Control Scale; STAI-TA: State-Trait Anxiety Inventory-Trait Subscale; tDCS: tDCS: Transcranial direct current stimulation; SD: Standard deviation.

Wilk test: all p>0.05). Therefore, results are reported as means and analyzed using parametric statistical tests. Mean SLs were analyzed using repeated-measures ANOVA. The within-subject factors included tDCS session (pre vs. post), face emotion (angry vs. neutral), and task condition (prosaccade vs. antisaccade), while the between-subject factor was group (left tDCS, right tDCS, or sham). Additionally, percent change scores were calculated using the following formula:

*((Pre-tDCS-Post-tDCS)/Post-tDCS)*100.*

Peak-to-peak amplitudes of EROs in the theta band were analyzed using repeated-measures ANOVA. Within-subject factors included electrode location (C3, C4, Cz, F3, F4, Fz, P3, P4, and Pz), tDCS session (pre vs. post), face emotion (angry vs. neutral), and task condition (prosaccade vs. antisaccade), while the between-subject factor was group (left tDCS, right tDCS, or sham). Subsequently, reduced repeated-measures ANOVA designs were employed to determine the source of the observed effects in terms of group and electrode location. To this end, separate post hoc ANOVAs were conducted for each electrode location, with within-subject factors including tDCS session (pre vs. post), face emotion (angry vs. neutral), and task condition (prosaccade vs. antisaccade), and the between-subject factor being group (left tDCS, right tDCS, or sham). The significance threshold was adjusted to p=0.006 (0.05/9) to correct for multiple comparisons.

Moreover, percent change scores were calculated for the three groups to evaluate the relative change in theta oscillatory responses between pre- and post-tDCS sessions, using the same formula as for the behavioral scores. Difference scores between prosaccade and antisaccade task conditions were then computed separately for angry and neutral faces and analyzed using one-way ANOVAs to determine which emotion or group contributed to the observed effect (corrected p=0.025 (0.05/2)). Finally, we explored potential correlations between SLs and significant theta oscillatory findings identified in the study, applying a Bonferroni-corrected significance threshold of p=0.0006.

RESULTS

No significant adverse events or unintended side effects were reported, and none of the participants realized they had received sham stimulation. For STAI-T (F(2.29)=0.88, p=0.43) and ACS (F(2.33)=1.83, p=0.18), the results indicate that the differences between groups were not statistically significant. In terms of age and gender, there were no statistically significant differences across the three groups (age: F(2.33)=0.64, p=0.53; gender: χ^2(2, N=36)=5.32, p=0.07). These results suggest that the groups were comparable in terms of age, gender, attentional control, and trait anxiety at baseline (Table 1).

Changes in Saccade Latencies

Descriptive statistics for antisaccade task SLs by condition are presented in Table 2.

A three-way repeated-measures ANOVA revealed significant main effects of tDCS session (pre vs. post) (F(1.32)=9.94, p=0.004) and congruency condition (antisaccade vs. prosaccade blocks) (F(1.32)=376.959, p=0.0001) on SLs. Participants exhibited slightly faster SLs following the tDCS session compared to pre-tDCS (mean SLs: 214.62±4.54 ms vs. 207.68±4.19 ms). Additionally, mean SLs were faster during prosaccade blocks, where participants were instructed to look at the faces, compared to antisaccade blocks, which required them to look away from the faces (170.35±3.31 ms vs. 251.95±5.79 ms). A significant interaction between emotion (angry vs. neutral) and tDCS session (pre vs. post) was also observed (F(1.32)=267.58, p<0.019). The mean change in SLs between pre- and post-tDCS sessions was significantly larger for neutral faces (216.04±4.79 ms vs. 207.1±4.17 ms) compared to angry faces (213.21±4.37 ms vs. 208.26±4.28 ms) (Fig. 1). In contrast, there was no significant tDCS session × group interaction (p>0.05).

Changes in Event-Related Oscillatory Responses

Peak-to-peak amplitudes of ERO in the theta band were analyzed using repeated-measures ANOVA. The results revealed a significant main effect of condition

Table 2: Summary of antisaccade task SLs by condition for three groups, pre- and post-tDCS

Condition	Group	Pre-tDCS		Post-tDCS	
		Mean	SD	Mean	SD
Prosaccade neutral	Left tDCS	181.62	30.52	167.83	28.20
	Right tDCS	168.29	8.40	166.39	11.48
	Sham	169.58	18.17	170.42	15.57
Prosaccade angry	Left tDCS	174.53	26.81	169.27	28.88
	Right tDCS	166.98	8.70	166.21	12.52
	Sham	172.16	23.26	170.89	15.50
Antisaccade neutral	Left tDCS	266.90	49.55	246.98	37.04
	Right tDCS	245.96	22.24	244.85	23.50
	Sham	263.85	41.55	246.13	37.06
Antisaccade angry	Left tDCS	258.55	43.42	246.60	36.93
	Right tDCS	247.61	23.05	244.24	27.24
	Sham	259.44	33.56	252.34	36.79

SLs: Saccade latencies; tDCS: Transcranial direct current stimulation; SD: Standard deviation.

(antisaccade vs. prosaccade blocks) ($F(1.33)=10.14$, $p=0.003$) and location ($F(8.264)=7.91$, $p=0.0001$) on theta oscillatory responses. Theta oscillatory responses were higher for all participants during prosaccade blocks, where participants were instructed to look at the faces, compared to antisaccade blocks, which required them to look away from the faces (4.665±0.196 vs. 4.156±0.16) (Fig. 2a). The group effect was marginally significant ($F(2.33)=2.94$, $p=0.06$). The right tDCS group showed the lowest theta oscillatory responses (left: 4.888±0.299>sham: 4.451±0.244>right: 3.893±0.285) (Fig. 2b).

Moreover, a significant interaction between electrode location, tDCS (pre vs. post), emotion (angry vs. neutral), condition (antisaccade vs. prosaccade), and group (left tDCS, right tDCS, or sham) was observed ($F(16.264)=2.83$, $p<0.007$). To further explore this interaction, follow-up ANOVAs were conducted. To examine the main effect of electrode location, each electrode group was analyzed separately. A significant interaction was observed exclusively at the F3 electrode ($F(2.33)=9.24$, $p=0.001$). When percentage change scores between pre- and post-tDCS sessions, as well as difference scores between prosaccade and antisaccade conditions, were evaluated across the three groups for the F3 electrode, the largest changes were observed in response to angry faces ($F(2.33)=4.21$, $p=0.024$) (Fig. 3). The Bonferroni post hoc test revealed that this effect was particularly prominent in the anodal tDCS over the right dlPFC group compared to the sham group ($p=0.02$) (Fig. 3b, also see Fig. 4 for difference scores in each condition).

Correlations

Potential correlations were examined between the significant theta oscillatory findings and SLs, as well as measures from the State-Trait Anxiety Inventory and the Attentional Control Scale. No significant correlations were observed between these scales and any of the identified behavioral or theta oscillatory effects.

DISCUSSION

The present study explored the effects of anodal tDCS over the dlPFC on EROs in the theta band during antisaccade tasks involving emotional face stimuli. Our findings indicated that anodal tDCS over the right dlPFC reduced theta oscillatory responses at frontal electrode sites (F3) compared to the sham group, with this effect being more pronounced in response to angry faces. These results highlight the significant role of the right dlPFC in regulating inhibitory control, particularly under emotionally salient conditions.

Theta Oscillations and Inhibitory Control

Theta oscillations are widely recognized as key neural markers of cognitive control, particularly response inhibition. The observed changes in theta oscillations following anodal tDCS over the right dlPFC align with prior research demonstrating increased activation in frontal regions, including the dlPFC, FEF, and supplementary motor area (SMA), during antisaccade tasks (32). Theta oscillations are linked to top-down cognitive control (16). Increased theta coupling between prefrontal and posterior regions during

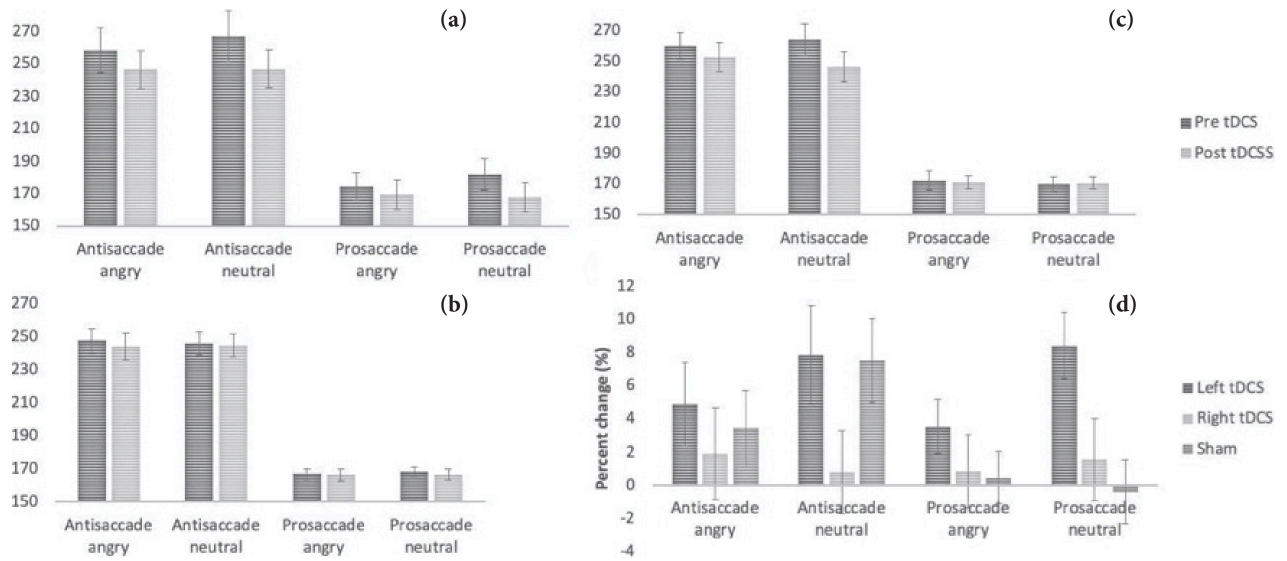

Figure 2. Panels a, b, and c display mean saccade latencies (SLs) (y-axis, in milliseconds) for the antisaccade task among participants receiving left transcranial direct current stimulation (tDCS) **(a)**, right tDCS **(b)**, and sham stimulation **(c)**. Each panel compares pre- and post-tDCS sessions (upper right legend), with separate bars for angry versus neutral face stimuli under both prosaccade and antisaccade conditions. Panel **d** presents the percentage change in SLs between pre- and post-tDCS applications for each group (bottom right legend). Error bars represent the condition-specific standard errors of the mean.

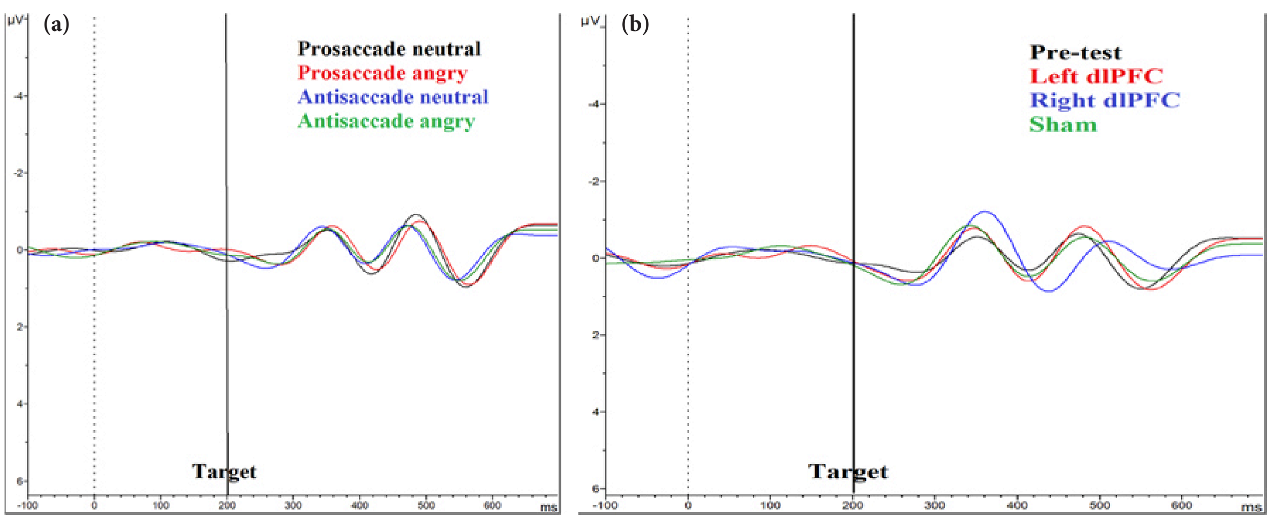

Figure 3. (Panel a) Grand-averaged event-related theta oscillations at the Fz electrode, pooled across all experimental conditions and participants during the pre-transcranial direct current stimulation (pre-tDCS) session. **(Panel b)** Grand average event-related theta oscillations in response to angry faces during antisaccade trials at the Fz electrode. The pre-tDCS line reflects the group average prior to stimulation, whereas the post-tDCS lines are shown separately for each group. The stimulus was presented at 200 ms.

task switching reflects increased cognitive control demands (33). Lower resting-state theta power has been associated with failures in response inhibition. Theta activity also increases with higher working memory load (34) and serves as a marker of motor inhibition, as evidenced by elevated frontal theta in No-Go trials (35).

Interestingly, our findings diverge from much of the existing literature, as we observed a decrease in theta EROs after antisaccade trials, precisely when cognitive control demands were heightened, particularly in response to angry faces. This contrasts with previous studies that typically report increased theta activity under conditions requiring greater inhibitory control,

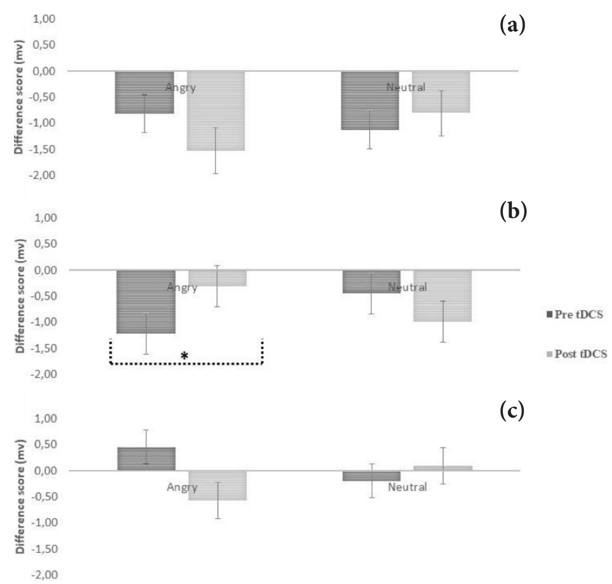

Figure 4. Difference scores for theta oscillatory responses were presented separately for the two emotional conditions by subtracting theta activity during prosaccade trials from that during antisaccade trials at the F3 electrode. These difference scores are presented for each transcranial direct current stimulation (tDCS) group before and after tDCS sessions: left tDCS **(a)**, right tDCS **(b)**, and sham **(c)**. Error bars represent the condition-specific standard errors of the mean.

suggesting that emotional valence may differentially modulate theta oscillatory dynamics in the context of response inhibition. On the other hand, this challenges the traditional view that theta oscillatory responses uniformly increase with cognitive effort. Notably, the relationship between theta oscillations and cognitive efficiency appears to follow a non-linear, inverted U-shaped pattern. Snipes et al. (36) demonstrated that moderate increases in theta power enhance cognitive performance, whereas excessive theta activity elevations due to cognitive overload or fatigue impair functional efficiency. In this context, the observed decrease in theta activity following anodal tDCS over the right dlPFC may reflect a shift toward optimized neural efficiency and resource allocation. This may indicate that tDCS helps streamline cognitive control processes, reducing the neural effort required to perform complex tasks such as the antisaccade paradigm.

Theta Oscillations and Emotional Processing

The heightened demand for inhibitory control aligns with prior research demonstrating increased activation in frontal regions, including the dlPFC, FEF, and SMA (26), as well as elevated theta power during antisaccade tasks (37). Furthermore, the greater theta activity observed in response to emotional faces (38) further supports the involvement of theta oscillations in regulating cognitive control under emotionally salient conditions. These findings reinforce the idea that emotionally charged stimuli necessitate stronger cognitive control mechanisms to override automatic responses, a process reflected in theta power modulation.

Furthermore, a network-based perspective from functional magnetic resonance imaging (fMRI) studies indicates that antisaccade trials show stronger functional connectivity between key regions, including the salience network, default mode network (DMN), frontoparietal network (FPN), and amygdala, compared to prosaccade trials. Additionally, angry facial expressions necessitate greater functional connectivity within the salience network, which likely facilitates the detection of emotionally relevant stimuli. The DMN may contribute to internal cognitive states, while the FPN is more involved in the cognitive control aspects of the antisaccade task. Increased engagement of the ventrolateral prefrontal cortex and orbital regions in response to angry faces suggests additional regulatory mechanisms involved in emotional inhibition and attentional reorientation (39), whereas happy faces predominantly recruit parieto-occipital, temporal, and cerebellar regions. These findings support the idea that emotionally salient stimuli, such as angry faces, demand greater cognitive resources and involve widespread neural recruitment for efficient inhibitory control and attentional modulation.

tDCS and Its Role in Inhibitory Control

Our results align with previous studies demonstrating the modulatory effects of tDCS on cognitive and emotional processing. Other studies have shown that anodal stimulation over the left dlPFC can increase theta power (40), whereas anodal stimulation over the right inferior frontal cortex has been associated with decreased theta amplitude at EEG recording sites during rest (41). These discrepancies highlight the importance of stimulation parameters and task demands in shaping tDCS effects on oscillatory dynamics.

We observed that anodal tDCS over the right dlPFC decreased theta oscillations on the left hemisphere (F3). Although we did not assess the effects of tDCS on functional connectivity, this result may reflect modulation of tDCS on interhemispheric connectivity. According to Zheng et al. (42), tDCS has a significant impact on interhemispheric connectivity; their study showed that applying anodal tDCS to the right inferior frontal gyrus (IFG) decreased interhemispheric connectivity between the right and left IFG.

The diminished theta activity observed post-tDCS in the right dlPFC group during antisaccade trials suggests that stimulation may reduce the need for compensatory cognitive control mechanisms. By enhancing functional connectivity and optimizing network efficiency, tDCS facilitates cognitive performance by shifting neural processing dynamics toward a more efficient state. This supports the potential application of tDCS as a non-invasive neuromodulatory tool for refining cognitive and emotional regulation processes.

tDCS over the right dlPFC enhances inhibitory control in antisaccade tasks by improving reaction times and reducing errors (43). However, findings remain mixed, likely due to variations in task complexity and individual differences (44). In our study, although tDCS modulated theta oscillatory activity, no significant behavioral effects on antisaccade accuracy were observed. This dissociation between neural and behavioral outcomes may suggest that EEG measures are more sensitive to subtle changes in cortical processing than overt behavioral performance, particularly in paradigms with high within-subject variability. It is important to explicitly acknowledge that EEG findings were not directly mirrored by behavioral effects. This may be due to the acute, relatively low-intensity (2 mA) stimulation. Higher intensities (≥2 mA) or repeated sessions may be needed to engage deeper cortical layers and induce longer-lasting neural plasticity (45). While the acute effects of brain stimulation have been observed in cortical areas, prolonging stimulation duration or incorporating repeated sessions could enhance learning-based plasticity, thereby increasing the likelihood of behavioral modulation. Moreover, individual differences, including baseline neurophysiological states and cognitive traits, likely contribute to variability in behavioral responses to noninvasive neuromodulation.

Limitations

Although all participants were presumed to be right-handed based on self-report, handedness was not formally assessed in this study. This represents a notable limitation, as individual differences in hemispheric dominance may influence the effects of lateralized tDCS stimulation. While participants did not use their hands to respond during the antisaccade task, hemispheric asymmetries related to handedness could still impact neural processing. Future studies employing lateralized neuromodulation protocols should include a standardized assessment of handedness to account for its potential influence on outcomes. Another limitation of the study is the absence of a structured diagnostic interview (e.g., Structured Clinical Interview for DSM; SCID). Although self-reported psychiatric or neurological conditions and past psychiatric/neurological history were used as exclusion criteria, formal clinical assessments were not conducted. Given that the study focused on healthy participants, structured interviews were not implemented; however, their inclusion would have strengthened the screening process. Additionally, the exclusive focus on angry facial expressions limits the generalizability of the findings to other emotional contexts. Moreover, the complexity of the 2×2×2×3 factorial design applied across nine electrode sites may have exceeded the statistical power provided by the available sample size, potentially limiting the interpretability of some effects even with Bonferroni correction. Although cluster-based permutation methods offer a powerful, data-driven approach for detecting spatiotemporal clusters of activity, they are less well suited for testing predefined interaction effects within complex factorial designs. A key limitation of the study is the absence of eye-tracking data; relying solely on EEG and behavioral measures to infer saccadic activity may limit the precision in capturing oculomotor dynamics such as saccade amplitude and velocity, which are more accurately measured using dedicated eye-tracking systems. This limitation may partly explain the lack of significant behavioral findings observed in the study. Additionally, the lack of effective connectivity analyses (e.g., Granger causality) limits insights into directional interactions between brain regions. Future studies should incorporate such methods to clarify the network-level effects of tDCS during emotional antisaccade tasks.

Implications and Future Directions

The present study contributes to the growing body of research on the neurophysiological underpinnings of cognitive control and the role of tDCS in modulating neural activity. Our results suggest that anodal tDCS over the right dlPFC may potentially, though speculatively, enhance inhibitory control by reducing theta oscillatory responses, particularly in the presence of threatening stimuli. The findings support the use of tDCS in modulating underlying neural oscillations to enhance inhibitory control, highlighting its potential as a valuable tool for cognitive and affective interventions. Future studies should explore the long-term effects of repeated tDCS sessions in larger samples, individual differences in tDCS responsiveness, and the potential translational applications of these findings in clinical populations, such as individuals with anxiety or impulse control disorders.

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