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The effect of tDCS on emotion-related risk-taking behavior and delay discounting in adults with ADHD

Zehra Uçar Hasanlı [a,*], Erguvan Tuğba Özel Kızıl [a], Burçin Çolak [a], Farhad Nassehi [b], Zeynel Baran [c], Deha Onar [a], Ayşe Handenur Bayraktar Özdemir [a], Jamal Hasanlı [d]

[a] Ankara University, Faculty of Medicine, Department of Psychiatry, Ankara, Turkey
[b] TOBB University of Economics and Technology, Faculty of Engineering, Department of Biomedical Engineering, Ankara, Turkey
[c] Hacettepe University, Faculty of Psychology, Ankara, Turkey
[d] Başkent University, Faculty of Medicine, Department of Psychiatry, Ankara, Turkey

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ABSTRACT

Introduction: Adults with Attention Deficit Hyperactivity Disorder (ADHD) often engage in risky behaviors due to impaired decision-making processes. This study aims to investigate the effects of transcranial direct current stimulation (tDCS) over the dorsolateral prefrontal cortex (dlPFC) and ventromedial prefrontal cortex (vmPFC) on emotion-related risk-taking behavior and delay discounting in adults with ADHD.

Methods: Thirty adults with ADHD underwent three tDCS conditions, administered in a randomized order with at least one week between sessions: (1) left dlPFC anode/right vmPFC cathode, (2) left dlPFC cathode/right vmPFC anode, and (3) sham stimulation. In each session, participants completed the Delay Discounting Task (DDT) and the Modified Balloon Analogue Risk Task (mBART) under three emotional conditions (neutral, positive, and negative) which were induced using emotionally congruent photographs and sounds. Galvanic skin responses (GSR) were also recorded. In the DDT, both area under the curve (AUC) values and log-transformed discounting rates (log k) were calculated for small, medium, and large reward magnitudes (RM). Exploratory electric field modeling was also performed to characterize current distribution.

Results: The findings demonstrated task-specific effects of tDCS on decision-making. Although no overall tDCS effect was observed on DDT performance, significant tDCS × RM interactions emerged, particularly for smaller rewards. In contrast, exploratory analyses suggested that tDCS affected all mBART scores. Emotional condition did not influence consistently behavioral performance in either task, whereas both emotional stimulation and tDCS significantly affected GSR responses. However, exploratory electric field modeling indicated a broad prefrontal current distribution extending beyond the intended cortical targets.

Conclusions: These findings suggest preliminary evidence that prefrontal tDCS can influence risk-related decision-making and autonomic responses in adults with ADHD. However, its effects on delay discounting appear to be context-dependent and limited to specific RMs. Future studies combining neuroimaging with individualized electric field modeling are needed to clarify the neural mechanisms underlying the observed effects of tDCS and to optimize stimulation protocols in adults with ADHD.

1. Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is a neurodevelopmental condition that typically begins in childhood and is characterized by persistent difficulties with attention, hyperactivity, and impulsivity, often accompanied by impairments in academic and social functioning (American Psychiatric Association, 2013). In adulthood, individuals with ADHD are more likely to experience difficulties in interpersonal relationships and occupational settings, along with an increased risk of accidents, substance use, and risky sexual behaviors compared to their neurotypical peers (Kosheleff et al., 2023). A key factor contributing to this elevated vulnerability may be risky decision-making (RDM) (Pollak et al., 2019). Core aspects of impulsivity, such as lack of foresight, devaluation of delayed rewards, and deficits in inhibitory control, have been shown to contribute to RDM in both experimental settings and real-world contexts (Buelow, 2020).

* Corresponding author. Kızılay Kan Merkezi Yanı, Mamak Caddesi Dikimevi Ankara Üniversitesi Tıp Fakültesi Cebeci Hastanesi, Mamak, 06590, Ankara, Turkey.
E-mail address: zehraucar93@gmail.com (Z.U. Hasanlı).

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Delay discounting (DD) refers to the reduction in the perceived value of rewards that are delayed (Odum, 2011), and DD paradigms are commonly used to assess RDM. In these tasks subjects select between a small, immediate reward and a larger, delayed one. In these tasks, individuals choose between a smaller, immediate reward and a larger, delayed one. In some cases, suboptimal decision-making occurs, where larger future rewards are sacrificed for smaller immediate ones (Marx et al., 2021). For instance, adults with ADHD demonstrate a greater tendency to choose smaller, immediate rewards compared to neurotypical individuals, as shown in studies by Krause-Utz et al. (2016) and Mostert et al. (2015). DD has been attributed to impairments in cognitive control and reward processing (Buelow, 2020). The Dual Pathway Model suggests that dysfunction in at least two distinct neural circuits contributes to ADHD symptoms (Sonuga-Barke, 2002). These include the ventrolateral and dorsolateral corticostriatal circuits, associated with executive functioning, and the mesolimbic circuit (including the medial prefrontal and orbitofrontal cortices) linked to motivation and reward processing. Dysfunction across these networks is believed to underlie the preference for smaller, immediate rewards (Groen et al., 2013). A meta-analysis highlighted that, during DD tasks, individuals with ADHD exhibit hypoactivation in the dorsolateral prefrontal cortex (dlPFC) and hyperactivation in the ventromedial prefrontal cortex (vmPFC) and striatum compared to neurotypical controls (Chen et al., 2021).

The DDT can be considered an explicit gambling task in which individuals choose between two clearly defined options. Performance on such tasks is typically classified as risk-based decision-making (Groen et al., 2013). However, judgements in everyday life are not always made under such transparent conditions. Therefore, a variety of gambling tasks have been employed to investigate the relationship between ADHD and RDM. The Iowa Gambling Task (IGT) (Bechara et al., 1994) and the Balloon Analogue Risk Task (BART) (Lejuez et al., 2003), are among the most frequently used paradigms to assess decision-making under ambiguity or implicit risk, where outcomes are initially unknown. Both tasks begin without providing prior information about the nature of the card decks or the balloon explosion probabilities and are thus considered implicit gambling tasks. As the task unfolds, participants gradually acquire task-relevant knowledge, and their decisions shift from those made under uncertainty to those made under risk. Successful performance in both tasks depends on intact learning and working memory capacities.

Although everyday decisions may appear straightforward, making optimal choices often requires careful consideration of both immediate and long-term consequences. Therefore, intact global cognitive functioning is essential for sound decision-making. Emotions are associated with an instinctive form of decision-making that is related to—but distinct from—cognitive processes. The “Dual Process Model” (DPM) posits that decision-making is governed by two separate systems (Evans and Stanovich, 2013). The first, known as Type 1 or the “hot system,” is fast, automatic, and emotion-driven. It operates without engaging deliberate cognitive resources and is typically impulsive in nature. The second, referred to as Type 2 or the “cold system,” involves higher-order cognitive abilities and is characterized as slow, deliberate, and logical (Stanovich et al., 2011). Optimal decision-making requires a balance between these two systems, neither of which should dominate or inhibit the other. The prefrontal cortex is associated with both Type 1 and Type 2 cognitive processes. The prefrontal cortex plays a central role in both systems: cognition-based decision-making (Type 2) has been associated particularly with dlPFC-mediated executive control processes, while emotion-based decision-making (Type 1) has been linked more strongly to vmPFC and its interactions with limbic structures such as the amygdala (Adolphs and Tranel, 2004).

In summary, transient emotional states are thought to influence decision-making processes, particularly through the Type 1 system (Andrade and Ariely, 2009). Two opposing theories have been proposed in the literature to explain this relationship (Colasante et al., 2017): the Affect Infusion Model(AIM) (Forgas, 1995) and the Mood Maintenance Hypothesis (MMH) (Isen and Patrick, 1983). According to the AIM, the influence of affect is amplified in complex situations that demand substantial cognitive effort. In other words, as situations become more intricate and less predictable, mood and emotions exert a greater impact on decisions and behaviors (Forgas, 1995). The model also suggests that positive affect enhances the perceived favorability of a given situation, thereby increasing the likelihood of risk-taking. In contrast, the MMH posits that individuals experiencing positive affect are less inclined to engage in risky behaviors compared to those in neutral or negative affective states (Isen et al., 1988). This tendency is thought to arise from a desire to preserve their positive emotional state and avoid potential threats to well-being.

The literature presents inconsistencies regarding how RDM is influenced by different emotional states. Some studies have shown that inducing a positive mood can reduce risky behaviors (Juergensen et al., 2018; Nygren et al., 1996). In contrast, other studies suggest that both positive and negative emotional stimuli may lead to risk avoidance (Drichoutis and Nayga Jr, 2013), while some report that both emotional states are associated with increased risk-taking (Conte et al., 2018). A recent systematic review and meta-regression identified a modest positive association between emotion-related impulsivity and RDM (Elliott et al., 2023). One of the most critical factors in studies involving emotional stimulation (ES) is the extent to which the stimuli effectively elicit emotional responses in participants The arousal characteristics of stimuli such as images or sounds are often determined using self-report measures (Bradley and Lang, 2007; Lang et al., 2005). However, objective physiological indicators such as heart rate and galvanic skin response (GSR) are also essential for linking decision-making paradigms to emotional states. These autonomic nervous system responses provide valuable insight into the intensity and nature of emotional arousal (Damasio, 1996).

tDCS is a non-invasive neuromodulation technique that delivers low-intensity direct current between anodal and cathodal electrodes placed on the scalp (Rezaei et al., 2023). Although findings remain inconsistent, tDCS has been studied for its potential effects on various cognitive domains, including working memory, inhibitory control, cognitive flexibility, attention, and impulsivity (Allenby et al., 2018; Breitling-Ziegler et al., 2021; Huang and Liu, 2025; Salehinejad et al., 2022; Soff et al., 2017; Soltaninejad et al., 2019). However, to the best of our knowledge, to date, no studies have examined the effects of tDCS on risk-taking and decision-making specifically in adults with ADHD. Only one study, conducted with children diagnosed with ADHD, reported that right vmPFC anodal stimulation was associated with reduced risk-taking and delay discounting, particularly in conditions involving large rewards (Nejati et al., 2021).

Currently, there is a lack of research on the effects of tDCS on emotion-related risk-taking behavior in adults with ADHD. Only one study, conducted in healthy adults, has investigated the effects of three tDCS conditions (anodal FPz–cathodal Cz, the reverse configuration, and sham) on emotion-related performance in the DDT. While a significant interaction was found between emotional condition, reward magnitude (RM), and tDCS condition, no significant main effects were observed (Manuel et al., 2019). Therefore, the present study was designed to examine whether emotion-related risk-taking and delay discounting could be influenced by tDCS montages targeting the dlPFC and vmPFC. The main hypothesis was that stimulation with a left dlPFC anode and right vmPFC cathode was expected to be associated with lower delay discounting and risk-taking compared to the reverse configuration and sham. Additionally, it was hypothesized that both RM and emotional condition would influence decision-making performance: smaller rewards were expected to increase DD, while positive and negative emotional states were expected to alter risk-taking and discounting behavior in distinct ways.

2. Methods

2.1. Participants

The study comprised 30 right-handed individuals, 15 men and 15 women, ranging in age from 18 to 45 years. All individuals fulfilled the diagnostic criteria for ADHD as outlined in the Diagnostic and Statistical Manual of Mental Disorders-5 (DSM-5) (American Psychiatric Association, 2013). ADHD diagnoses were confirmed using the Diagnostic Interview for ADHD in Adults-5 (DIVA-5) (Kooij et al., 2019). Detailed interviews according to ther DSM-5 criteria were conducted with all participants; current mood and anxiety disorders, as well as psychiatric disorders other than ADHD, were excluded. Exclusion criteria also included left-handedness, mental retardation, neurological disorders, and contraindications for tDCS such as metallic implants, pregnancy, evidence of elevated intracranial pressure, and history of head trauma. The executive functions were assessed by using Trail Making Tests A and B (TMT-A and TMT-B) (Reitan, 1955), while ADHD-related symptoms were evaluated by using the Adult ADHD Self-Report Scale (ASRS) (Kessler et al., 2007), the Wender Utah Rating Scale (WURS) (Ward et al., 1993), and the Difficulties in Emotion Regulation Scale-Short Form (DERS-16) (Bjureberg et al., 2016). No participants were excluded from the study based on these evaluations. All participants provided written informed consent and the study was approved by the Ethics Committee of the Ankara University (approval number İ02-71-22).

Also 17 participants reported using psychostimulants, and 13 reported smoking. To ensure that these uses did not affect the experiment, participants were given some instructions. Participants who smoked were instructed not to smoke during the 4 h preceding each experimental session. This interval was selected to minimize the acute cognitive and attentional effects of nicotine while reducing the likelihood of substantial nicotine withdrawal during testing (McLaughlin et al., 2015; Waisman Campos et al., 2016). Participants using psychostimulant medication were instructed not to take short-acting stimulants within 4 h before testing and long-acting stimulants within 12 h before testing. All participants were instructed to attend each session under the same medication and smoking conditions and verbally confirmed adherence before each session.

2.2. Procedure

The study is a single-blind, sham-controlled experiment where participants had three different tDCS conditions in three separate sessions

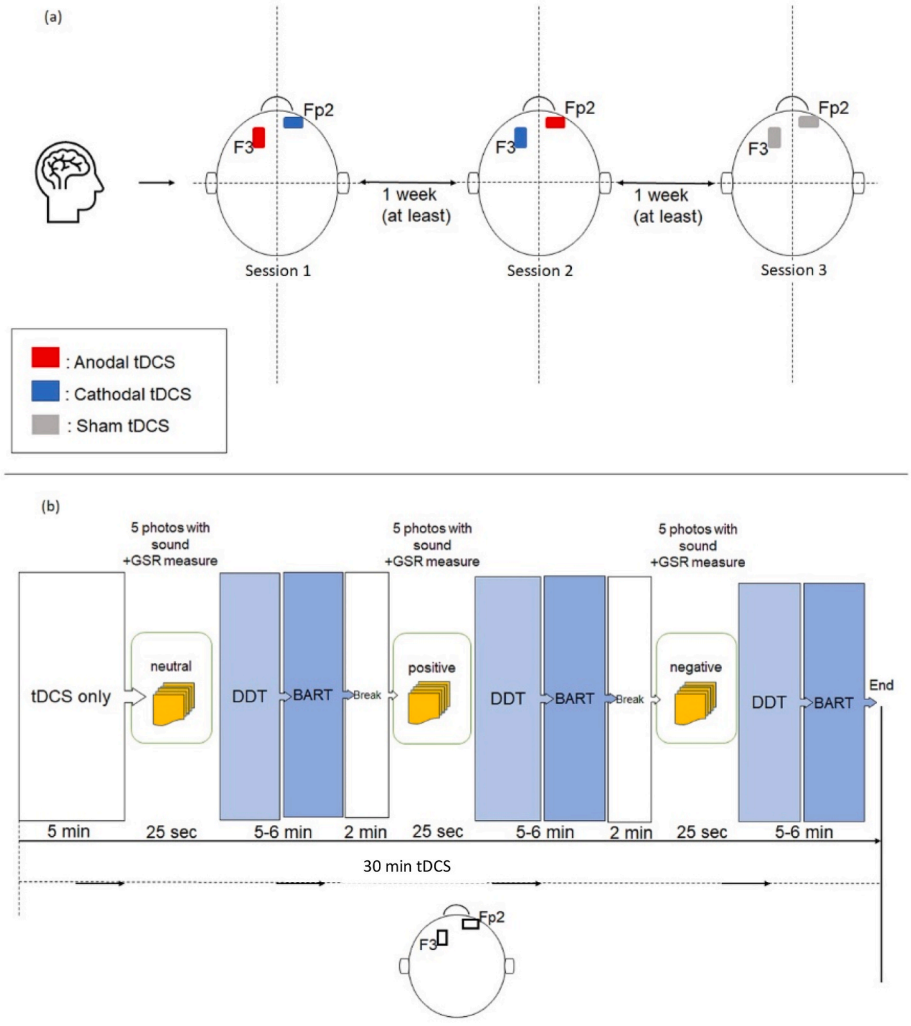


Fig. 1. Study design and experimental procedure.
Note: (a) Randomized, sham-controlled crossover design. Participants completed three sessions (active1, active2, and sham tDCS) separated by at least 1 week. (b) Experimental timeline within each session. Following 5 min of tDCS, participants completed emotional stimulation blocks with concurrent GSR recording, followed by the DDT and mBART during ongoing stimulation.
tDCS = transcranial direct current stimulation; GSR = galvanic skin response; DDT = Delay Discounting Task; mBART = modified Balloon Analogue Risk Task.

spaced at least one week apart to avoid carry-over effects. The sessions involved administering tDCS with different electrode placements: left dlPFC anode/right vmPFC cathode (Active 1), left dlPFC cathode/right vmPFC anode (Active 2), and sham tDCS. The order was randomized using Research Randomizer software (Research Randomizer). Fig. 1(a) displays an example of the tDCS sessions. During each session, three blocks were presented with Nu, P, and Ng pictures while tDCS was administered. After initiating tDCS, a 5-min interval was applied for emotional stimulation. The Galvanic Skin Response (GSR) was recorded while participants were exposed to emotional stimuli consisting of pictures accompanied by sounds. Participants completed the Delay Discounting Task (DDT) and the Modified Balloon Analogue Risk Task (mBART) in a fixed order after each emotional stimulation. Fig. 1(b) displays the layout of each session.

2.3. Transcranial direct current stimulation (tDCS) procedure

The NeuroConn DC Stimulator was used to apply tDCS. Stimulation was delivered through two 5 × 7 cm sponge electrodes soaked in .9% isotonic saline solution. The International 10–20 EEG System established by the International Federation of Clinical Neurophysiology was used to localize the dlPFC and vmPFC targets (Klem et al., 1999). Electrode placement was individualized for each participant using cranial measurements including nasion-to-inion distance, tragus-to-tragus distance, and head circumference. Based on these individualized measurements, the F3 location corresponding approximately to the left dlPFC and the Fp2 location corresponding approximately to the right vmPFC were identified according to the system described by Rojas et al. (2018). The computational localization approach described(Borckadt andHanlon, 2015) was additionally used to refine electrode positioning for each participant. Once the target regions were identified, a 2 mA current was administered for 30 min in active conditions; the left dlPFC- anode and the right vmPFC- cathode (Active 1), the left dlPFC-cathode and the right vmPFC-anode (Active 2). During the sham tDCS, electrodes were positioned in the specified locations, and 30-s ramp stimulations at the beginning and at the end of the 30-min session were applied.

To further characterize the spatial distribution of the stimulation montage, an exploratory electric field simulation was additionally performed using SimNIBS 4.6 with a standard template head model (Ernie Extended)(Saturnino et al., 2019; SimNIBS Developers). Simulations were conducted using the same stimulation parameters as the experimental protocol (F3–Fp2 montage, 5 × 7 cm sponge electrodes, 2 mA stimulation intensity). Because participant-specific MRI data were unavailable, simulations were conducted using a template head model rather than individualized anatomical models. According to the modeling, the affected regions in active and active 2 stimulations are shown in Figs. 2 and 3.

2.4. Emotional stimulation

Each session consisted of three blocks designed to induced neutral, positive, and negative emotions by showing 5 photos for each, that were chosen from the International Affective Pictures System (IAPS) (Lang et al., 2005). Initially based on the IAPS assessments, 30 positive photos with high ratings of valence and arousal, 30 negative photos with low valence and high arousal scores, and 30 neutral photos with moderate valence and low arousal scores were chosen and these photos were administered to 44 healthy adult volunteers (22 male and 22 female). They rated their valence and arousal levels. Mean emotional valence and

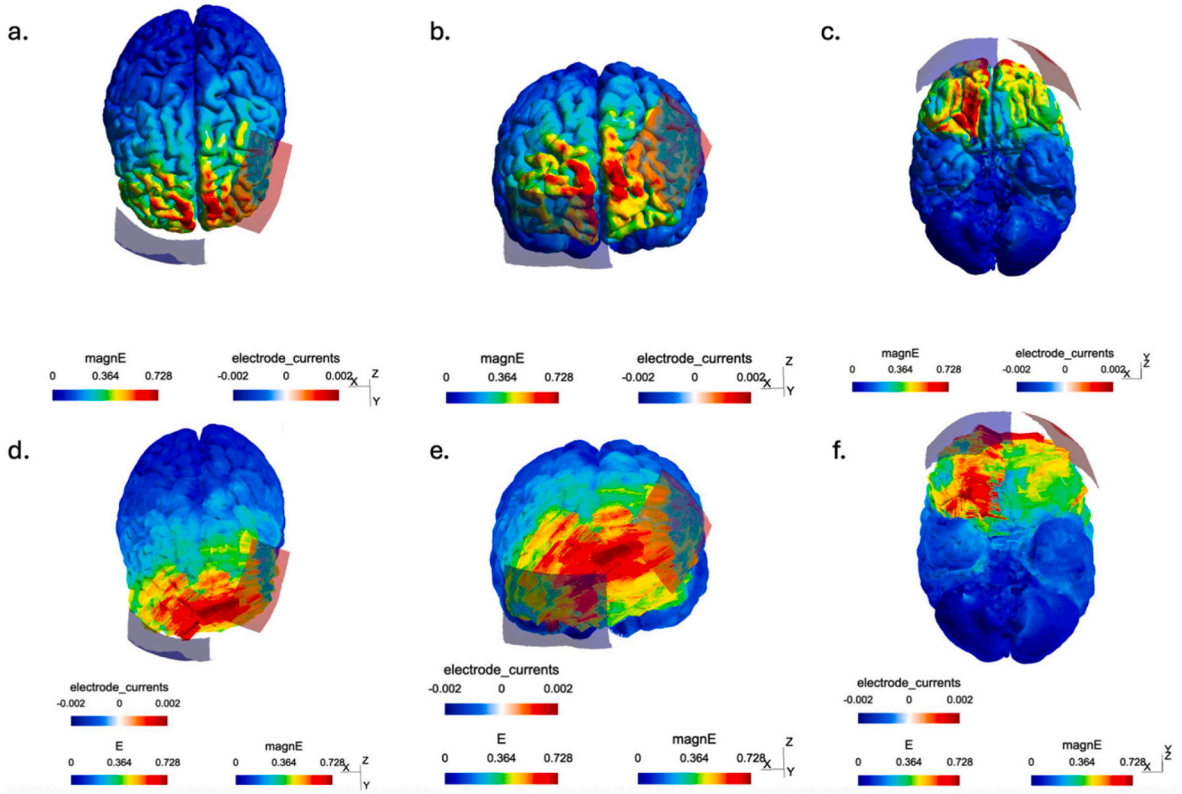


Fig. 2. Active1 tDCS Stimulation Modeling.
Note: Exploratory electric field simulation of the active1 tDCS montage performed using SimNIBS 4.6 with the Ernie Extended template head model. The upper panels illustrate representative cortical surface views of the estimated electric field distribution, whereas the lower panels present sectional/slice views demonstrating the spatial spread of current across deeper cortical regions. Different viewing orientations are shown to visualize the distribution of the electric field across cortical surfaces.

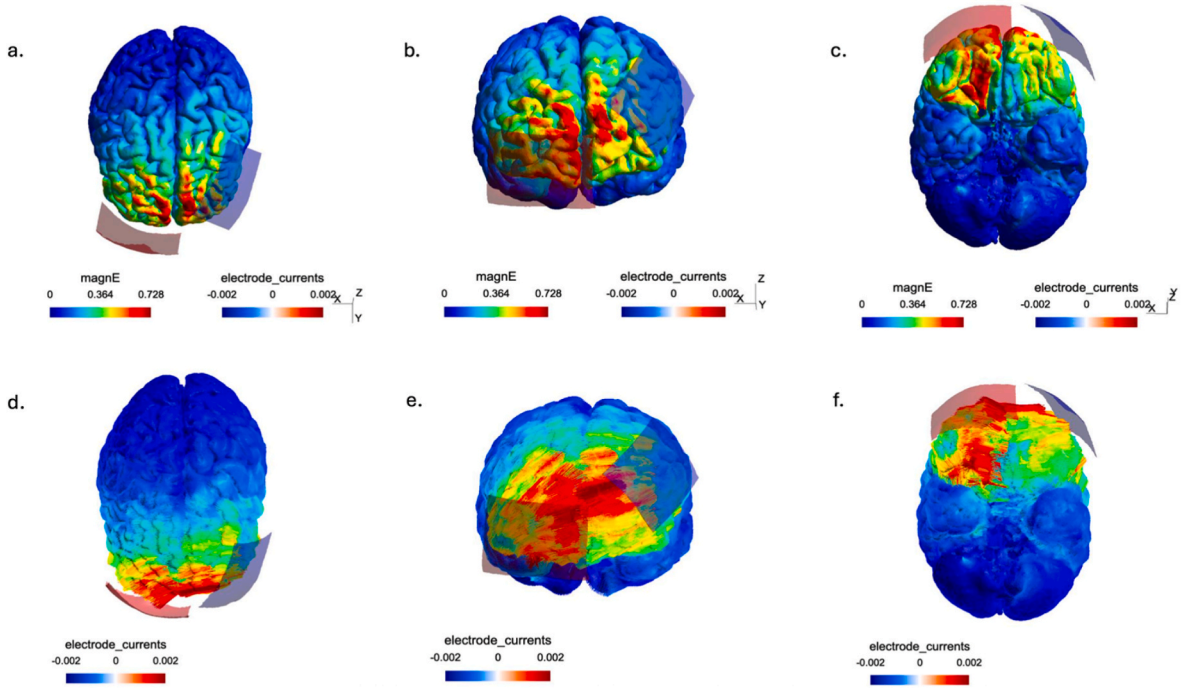


Fig. 3. Active2 tDCS Stimulation Modeling.
Note: Exploratory electric field simulation of the active2 tDCS montage performed using SimNIBS 4.6 with the Ernie Extended template head model. The upper panels depict representative cortical surface views of the estimated electric field distribution, while the lower panels display sectional/slice views illustrating the distribution of current across deeper cortical regions. Multiple viewing orientations are presented to demonstrate the spatial characteristics of the stimulation field.

arousal scores were computed for all photos (n = 90), and the top ones (5 positive, 5 negative, and 5 neutral) were chosen for the main experiment. In addition, photograph-related sounds from the International Affective Digitized Sounds-2 (IADS-2) (Bradley and Lang, 2007) were incorporated into the images to enhance the level of arousal. Each photograph was displayed for a duration of 5 s, so the emotional stimulation in a block lasted for 25 s. To control the emotional arousal of the participants, GSR were recorded before and throughout the exhibition of the photos. Both the original IAPS ratings (Lang et al., 2005) and the ratings of the healthy adults showed that the stimulus arousals were negative, positive, and neutral in descending order. Thus, neutral photos were shown first and negative photos were presented at last to avoid influencing each other. Participants were also required to assess the photographs based on emotional valence (1-9 points) and arousal level (1-9 points) at the end of the experiment; the subjective valence rating (SVR) was based on the feeling created by the photo(1- highly unpleasant, 5- neutral, 9- highly pleasant) and subjective arousal rating (SAR) was related to the extent to which the photo caused arousal independent of whether it was pleasant or unpleasant (1- least arousal, 5- moderate arousal, 9- highest arousal).

2.5. Delay discounting task

DDT examines the extent to which participants' subjective value diminishes as the reward they receive is postponed (Odum, 2011). Participants are presented with two choices to potentially earn a prize. One alternative involves receiving a lesser sum of money now and a greater sum at a later time, as proposed by Yeh et al. (2021). The rewarded amount reduces as the participant chooses present prizes and increases when they choose future ones. The moment when immediate and delayed rewards are perceived as equal by the individual is referred to as the indifference point.

The DDT defines bias as a hyperbolic function where the subjective value of a reward declines as delays increase. According to Mazur's hyperbola (Yoon et al., 2017), the discount function may be expressed as $V = A(1+kD)$, where V represents the subjective value of the reward, A is the future money amount, D is the delay, and k is the discount rate. The k value is frequently utilized as the primary dependent variable in the DDT paradigm and is regarded as an empirical substitute for impulsive traits like delay of gratification. The AUC (area under curve) value that reflects the decrease in value of delayed rewards is also calculated. Lower AUC values suggest more pronounced DD.

This study utilized a DDT that had been previously developed on E-Prime and made available online by Norbury (2017). Three varying prize amounts each with a delay are provided in this task. Periodic delays range from 1 week to 10 years, depending on the decision. The current reward is decided randomly from a range of percentages established in E-Prime 3.0, based on the delay time. When the participant selects the delayed reward, the present prize is augmented by certain increments. However, after the individual chooses the current reward, it is subsequently decreased by 66%. If the individual selects delayed rewards, the present incentive is further raised. Once the individual selects the current incentive, the average is calculated with the reward he has previously chosen, and the indifference point is determined. The algorithm computes “k” and “AUC” values for various delay times corresponding to different amounts of delayed rewards. Three k values and AUC values are achieved for three distinct reward amounts (small, medium and large) in a single DDT. The program and its instructions are translated into Turkish by the researchers and three prize amounts are determined as 100 TL, 1000 TL, and 10000 TL.

2.6. Modified balloon analog risk task

The BART (Banerjee et al., 2020) is a computer-based task used to assess an individual's propensity for taking risks. BART was created under the premise that engaging in risky behavior is encouraged to a certain extent, but engaging in excessive risky behavior leads to undesirable consequences. The experiment utilized a modified version of the BART (mBART), which has been previously adapted by the researchers (Ayidaga et al., 2022). The mBART that was created by using E-Prime

3.0. provides a single-colored balloon to eliminate the confounding effect of working memory, unlike the original BART. The task comprises 30 balloons that are programmed to explode at varying intervals, ranging from 1 to 100 pumps and the participants are asked to inflate the baloons to gain prize.

Four scores are calculated from the mBART data(Ayidaga et al., 2022):

Score A Total number of inflations of unexploded balloons after exploded ones/Total number of unexploded balloons after exploded balloons (RDM after punishment)
Score B Total number of inflations of unexploded balloons after unexploded ones/Total number of unexploded balloons after unexploded balloons (RDM after reward)
Score C Total number of balloons that explode
Score D Total inflation time of all balloons/Total number of inflations of all balloons

2.7. Galvanic skin response

Skin conductance is regulated by the sympathetic nervous system and serves as a measure of psychological or physiological arousal. Emotional arousal and sympathetic activity impact the electrical changes that occur, but they do not solely determine which specific emotion is generated. The autonomic sympathetic alterations impact perspiration and blood flow, thus influencing skin conductance (Pop-Jordanova and Pop-Jordanov, 2020). The study utilized GSR to investigate the impact of emotional stimulus (photo with sound) on inducing arousal and emotional responses in participants. A 30-s GSR recording (as the basal measurement) was obtained before showing neutral photos, followed by recording GSR during the whole session. Shimmer3 GSR device was used for the recordings. The electrodes were attached to the inside side of the lower knuckle of the non-dominant (left) index and middle fingers of the subjects. The recording frequency was 50.03 Hz.

The data was analyzed using MATLAB software. The raw GSR signals were denoised using a sliding-window smoothing procedure to reduce high-frequency noise and abrupt signal fluctuations. The Shimmer3 GSR system automatically decomposed the electrodermal activity into tonic skin conductance level (SCL) and phasic skin conductance response (SCR) components, and the subsequent signal processing and analyses were conducted based on the SCR component. Participants were instructed to minimize body and hand movements during recordings, and signals were visually inspected for major movement-related artifacts before analysis. GSR recordings were obtained continuously during each emotional stimulation block, and mean SCR values were calculated for each emotional condition to evaluate autonomic arousal differences associated with emotional induction.

2.8. Statistical analysis

A priori power analysis was conducted using G*Power 3.1.9.7 software. Based on the studies by Nejati et al. (2021) and Minarik et al. (2016), a moderate effect size (f = .40), an alpha level of .05, and a desired statistical power of .95 were assumed. The analysis indicated that a minimum of 24 participants would be required. To account for potential dropouts, missing data and to increase statistical power, we recruited 30 participants for the study.

All statistical analyses were performed using IBM SPSS Statistics version 23. Repeated-measures data were analyzed using linear mixed-effects models (LMMs), with participant included as a random intercept to account for within-subject dependency and inter-individual differences in baseline performance. Restricted maximum likelihood estimation was used, and Type III tests of fixed effects were reported.

For the DDT, AUC and k were analyzed as dependent variables. Because raw k values typically exhibit substantial positive skewness, a base-10 logarithmic transformation was applied prior to analysis. Fixed effects included stimulation condition (three levels), emotional condition (three levels), RM (100 TL, 1000 TL, and 10000 TL), and all corresponding interaction terms. To explicitly evaluate potential order and carryover effects inherent to the crossover design, period (the session number in which a stimulation condition was administered) and sequence (the randomized order of stimulation conditions across sessions) were additionally included in the model. For the mBART, the four task scores (Scores A, B, C, and D) were analyzed separately as dependent variables. These analyses were considered exploratory, and no correction for multiple testing was applied across the four outcome measures. The model included stimulation condition, emotional condition, their interaction, as well as period and sequence effects. GSR responses were similarly analyzed using a linear mixed-effects model including stimulation condition, emotional condition, period, and stimulation sequence as fixed effects, with participant modeled as a random intercept. When significant main effects were identified, Bonferroni-corrected pairwise comparisons were performed within each linear mixed-effects model. Statistical significance was set at $p < .05$ (two-tailed).Also smoking status, antidepressant use, and psychostimulant use were recorded and coded as binary variables (present/absent). In addition to the primary analyses, exploratory models were conducted by including these variables as covariates. These exploratory models are presented in the Supplementary Material.

3. Results

3.1. Descriptive statistics

The study included 30 adults (15 females, 15 males) diagnosed with ADHD. The ages of the participants were between 20 and 45 years with a median value of 25. A total of 21 participants (70%) were taking psychotropic medication. Also 13 participants were current smokers and 17 participants were using psychostimulant medication. Detailed information regarding smoking and medication characteristics is provided in Supplementary Table S1.

All participants tolerated tDCS well (except for a slight tingling sensation on the scalp for a short amount of time) and completed the experiment appropriately. Table 1 presents the clinical scale scores of the participants. TMT performances of all of the participants were within normal ranges according to age and education.

3.2. Galvanic skin response

The analysis revealed significant main effects of tDCS condition ($F(2,317) = 7.78$, $p = .001$), emotion condition ($F(3,317) = 23.51$, $p < .001$), and period ($F(2,317) = 7.02$, $p = .001$) on GSR responses. However, the tDCS × emotion interaction was not significant ($F(6,317) = .63$, $p = .709$). The effect of stimulation sequence did not reach statistical significance ($F(5,24) = 2.59$, $p = .052$).

Table 1
Clinical scale scores of the sample.

Scale		Participants
ASRS *Mean* ± *SD*		27.17 ± 5.17
WURS *Mean* ± *SD*		47.03 ± 17.10
DERS-16 *Mean* ± *SD*		48.03 ± 11.87
TMT-A (sec) *Mean* ± *SD*		33.41 ± 12.85
TMT-B (sec) *Mean* ± *SD*		69.44 ± 23.35
TMT B-A *Mean* ± *SD*		36.03 ± 16.20
TMT B-A	Negative	30 (%100)
	Positive	0 (%0)

ASRS = Adult ADHD Self-Report Scale, WURS = Wender Utah Rating Scale, DERS-16 = Difficulties in Emotion Regulation Scale – Short Form, TMT-A = Trail Making Test Part A, TMT-B = Trail Making Test Part B, sec = seconds, SD = Standard Deviation.

Bonferroni-corrected post-hoc comparisons demonstrated that GSR responses were significantly higher in the active1 condition compared with sham stimulation ($p < .001$). No significant differences were observed between active1 and active2 conditions ($p = .127$) or between active2 and sham conditions ($p = .170$).For emotion conditions, post-hoc analyses showed that GSR responses during the negative condition were significantly higher than those observed during baseline ($p < .001$), neutral ($p < .001$), and positive conditions ($p = .028$). In addition, GSR responses during the positive condition were significantly higher than those during baseline ($p < .001$) and neutral conditions ($p < .001$). No significant difference was observed between baseline and neutral conditions ($p = 1.00$). Post-hoc analyses for the significant period effect indicated that GSR responses were significantly higher during Period 1 compared with Period 2 ($p = .001$). However, no significant differences were observed between Period 1 and Period 3 ($p = .308$) or between Period 2 and Period 3 ($p = .110$).Additional exploratory linear mixed-effects analyses including smoking status, antidepressant use, and psychostimulant use as covariates yielded a broadly similar pattern of findings for GSR measures. None of these covariates showed significant main effects on GSR outcomes. Detailed results are presented in Supplementary Table S2.

3.3. Delay discounting task

In the linear mixed-effects analyses of DDT performance, the main effect of tDCS condition on AUC values did not reach statistical significance ($F(2, 752) = 2.64$, $p = .072$). In contrast, the main effect of emotional condition was significant ($F(2, 752) = 3.23$, $p = .040$). RM had a robust main effect on AUC values ($F(2, 752) = 29.99$, $p < .001$). In addition, the interaction between tDCS and RM was significant ($F(4, 752) = 2.66$, $p = .032$). In contrast, the tDCS × emotional condition interaction ($F(4, 752) = .24$, $p = .914$), the emotional condition × RM interaction ($F(4, 752) = .06$, $p = .994$), and the three-way interaction among tDCS, emotional condition, and RM ($F(8, 752) = .24$, $p = .983$) were not significant. The effect of period was significant ($F(2, 752) = 3.42$, $p = .033$), whereas the effect of sequence was not significant ($F(5, 24) = .82$, $p = .545$). The results of the LLMs for DDT performance are presented in Table 2.

Bonferroni-corrected pairwise comparisons indicated that AUC values in the 10000 TL reward condition differed significantly from those in both the 100 TL and 1000 TL reward conditions (both p values $< .001$), whereas no significant difference was observed between the 100 TL and 1000 TL reward conditions ($p = 1.000$). AUC values were significantly higher in the negative emotional condition than in the neutral condition ($p = .034$), whereas no significant differences were observed between the neutral and positive conditions ($p = .807$) or between the positive and negative conditions ($p = .459$). The significant tDCS × RM interaction was observed only at the 100 TL reward condition. At this reward level, AUC values in Active 1 tDCS were significantly higher than those in both Active 2 ($p = .001$) and the sham condition ($p = .020$), whereas Active 2 did not differ from the sham condition ($p = 1.000$). Bonferroni-corrected pairwise comparisons for period indicated that AUC values were significantly higher in the third period than in the first one ($p = .035$), whereas no significant differences were observed between the first and second periods ($p = 1.000$) or between the second and third periods ($p = .196$).

Sensitivity analyses using the logarithmically transformed discounting parameter (log k) yielded a broadly similar pattern of results to those observed for AUC. The main effect of tDCS condition was not significant ($F(2, 752) = .21$, $p = .810$). The main effect of emotional condition did not reach statistical significance ($F(2, 752) = 2.80$, $p = .061$). RM had a strong main effect on log k values ($F(2, 752) = 32.10$, $p < .001$). The interaction between tDCS and RM was also significant ($F(4, 752) = 4.34$, $p = .002$). In contrast, the tDCS × emotional condition interaction ($F(4, 752) = .12$, $p = .974$), the emotional condition × RM interaction ($F(4, 752) = .16$, $p = .957$), and the three-way interaction among tDCS, emotional condition, and RM ($F(8, 752) = .23$, $p = .985$) were not significant. The effect of period was also significant for log k ($F(2, 752) = 3.98$, $p = .019$), whereas the effect of sequence was not significant ($F(5, 24) = .57$, $p = .725$).

Bonferroni-corrected pairwise comparisons showed that log k values in the 10,000 TL reward condition differed significantly from those in both the 100 TL and 1000 TL reward conditions (both p values $< .001$), whereas no significant difference was observed between the 100 TL and 1000 TL reward conditions ($p = 1.000$). The significant tDCS × RM interaction was observed only at the 100 TL reward level. At this reward level, log k values in active1 tDCS were significantly lower than those in both Active 2 ($p = .005$) and the sham condition ($p = .020$), whereas Active 2 did not differ from the sham condition ($p = 1.000$). Bonferroni-corrected pairwise comparisons for period indicated that log k values were significantly lower in the third period than in the first one ($p = .017$), whereas no significant differences were observed between the first and second periods ($p = 1.000$) or between the second and third periods ($p = .196$). The graphs relating to the results are shown in Fig. 4.

Additional exploratory linear mixed-effects analyses including smoking status, antidepressant use, and psychostimulant use as covariates yielded a broadly similar pattern of findings. None of these covariates showed significant main effects on DDT performance measures. Detailed results of these supplementary analyses are presented in the Supplementary Material Table S3.

Table 2
Results of the Linear Mixed-Effects Models for DDT Performance (AUC and log k).

Fixed Effect	AUC F(df1, df2)	P	log k F(df1, df2)	p
tDCS condition	F(2, 752) = 2.64	.072	F(2, 752) = .21	.810
Emotional condition	F(2, 752) = 3.23	.040	F(2, 752) = 2.80	.061
RM	F(2, 752) = 29.99	< .001	F(2, 752) = 32.10	< .001
tDCS x Emotional condition	F(4, 752) = .24	.914	F(4, 752) = .12	.974
tDCS x RM	F(4, 752) = 2.66	.032	F(4, 752) = 4.34	.002
Emotional condition x RM	F(4, 752) = .06	.994	F(4, 752) = .16	.957
tDCS x Emotional condition x RM	F(8, 752) = .24	.983	F(8, 752) = .23	.985
Period	F(2, 752) = 3.42	.033	F(2, 752) = 3.98	.019
Sequence	F(5, 24) = .82	.545	F(5, 24) = .57	.725

AUC = area under the curve; DDT = delay discounting task; log k = logarithmically transformed delay discounting rate parameter; tDCS = transcranial direct current stimulation; RM = reward magnitude.

3.4. Modified balloon analog risk task

Exploratory linear mixed-effects analyses of mBART performance showed a significant main effect of tDCS condition for all four task scores: Score A ($F(2, 230) = 5.83$, $p = .003$), Score B ($F(2, 230) = 3.45$, $p = .034$), Score C ($F(2, 230) = 7.32$, $p = .001$), and Score D ($F(2, 230) = 5.43$, $p = .005$). In contrast, the main effect of emotional condition was not significant for Score A ($F(2, 230) = .22$, $p = .802$), Score B ($F(2, 230) = .93$, $p = .396$), Score C ($F(2, 230) = .02$, $p = .982$), or Score D ($F(2, 230) = .45$, $p = .640$). Likewise, the tDCS × emotional condition interaction was not significant for any of the four scores (Score A: $F(4, 230) = .63$, $p = .644$; Score B: $F(4, 230) = .69$, $p = .597$; Score C: $F(4, 230) = .79$, $p = .533$; Score D: $F(4, 230) = 1.10$, $p = .357$). In addition, neither period nor sequence had a significant effect on mBART performance. Detailed fixed-effect estimates are presented in Table 3.

Bonferroni-corrected pairwise comparisons indicated that, for Score A, both Active 1 ($p = .008$) and Active 2 ($p = .013$) yielded significantly higher values than the sham condition, whereas the two active

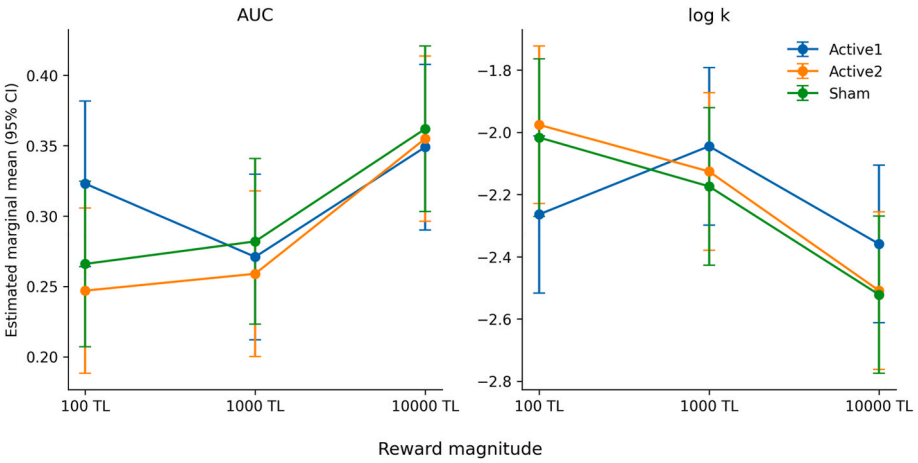


Fig. 4. Estimated marginal means of DDT performance across reward magnitudes and tDCS conditions.
Estimated marginal mean AUC (left panel) and log k values (right panel) derived from the linear mixed-effects models. Error bars indicate 95% confidence intervals. AUC = area under the curve; log k = log-transformed discounting rate parameter; DDT = Delay Discounting Task; tDCS = transcranial direct current stimulation.

Table 3
Linear Mixed-Effects Model Results for mBART Outcomes.

Fixed Effect	Score A F(df1, df2)	p	Score B F(df1, df2)	p	Score C F(df1, df2)	p	Score D F(df1, df2)	p
tDCS condition	F(2,230) = 5.83	.003	F(2, 230) = 3.45	.034	F(2, 230) = 7.32	.001	F(2, 230) = 5.43	.005
Emotional condition	F(2,230) = .22	.802	F(2, 230) = .93	.396	F(2, 230) = .02	.982	F(2, 230) = .45	.640
tDCS × Emotional condition	F(4,230) = .63	.644	F(4, 230) = .69	.597	F(4, 230) = .79	.533	F(4, 230) = 1.10	.357
Period	F(2,230) = 2.47	.087	F(2, 230) = 1.31	.271	F(2, 230) = 1.02	.362	F(2, 230) = .36	.700
Sequence	F(5,24) = 2.31	.075	F(5, 24) = 2.56	.054	F(5, 24) = 2.14	.095	F(5, 24) = 2.30	.076

Note: mBART = modified Balloon Analogue Risk Task; tDCS = transcranial direct current stimulation.

conditions did not differ from each other (p = 1.000). For Score B, Active 1 yielded significantly higher values than the sham condition (p = .037), whereas neither the comparison between Active 2 and sham (p = .179) nor the comparison between the two active conditions (p = 1.000) was statistically significant. For Score C, both Active 1 (p = .004) and Active 2 (p = .002) yielded significantly higher values than the sham condition,

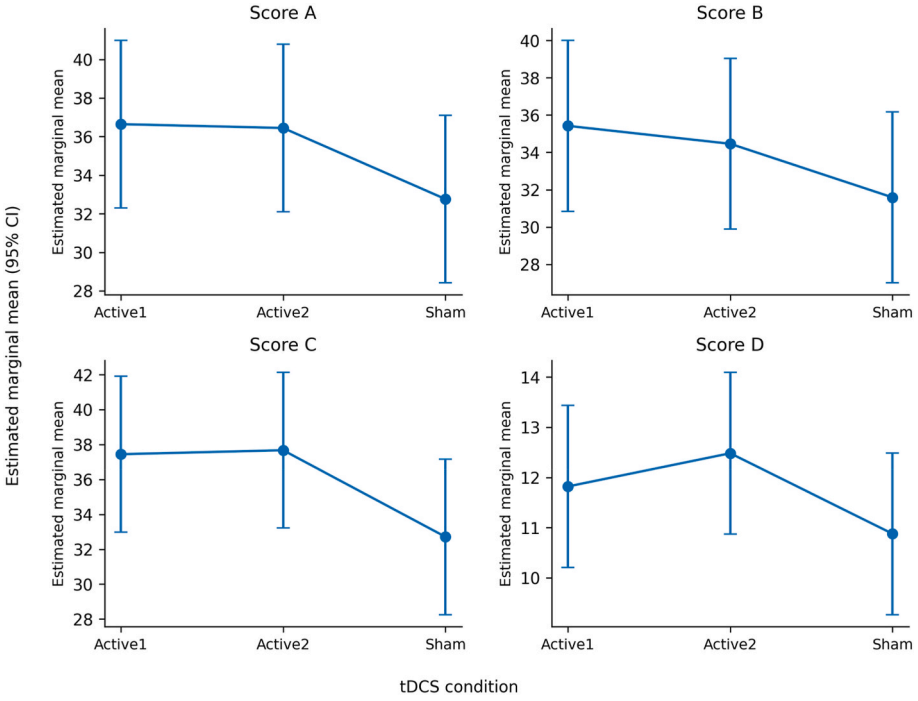


Fig. 5. Estimated marginal means of mBART performance across tDCS conditions.
Estimated marginal means for Score A, Score B, Score C, and Score D derived from the linear mixed-effects models across the active1, active2, and sham tDCS conditions. Error bars indicate 95% confidence intervals. mBART = modified Balloon Analogue Risk Task; tDCS = transcranial direct current stimulation; CI = confidence interval.

with no significant difference between the two active conditions ($p = 1.000$). For Score D, Active 2 yielded significantly higher values than the sham condition ($p = .004$), whereas neither the comparison between Active 1 and sham ($p = .167$) nor the comparison between the two active conditions ($p = .532$) was statistically significant. The graphs relating to the results are shown in Fig. 5.

Additional exploratory linear mixed-effects analyses including smoking status, antidepressant use, and psychostimulant use as covariates yielded a broadly similar pattern of findings for mBART performance measures. None of these covariates showed significant main effects on mBART outcomes. Detailed results of these supplementary analyses are presented in the Supplementary Material Table S4.

4. Discussion

The present study investigated the effects of different prefrontal tDCS montages on emotion-related RDM and delay discounting in adults with ADHD. Overall, the findings demonstrated partially selective effects of tDCS on decision-making performance. In the DDT, no significant overall main effect of tDCS condition was observed for either AUC or log k values. However, significant interactions emerged between tDCS condition and RM, particularly for smaller rewards. In contrast, mBART performance showed significant main effects of tDCS across all task scores, whereas emotional condition did not significantly influence performance in either the DDT or the mBART. Also GSR analyses demonstrated significant effects of both emotional stimulation and tDCS condition.

The present findings from the DDT, a measure of explicit intertemporal decision-making, indicate that RM exerted influence on performance, whereas the effects of emotional condition and tDCS were relatively limited and context-dependent. Across both AUC and log k analyses, participants demonstrated a greater willingness to wait for delayed rewards in the 10000 TL condition compared to the 100 TL and 1000 TL conditions. This finding is consistent with the well-established magnitude effect in intertemporal choice, whereby increasing RM is associated with lower discounting rates and reduced impulsive decision-making (Harman et al., 2020; Kirby, 1997; Manuel et al., 2019; Schulz van Endert and Mohr, 2022; Yi et al., 2016). Several theoretical accounts have been proposed to explain this phenomenon. According to one perspective, when two equivalent ratios are compared (e.g., 1 TL versus 5 TL and 100 TL versus 500 TL), the larger reward pair involves a greater absolute difference between the immediate and delayed options. As a result, the delayed option may be perceived as more valuable, leading individuals to exhibit a stronger preference for delayed rewards (Loewenstein and Prelec, 1992). An alternative explanation suggests that larger rewards engage cognitive control processes to a greater extent (Gershman and Bhui, 2020). Whereas delayed rewards of relatively small value may be dismissed with minimal deliberation, larger delayed rewards may prompt more extensive cognitive evaluation, thereby increasing the likelihood that individuals choose the larger, later reward over the smaller, immediate alternative.

Beyond the main effect of RM, a significant tDCS × RM interaction emerged in both the AUC and log k analyses. This interaction was seen exclusively by the smallest RM (100 TL), for which the Active 1 tDCS (left dlPFC anodal/right vmPFC cathodal montage) was associated with less impulsive decision-making than both the Active 2 (left dlPFC cathodal/right vmPFC anodal montage) and sham conditions. The absence of similar effects for medium and large RMs is noteworthy. The RM specificity observed in the present study may be interpreted in light of neurocognitive models of intertemporal choice. Theoretical accounts propose that larger rewards recruit greater cognitive effort and more elaborate future simulation, resulting in more precise representations of delayed outcomes and lower discounting rates, as we mentioned before (Gershman and Bhui, 2020). Neuroimaging studies further indicate that the dlPFC plays a central role in the processing of delay-related information and executive function (Figner et al., 2010; Peters and Büchel, 2011; Wang et al., 2021), whereas vmPFC activity is more closely associated with subjective reward valuation (Bartra et al., 2013; Wang et al., 2021). Accordingly, Active 1 bifrontal prefrontal montage of tDCS may have increased the contribution of delay information while reducing the relative influence of immediate reward valuation. One possible explanation is that these evaluative and control-related mechanisms may already be strongly engaged under high-magnitude conditions, leaving less opportunity for additional modulation.

The broader literature examining tDCS effects on delay discounting remains inconsistent. Most studies have focused on the dlPFC and generally report reduced discounting following anodal stimulation of the left dlPFC and increased discounting following cathodal stimulation (He et al., 2016; Kekic et al., 2017; Nejati et al., 2018; Shen et al., 2016), although several studies have failed to observe significant effects (Colombo et al., 2020; Nejati et al., 2021). Similarly, anodal stimulation of the vmPFC has been associated with reduced temporal discounting in some studies (Manuel et al., 2019; Nejati et al., 2021). Such variability suggests that delay discounting is unlikely to depend on a single cortical region. Rather, converging evidence from neuroimaging and neuromodulation studies points to the involvement of a distributed network including the dlPFC, vmPFC, orbitofrontal cortex, dorsomedial prefrontal cortex (dmPFC), striatum, and parietal regions, each contributing to distinct aspects of reward valuation, future simulation, and cognitive control(Moro et al., 2023). Importantly, some studies in this field, including the present one, employed conventional 5 × 5 cm (Kekic et al., 2017; Manuel et al., 2019) or 5 × 7 cm sponge electrodes(Nejati et al., 2018). Computational modeling studies have demonstrated that such montages generate diffuse electric fields extending beyond the intended targets, potentially modulating neighboring prefrontal, orbitofrontal, cingulate, and frontostriatal regions. Therefore, variability in current distribution, together with the network-based nature of delay discounting, may partly explain the heterogeneous findings reported across the literature.

In addition, emotional condition exerted only a modest effect on AUC values and did not significantly influence log k values. Post-hoc analyses indicated that AUC values were higher during the negative emotional block than during the neutral block. However, because emotional conditions were presented in a fixed order, this finding should be interpreted as an association observed during the negative emotional block rather than as evidence that negative emotional states themselves reduced impulsive decision-making. Although the present finding cannot be attributed specifically to negative emotion because of the fixed block order, previous studies examining the effects of emotional states on delay discounting and risk-taking have reported mixed findings. While some studies have reported that negative emotional states are associated with reduced risk-taking and lower discounting rates (Drichoutis and Nayga Jr, 2013; Nygren et al., 1996), others have failed to identify such effects (Conte et al., 2018; Guan et al., 2015). In contrast to our initial hypothesis, positive emotional induction did not significantly influence delay discounting relative to the other emotional conditions. Given that negative images elicited the highest GSR responses, the absence of significant effects in the positive emotional condition may partly reflect the relatively lower level of physiological arousal induced by positive stimuli. This interpretation is broadly consistent with a recent systematic review and meta-regression by Elliott et al. (2023), which reported only a small positive association between emotion-related impulsivity and delay discounting and suggested that positive emotional inductions often produce insufficient arousal to reliably alter decision-making behavior. Nevertheless, the emotional findings of the present study should be interpreted with caution. First, the effect of emotional condition was observed only for AUC values and did not replicate across log k analyses, limiting confidence in the robustness of the finding. Second, emotional blocks were administered in a fixed order (neutral, positive, and negative), making it difficult to disentangle the effects of emotional valence from potential order, practice, or time-related influences. Importantly, supplementary

analyses revealed a significant period effect, with both AUC and log k values indicating less impulsive decision-making during the third session relative to first one, suggesting that participants may have gradually adopted more deliberative decision-making strategies over time. Furthermore, a similar pattern emerged within the experimental sessions, raising the possibility that learning, task familiarity, fatigue-related changes in responding, or increasing adaptation to the decision-making context may have contributed to the observed reduction in discounting. Consequently, the lower impulsivity observed during the negative emotional condition cannot be unequivocally attributed to emotional valence alone. Rather, it may reflect a combination of emotional, temporal, and practice-related influences. Finally, although GSR was recorded during emotional induction, physiological responses were not assessed during task performance. Therefore, it remains unclear whether the induced emotional states persisted throughout completion of the DDT, representing an additional limitation when interpreting the observed emotional effects.

In contrast to the relatively limited effects observed in the DDT, prefrontal tDCS significantly influenced performance across all mBART scores, suggesting a more pronounced impact on decision-making under uncertainty and dynamic feedback conditions (where balloon explosions and the associated loss of accumulated points serve as negative feedback, whereas successful balloon inflations without explosion and the resulting point accumulation serve as positive). Notably, both active stimulation conditions were generally associated with higher mBART scores than sham stimulation, whereas no significant differences emerged between the two active montages. Although this finding is partly consistent with our a priori hypothesis that the Active 2 montage would increase risk-taking behavior, the observation that Active 1 stimulation produced a similar pattern was unexpected. Nevertheless, the fact that both active stimulation conditions were associated with higher risk-taking across all mBART outcomes is noteworthy and suggests that modulation of the broader prefrontal networks may influence behavior in ambiguous risk contexts regardless of stimulation polarity. Interestingly, both active montages produced similar behavioral effects despite their opposite stimulation polarities. This pattern may suggest that the observed effects were not driven by simple polarity-dependent modulation of a single cortical target. Instead, both montages may have influenced broader frontostriatal and salience-related networks involved in uncertainty processing and reward sensitivity.

Previous studies examining the effects of prefrontal tDCS on risk-taking in BART have yielded highly heterogeneous findings. A study conducted with children with ADHD (Nejati et al., 2021), reported increased risk-taking under a left dlPFC cathode/right vmPFC anode montage compared with sham stimulation, whereas other stimulation configurations did not significantly alter performance. Several studies have suggested that dlPFC stimulation may reduce risk-taking behavior (Cheng and Lee, 2016; Guo et al., 2018). Similarly, Gorini et al. (2014) demonstrated that bilateral dlPFC stimulation was associated with reduced risk-taking behavior in both healthy individuals and cocaine-dependent participants. However, other investigations have reported null effects of dlPFC stimulation on BART performance (Minati et al., 2012; Russo et al., 2017). Taken together, the existing literature does not provide a consistent picture regarding the direction or magnitude of tDCS effects on risky decision-making, highlighting the complexity of the underlying neural mechanisms. Finally, because no correction for multiple testing was applied across the four mBART outcome measures, the mBART findings should be interpreted as exploratory and with appropriate caution.

Several methodological factors may contribute to these inconsistencies, including differences in sample characteristics, stimulation intensity and duration, electrode size and placement, task parameters, and outcome measures. Besides them, from a neurocognitive perspective, the present findings may also reflect the distributed neural architecture underlying BART performance. Although the dlPFC and vmPFC are known to play important roles in cognitive control, reward valuation, and affective decision-making, risk-taking during the BART is not mediated exclusively by these regions (dlPFC, vmPFC). Recent evidence suggests that BART performance depends on coordinated activity across multiple large-scale networks, including reward-processing, salience, and executive-control systems. Meta-analytic findings indicate that active risk-taking during the BART is associated with activation of the bilateral insula, right putamen, left caudate, right dlPFC, dorsal anterior cingulate cortex, and midbrain regions(Qin et al., 2025; Schmidt et al., 2024; Wang et al., 2022). Therefore, the observed increase in risk-taking following both active stimulation conditions may reflect network-level modulation of distributed decision-making circuits rather than polarity-specific effects on a single cortical region. An additional consideration is that the observed increase in post-reward risk-taking was not strongly polarity-dependent. Although the two active stimulation montages were designed to differentially modulate prefrontal activity, both were associated with greater risk-taking relative to sham. This pattern may indicate that the behavioral effects were driven not only by polarity-specific modulation of dlPFC-vmPFC circuitry but also by more general changes in arousal, attentional engagement, expectancy, or broader perturbations of prefrontal network function. Such interpretations remain speculative, however, because the present study was not designed to directly dissociate these mechanisms.

The differential effects observed between the DDT and mBART may also reflect important differences in the structure of the tasks. Whereas delay discounting primarily involves explicit valuation of temporally separated rewards and choices between fully specified alternatives, the mBART requires sequential decisions under uncertainty, incorporating reward anticipation, performance monitoring, and continuous feedback processing. Notably, participants in the DDT always choose between two rewarding outcomes, and no explicit negative feedback is delivered following a decision. In contrast, the mBART includes salient loss-related events, as balloon explosions result in the immediate loss of accumulated points and may therefore function as punishments. Such punishment-related feedback may engage neural systems involved in salience detection, reward processing, and behavioral adaptation to a greater extent than DD choices.

In our analyses regarding the adequacy of emotional stimuli, the GSR findings indicate that the emotional stimuli paradigm modulated physiological arousal. Consistent with our hypotheses, both positive and negative emotional stimuli elicited greater electrodermal responses than neutral stimuli, with the strongest responses observed during the negative condition. Despite this successful induction of emotional arousal, emotional effects did not translate into significant behavioral changes (especially in mBART). One possible explanation is that the emotional stimulation was sufficiently strong to induce transient autonomic activation but insufficient to produce sustained alterations in higher-order decision-making processes. Emotional photos typically evoke relatively short-lived physiological responses, whereas decision-making tasks require continuous cognitive evaluation over a longer time period. Consequently, emotional activation may have dissipated before exerting a measurable influence on task performance.

Unexpectedly, a significant main effect of tDCS condition emerged for GSR responses. Participants exhibited higher electrodermal activity during the Active 1 condition compared with sham stimulation, whereas Active 2 did not significantly differ from either condition. Previous neuroimaging studies have demonstrated that sympathetic arousal is closely associated with corticolimbic networks. Henderson et al. (2012) reported increased blood oxygen level-dependent (BOLD) signal intensity in the vmPFC, dlPFC, amygdala, OFC, and anterior insula during increases in skin sympathetic nerve activity (SSNA). Subsequent experimental studies further showed that unilateral transcranial alternating current stimulation (tACS) of the dlPFC can modulate SSNA (Wong et al., 2023), while vmPFC stimulation produces similar modulatory effects on autonomic activity (Patel et al., 2024). Moreover, in a biofeedback study combining simultaneous fMRI and skin conductance

measurements, neural activity within the vmPFC and OFC was found to covary with skin conductance levels irrespective of task demands. Activity in the anterior cingulate cortex, insula, thalamus, hypothalamus, and lateral prefrontal regions also tracked the rate of change in electrodermal activity, further supporting their involvement in skin conductance responses(Nagai et al., 2004). Collectively, these findings support a central role of prefrontal and limbic regions in the regulation of autonomic arousal. In the present study, although the tDCS × emotion interaction did not reach statistical significance, a significant main effect of tDCS condition on GSR responses was observed. Specifically, the Active 1 condition was associated with higher GSR responses compared with sham stimulation. In contrast, no comparable effect was observed in the Active 2. Consistent with the broader pattern of findings observed in the present study, suggesting context-dependent and function-specific effects of tDCS, this asymmetric result indicates that the physiological effects of tDCS cannot be adequately explained by the traditional polarity-based framework, which assumes that anodal stimulation increases and cathodal stimulation decreases cortical excitability. Current evidence suggests that the behavioral and physiological effects of tDCS are influenced by multiple factors, including the functional state of the targeted regions, network-level connectivity patterns, and current spread beyond the intended stimulation sites. Accordingly, the observed increase in GSR may reflect modulation of broader autonomic regulatory networks involving the dlPFC and vmPFC, rather than purely local effects within either region alone.

Another unexpected finding was the significant period effect, with GSR responses being higher during the first session than during the second session. This pattern may reflect habituation to both the emotional stimuli and the experimental environment. Repeated exposure to emotional photos is known to reduce autonomic responsiveness over time, and participants may also become progressively more familiar with laboratory procedures across sessions. Notably, no significant differences emerged between the first and third sessions or between the second and third sessions, suggesting that this effect was modest rather than reflecting a linear decline across the study. Additionally, the absence of significant effects of smoking status, antidepressant use, and psychostimulant treatment on GSR responses in the exploratory analyses further supports the robustness of the observed findings.

Several methodological characteristics of the emotional stimulation procedure should also be considered when interpreting these findings. First, emotional conditions were presented in a fixed order within each session rather than being fully counterbalanced. Although this approach was chosen to minimize carryover effects from negative stimuli, it may have introduced order-related influences on physiological and behavioral responses. Second, emotional induction was achieved through passive viewing of affective images. Compared with more immersive emotional manipulations, such as autobiographical recall, film clips, or social feedback paradigms, static pictures may induce relatively modest and short-lived emotional states. Third, stimulation was delivered during picture presentation rather than throughout task performance. Consequently, the emotional and neuromodulatory effects may not have been maintained during the subsequent decision-making processes. These factors may partly explain why robust physiological effects were observed in GSR measurements whereas corresponding behavioral effects were largely absent.

This study makes an important contribution to the limited literature in the field by systematically examining the effects of both tDCS and emotional states on risky decision-making in adults with ADHD. One of the study's key strengths is the high reliability of its findings, thanks to its randomised, sham-controlled, and single-blind design. Additionally, the use of GSR, an objective physiological measure, to assess emotional arousal beyond subjective scales enhances the validity of emotional manipulations. The comprehensive evaluation of both risky decision-making and delayed reward discounting under different emotional and neuromodulation conditions enables a more detailed understanding of impulsivity in ADHD. These methodological strengths enhance the value and reliability of the study's findings and provide a solid foundation for future research.

The study also has some limitations. One important limitation of our study is the relatively small sample size, which may have limited the statistical power to detect subtle effects. However the power analysis indicated that a sample of 24 participants would be sufficient for detecting moderate effects. Another important limitation of our study is that a substantial proportion of participants were taking psychotropic medication. Although participants were instructed not to take their psychoactive drugs on the days of the experiment (with different time restrictions), the long-term or residual effects of psychostimulants and other psychotropic drugs could not be fully eliminated. Therefore, it is possible that these medications may have influenced the effects o f tDCS and the behavioral outcomes. Future studies should consider more stringent control of medication status or include only medication-free participants to better isolate the effects of tDCS. An additional limitation is that emotional conditions were presented in a fixed order, which may have introduced order- and practice-related influences and limits causal interpretation of the observed emotional effects.

Another limitation relates to the spatial specificity of the stimulation protocol. Although electrode placement was designed to target the left dlPFC and right vmPFC, the use of conventional 5 × 7 cm sponge electrodes inevitably results in widespread current distribution. Consistent with our exploratory electric field simulations, the induced electric field extended beyond the intended cortical targets and involved broader prefrontal regions. Consequently, stimulation effects were unlikely to be restricted to the left dlPFC and right vmPFC and may have also affected adjacent and functionally interconnected cortical areas. Furthermore, individualized neuroimaging-based electric field modeling was not available, preventing precise estimation of the actual current distribution in each participant. Therefore, although electrode placement was guided by established neuroanatomical landmarks, the observed behavioral and physiological effects cannot be unequivocally attributed to modulation of the left dlPFC and right vmPFC alone.

An additional limitation is the single-blind design. Although sham stimulation was implemented using a conventional ramp-up/ramp-down procedure, participants may have perceived differences between active and sham sessions during the 30-min stimulation period. Therefore, expectancy effects, nonspecific arousal, or stimulation-related discomfort cannot be completely excluded as potential contributors to the observed behavioral effects.

However, it is well known that the effects of tDCS can vary depending on stimulation parameters such as duration, current intensity, electrode placement, and especially the use of multiple sessions. Studies have shown that repeated tDCS sessions have beneficial effects on attention(Breitling-Ziegler et al., 2021), working memory and planning (Barham et al., 2022) in patients with ADHD. Therefore, future studies should systematically investigate the effects of different tDCS protocols (e.g., longer or repeated sessions) and stimulation parameters on risk-taking and impulsivity in adults with ADHD.

In conclusion, although this study did not find consistent effects of tDCS on risk-taking and delay discounting in adults with ADHD, the findings underscore the complexity of neuromodulation and emotional influences on decision-making in this population. The results suggest that single-session tDCS may not be sufficient to produce robust behavioral changes, and that emotional context may contribute to decision-making under certain conditions, although these effects appeared modest and inconsistent across measures. However, tDCS remains a practical and safe neuromodulation technique with therapeutic potential for adults with ADHD and further research is needed to determine the effective stimulation protocols, including frequency, localization, and stimulus characteristics in larger samples. Also, given the broad prefrontal current distribution observed in the exploratory electric field modeling, future studies integrating neuroimaging with individualized electric field modeling will be important for improving

anatomical specificity and optimizing stimulation protocols.

CRediT authorship contribution statement

Zehra Uçar Hasanlı: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Erguvan Tuğba Özel Kızıl:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Writing – review & editing. **Burçin Çolak:** Data curation, Methodology, Writing – review & editing. **Farhad Nassehi:** Data curation, Software. **Zeynel Baran:** Formal analysis, Methodology, Software, Writing – review & editing. **Deha Onar:** Data curation, Methodology, Writing – review & editing. **Ayşe Handenur Bayraktar Özdemir:** Data curation, Methodology, Writing – review & editing. **Jamal Hasanlı:** Data curation, Methodology, Writing – review & editing.

Ethics declaration

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place. This study was approved by the Ethics Committee of Ankara University Faculty of Medicine. (Approval No. İ02-71-22)

Ethical standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. Ethical approval for this research was obtained from the Ethics Committee of Ankara University (approval number İ02-71-22).

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jpsychires.2026.08.011.

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