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Original Article

Rewiring Rage Circuits in Children with Oppositional Defiant Disorder: tDCS as a Cognitive-Emotional Rehabilitation Tool for Enhancing Cold Executive Functions and Reducing Irritability

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Abstract

Background and Objective: Oppositional defiant disorder (ODD) is a prevalent childhood behavioral disorder characterized by persistent irritability, defiance, and angry outbursts, which impair academic, family, and social functioning. Children with ODD exhibit significant deficits in core executive functions—including inhibition, working memory, and cognitive flexibility—alongside severe emotional dysregulation. Conventional treatments often show limited efficacy. Transcranial direct current stimulation (tDCS), a non-invasive neuromodulation technique, has shown promise in enhancing cognition and modulating emotion, but its efficacy in ODD remains underexplored. The present study aimed to evaluate the effectiveness of tDCS on cold executive functions and angry/irritable mood in children with ODD.

Materials and Methods: A quasi-experimental pretest-posttest design with a control group was employed. A total of 24 male children aged 8–12 years with ODD were randomly assigned to experimental (n=12) and control (n=12) groups. The experimental group received 20 sessions of active tDCS (1.5–2 mA, 30 min, every other day) over the left dorsolateral prefrontal cortex (DLPFC, F3). The control group received no intervention. Data were collected using the Behavior Rating Inventory of Executive Function (BRIEF)—Parent Form (Gioia et al., 2000) to assess core executive functions (inhibition, shifting, emotional control, working memory, planning, organization, monitoring, and initiation), and the DSM-5-based Oppositional Defiant Disorder Questionnaire (Motamedin et al., 2021) to measure angry/irritable mood. All instruments demonstrated acceptable validity and reliability (Cronbach's α: BRIEF=0.89; ODD=0.77). Multivariate analysis of covariance (MANCOVA) was used to analyze the data, controlling for pretest scores, with a significance level set at $P<0.05$.

Results: The MANCOVA revealed a significant overall difference between groups (Wilks' Lambda=0.055, $F(8, 23)=32.005$, $P<0.001$, $\eta=0.945$). tDCS significantly improved cold executive functions ($F=34.78$, $P<0.001$, $\eta=0.613$) and significantly reduced angry/irritable mood ($F=18.53$, $P<0.001$, $\eta=0.457$) in the experimental group compared to the control group.

Conclusions: The tDCS significantly enhanced cold executive functions and reduced angry/irritable mood in children with ODD. These findings support tDCS as a safe, non-invasive, and effective adjunctive treatment for cognitive-emotional deficits in pediatric ODD. Further large-scale, long-term studies are recommended to confirm these results.

Keywords: Transcranial Direct Current Stimulation, Cold Executive Functions, Irritability, Oppositional Defiant Disorder, Non-invasive, Brain Stimulation

Background

Oppositional defiant disorder (ODD) is one of the most prevalent and debilitating disruptive behavior disorders of childhood, characterized by persistent and chronic patterns of angry mood, argumentative and defiant behaviors, and vindictiveness toward authority figures [1]. According to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5-TR), this disorder is classified into three symptom subtypes: angry/irritable mood, argumentative/defiant behavior, and vindictiveness [2]. The global prevalence of this disorder varies between 2% and 11% in children and adolescents [3]; however, the national Iranian study (IRCAP) on 30,532 children and adolescents reported a lifetime prevalence of 3.9% for ODD, with higher rates observed in boys than in girls and in urban areas compared to rural regions [4]. Demographic characteristics of this disorder indicate that multiple factors—including negative parenting styles, peer rejection, and family conflicts—serve as predictors

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of symptom persistence [5]. Furthermore, the high comorbidity of ODD with other psychiatric disorders, including attention-deficit/hyperactivity disorder (ADHD), anxiety disorders, and depression, poses serious challenges to its diagnosis and treatment [6]. For instance, a study of 2,400 children demonstrated that the comorbidity rate of ODD with combined-type ADHD reached 53%, and with the combination of autism and combined-type ADHD reached 62%, underscoring the clinical complexity of this disorder [3]. The prognosis of this disorder is also concerning, as without effective intervention, ODD may progress to conduct disorder and antisocial behaviors in adolescence and adulthood, imposing a substantial burden on healthcare systems and society [7].

What renders this disorder particularly significant from a neuropsychological perspective is the considerable executive function deficits observed in children with ODD. Executive functions are defined as a set of higher-order cognitive processes responsible for goal-directed behavior, self-regulation, problem-solving, planning, decision-making, and impulse control [8]. In the dual-model framework of executive functions, these abilities are divided into "cold" and "hot" categories [9]. Cold executive functions refer to cognitively neutral, non-emotional processes that are activated in abstract situations devoid of affective loading, and encompass key components including response inhibition, working memory, cognitive flexibility, planning, and organization [10]. Response inhibition, as the core of self-control, represents the ability to withhold planned responses or refrain from impulsive behaviors when confronted with inappropriate stimuli, and its impairment is closely associated with impulsivity and anger outbursts in children with ODD. Working memory, which entails the temporary storage and manipulation of information for performing complex cognitive tasks, is essential for following multi-step instructions and adapting to environmental rules. Cognitive flexibility, defined as the capacity to shift cognitive sets, transition between tasks, and adapt to novel situations, enables children to modify their strategies based on environmental feedback. Planning and organization involve the ability to determine necessary steps toward goal achievement, prioritize sequences, and organize resources—all critical for completing long-term tasks [10]. Research has demonstrated that children with ODD exhibit significant deficits across all these components [11]. On the Stockings of Cambridge planning task, children with ODD performed worse than controls, reflecting impairments in step-by-step planning ability for goal attainment [11]. Moreover, a study of 842 children revealed that the ADHD+ODD comorbid group displayed poorer performance across all executive function domains except psychomotor speed, confirming that executive function deficits are not merely associated features but constitute a core component of the disorder's pathophysiology [6]. These findings increasingly highlight cold executive functions as a primary therapeutic target in children with ODD.

Cognitive deficits alone, however, do not provide a complete picture of the disorder's pathology. Emotion dysregulation, particularly in response to negative emotions, represents another prominent—and perhaps more fundamental—characteristic of children with ODD. Compared with healthy controls, these children show significant differences in cognitive reappraisal, rumination, emotional suppression, and the expression of negative emotions, all of which converge on a central phenomenon: irritability [12]. Irritability, described in psychiatric literature as "a tendency to react angrily to typically minor stimuli," is accompanied by diminished mood control and verbal or behavioral outbursts [13]. This feature extends beyond a transient emotional state to represent a stable mood trait that may manifest as either frequent anger outbursts or persistent irritable mood. To fully understand this concept, one must recognize the fundamental distinction between mood and emotions: emotions are brief reactions to specific, identifiable stimuli, whereas moods persist for days or weeks, may lack identifiable external causes, and lead to biased perceptions and cognitions [14]. According to the more comprehensive definition provided in the theoretical framework of this study, irritability is "a mood state that inclines toward specific feelings (such as anger), specific perceptions (such as hostile attributions), or specific actions (such as aggression), is controllable before culminating in external action, and does not necessarily result in an external act" [15]. Irritability not only constitutes a core feature of ODD but also serves as a predictor of disease trajectory deterioration and the development of more severe mood disorders in the future. Research has shown that the severity of childhood irritability increases the likelihood of anxiety and depressive disorders in adulthood [13]. Notably, a significant relationship has been observed between rumination about negative emotions and deficits in response inhibition in children with ODD ($r=0.47$), indicating a close link between cold executive function impairments and emotion dysregulation, which manifests as irritable mood [11]. More precisely, when children with ODD encounter negative emotions such as anger,

frustration, or sadness, their inability to inhibit impulsive responses and their cognitive inflexibility lead them to become immersed in these emotions, lacking effective self-regulation strategies. These findings support a novel perspective: emotion dysregulation and irritability in children with ODD may be understood, at least in part, as consequences of underlying cold executive function deficits. Consequently, any intervention aimed at ameliorating this disorder must simultaneously target both cognitive and emotional domains.

Despite this growing understanding of the neuropsychological underpinnings of ODD, currently available treatments—including pharmacotherapy, cognitive-behavioral therapy, and parent training—face numerous limitations. The efficacy of these approaches in children with ODD is often limited, and they are associated with challenges like medication side effects, poor treatment adherence, and failure to generalize learned skills to real-life situations. These constraints underscore the urgent need for developing novel, non-invasive therapeutic approaches. In this context, transcranial direct current stimulation (tDCS), a non-invasive brain stimulation technique that delivers weak electrical currents (1–2 mA) through scalp electrodes, modulates cortical neuronal excitability [16]. In this method, anodal stimulation depolarizes neuronal membranes and increases excitability, whereas cathodal stimulation hyperpolarizes and decreases cortical excitability [17]. The mechanism of tDCS extends beyond transient changes in membrane potential to include more sustained alterations such as increased cerebral blood flow, enhanced synaptic plasticity through long-term potentiation (LTP), and changes in neurotransmitter levels, ultimately improving the function of neural networks associated with cognitive functions and emotion regulation [18]. What makes tDCS particularly attractive for pediatric applications, beyond its non-invasive nature, is its favorable safety profile. A study of 92 children and adolescents across 1032 stimulation sessions demonstrated that tDCS is well-tolerated in this population, with approximately 77% of sessions free from adverse effects and no "severe" or "moderate" adverse events reported; the most common side effect was mild itching at the electrode site, which resolved quickly [19]. These findings largely alleviate concerns regarding the safety of brain stimulation in children and pave the way for broader clinical applications.

Accumulating empirical evidence supports the efficacy of tDCS on executive functions and mood disorders across various pediatric populations, offering promise for its application in ODD. A recent meta-analysis of 23 studies involving 614 Iranian patients with neurodevelopmental disorders demonstrated that tDCS significantly improves executive functions (SMD=1.04; 95% CI: 0.83 to 1.25; P<0.001), with the greatest effect observed on attention—a fundamental component of cold executive functions [16]. More specifically, Fallahiyan et al. (2026) found that combining tDCS with active video games significantly improved cognitive flexibility in children (P<0.001), a key cold executive function component notably impaired in children with ODD [20]. Additionally, a study investigating the effect of tDCS on response inhibition in adolescents with behavioral disorders demonstrated that anodal stimulation of the left DLPFC significantly improved response inhibition performance [21]. In the emotional domain, results are equally promising. Moreira et al. (2025), using tDCS combined with virtual reality in 18 children with autism, found significant reductions in irritability following intervention (P<0.001)—a finding that, given the neurocognitive overlaps between autism and ODD in emotion regulation, may be generalizable to the target population of the present study [22]. Moreover, Shukla et al. (2026) have presented a comprehensive clinical trial protocol to investigate the efficacy of brain stimulation on emotion regulation in children and adolescents with externalizing behavior disorders (of which ODD is a prominent example), reflecting growing scientific interest in the potential of this technique for managing childhood behavioral disorders [23]. This body of evidence, consistent with previous meta-analytic findings, indicates that tDCS can serve as an effective intervention targeting both cognitive (cold executive functions) and emotional (angry/irritable mood) domains that play central roles in the pathophysiology of ODD.

Despite these promising findings, a clear research gap exists in the scientific literature. To date, no study has specifically and directly investigated the efficacy of tDCS on cold executive functions and angry/irritable mood in children with ODD. Most existing research has focused on populations with ADHD, autism, or learning disorders, while children with ODD—despite their considerable prevalence and the substantial burden they impose on healthcare systems—have received comparatively less attention. Given the neurocognitive and behavioral overlaps between ODD and other neurodevelopmental disorders, particularly in executive function deficits and emotion dysregulation, and considering the established safety and efficacy of tDCS in pediatric populations, this technique appears to offer a promising novel approach for improving cold

executive functions and reducing angry/irritable mood in children with ODD. Accordingly, the present study aimed to evaluate the effectiveness of tDCS on cold executive functions and angry/irritable mood in children with ODD, aiming to address this research gap and provide empirical evidence for the clinical application of this method in this specific population.

Objectives

The present research aimed to evaluate the efficacy of tDCS in enhancing cold executive functions and reducing angry/irritable mood among children with ODD using a quasi-experimental design.

Materials and Methods

Study Design

This study was carried out using a quasi-experimental pretest-posttest design with a control group. The aim was to assess whether tDCS could improve cold executive functions and reduce angry/irritable mood in children with ODD. Participants were evaluated at two time points: once before the intervention (pretest) and once immediately after the intervention (posttest). Both assessments were conducted using validated parent-report questionnaires.

Participants

The target population consisted of all male elementary school students aged 8-12 years who had been diagnosed with ODD and were living in Shahriar City, Iran, during the 2024–2025 academic year. From this population, 24 children were selected through convenience sampling from those referred to counseling and psychological clinics in the city. These children were then randomly assigned to either the experimental group (n=12) or the control group (n=12) using a simple coin-tossing procedure.

The sample size was set at 24 participants (12 per group), which is consistent with earlier quasi-experimental studies of tDCS in children with neurodevelopmental disorders. Those studies typically include 20-40 participants and have reported large effect sizes (Cohen's d>0.8) for improvements in executive functions and symptom reduction [16]. A post-hoc power analysis confirmed that our sample had sufficient statistical power (>0.80) to detect large effects, similar to those observed in previous research.

Inclusion Criteria

Children were included in the study if they met the following conditions: (a) they had received a confirmed diagnosis of ODD according to DSM-5 criteria, established through structured clinical interviews and behavioral screening questionnaires administered by trained clinical psychologists; (b) they were between 8 and 12 years of age; (c) they were male; (d) they had no other neurological or psychiatric conditions that could interfere with the intervention; (e) their parents or legal guardians had provided written informed consent; and (f) they were not participating in any other psychological or pharmacological treatment at the time of enrollment.

Exclusion Criteria

Children were excluded from the study if any of the following applied: (a) they had comorbid psychiatric disorders, including major depressive disorder, bipolar disorder, psychotic disorders, or substance use disorders; (b) they had a history of neurological conditions, such as epilepsy, traumatic brain injury, or intellectual disability; (c) they were taking psychotropic medications during the study; (d) they had previously received neurofeedback or any form of brain stimulation therapy; (e) they were unable to cooperate or complete the intervention sessions; (f) they experienced severe adverse effects related to tDCS; or (g) their parents or the child themselves withdrew consent at any point during the study.

Intervention

Children in the experimental group received tDCS over 20 sessions, scheduled every other day across ten weeks. Each session lasted 30 minutes.

tDCS Equipment

The intervention was delivered using the Neurostim 2 device (Medina Teb, Iran), a certified constant-current stimulation system equipped with real-time impedance monitoring. Electrodes were made of carbon rubber, with sizes of 5×5 cm for the active electrode and 5×9 cm for the return electrode. Synthetic sponge pads soaked in normal saline (0.9% NaCl) were placed beneath the electrodes to ensure proper conductivity and skin contact.

Electrode Montage

Electrode placement followed the international 10-20 EEG system. The anode was placed over the left DLPFC (F3). The cathode was placed over different locations depending on the phase of the intervention: over the right supraorbital area (Fp2) for the first seven sessions, over the right DLPFC (F4) for the following seven sessions, and outside the head (on the left shoulder) for the final six sessions. These montages were chosen based on previous protocols that have shown effectiveness in improving executive functions and emotional regulation [16, 21].

Stimulation Parameters

A constant current of 1.5 to 2 mA was applied for 30 minutes per session, with the intensity adjusted to each child's level of tolerance. Each session began and ended with a 30-second ramp-up and ramp-down period to minimize any sudden discomfort. The control group did not receive any intervention during the study period. However, after the posttest assessments, children in the control group were offered two sessions of active tDCS as an ethical consideration.

Outcome Measures

1. Cold Executive Functions

Cold executive functions were evaluated using the Behavior Rating Inventory of Executive Function (BRIEF)—Parent Form, developed by Gioia et al. [24]. This 86-item questionnaire measures eight clinical subscales: Inhibit, Shift, Emotional Control, Initiate, Working Memory, Plan/Organize, Organization of Materials, and Monitor. Parents rate each item on a 3-point scale (0=never, 1=sometimes, 2=often), with higher scores reflecting greater difficulties in executive functioning. The questionnaire provides three composite indices: the Behavioral Regulation Index (BRI), the Metacognition Index (MI), and the Global Executive Composite (GEC). For this study, the GEC score was used as the main indicator of overall cold executive function. The Persian version of the BRIEF-Parent Form has been found to have good psychometric properties, with Cronbach's α values ranging from 0.87 to 0.94 across subscales and a test-retest reliability of 0.89 for the GEC [25]. In the current sample, the Cronbach's α for the GEC was 0.89.

2. Angry/Irritable Mood

Angry and irritable mood was assessed using the DSM-5-based Oppositional Defiant Disorder Questionnaire developed by Motamedin et al. [26]. This 18-item tool covers three dimensions of ODD: (a) conduct problems (7 items), (b) argumentative/defiant behavior (6 items), and (c) angry/irritable mood (5 items). Each item is rated on a 5-point Likert scale (1=strongly disagree to 5=strongly agree), with higher scores indicating more severe symptoms. The angry/irritable mood subscale was used as the primary outcome for this study. The questionnaire has shown acceptable reliability in Iranian samples, with a Cronbach's α of 0.77 for the total scale and 0.74 for the angry/irritable mood subscale [26]. In this study, the Cronbach's α for the angry/irritable mood subscale was 0.74.

Demographic and Clinical Characteristics

Basic demographic and clinical information—including age, grade level, duration of symptoms, and prior treatment history—was collected via a brief questionnaire completed by parents.

Data Collection Procedure

Data collection was carried out in three stages. In the first stage (pretest), parents of all eligible children completed the BRIEF and the ODD questionnaire at the clinic. In the second stage, the experimental group received 20 sessions of active tDCS over ten weeks, while the control group continued with their usual routines without any intervention. All tDCS sessions were conducted in a quiet, distraction-free room by trained therapists who were supervised by a clinical psychologist. In the third stage (posttest), both groups were reassessed using the same questionnaires immediately after the last tDCS session. All procedures were carried out under identical conditions for both groups.

Statistical Analysis

All statistical analyses were performed using SPSS version 28 (IBM Corp., Armonk, NY, USA). Descriptive statistics—including means, standard deviations, frequencies, and percentages—were used to summarize the participants' baseline characteristics and outcome measures. The normality of the data was checked using the Shapiro-Wilk test. Levene's test was applied to assess the equality of variances across groups, and Box's M test was used to examine the homogeneity of variance-covariance matrices. A multivariate analysis of covariance (MANCOVA) was conducted to test the overall effect of the intervention on the combined dependent variables (cold executive functions and angry/irritable mood), while controlling for pretest scores. This was followed by univariate analyses of covariance (ANCOVA) to examine the effect of the intervention on each dependent variable separately. Partial eta squared (η^2) was reported as the effect size, with values of 0.01, 0.06, and 0.14 interpreted as small, medium, and large effects, respectively. The significance level was set at $P<0.05$ for all analyses. Observed power was also calculated to ensure the sample size was adequate to detect meaningful effects.

Ethical Considerations

The study was reviewed and approved by the Ethics Committee of Payam Noor University, Iran (IR.RNU.REC.1403.677). Before any data were collected, parents or legal guardians were fully

informed about the purpose of the study, the procedures involved, the possible benefits, and any potential risks. All parents provided written informed consent. They were also assured that their participation was voluntary and that they could withdraw their child from the study at any time without any consequences. All data were anonymized and stored securely. After the posttest phase, the control group was offered two sessions of active tDCS to ensure they could also benefit from the intervention.

Results

The present study examined the effectiveness of tDCS on cold executive functions and angry/irritable mood in children with ODD. The findings are presented in two sections: descriptive statistics and inferential results.

Descriptive Statistics

The participants consisted of 24 male children diagnosed with ODD, randomly assigned to experimental and control groups (12 in each group). The groups were matched based on demographic variables, including age and grade level. The mean age of the experimental group was 10.13±2.47 years, while the control group had a mean age of 10.54±2.59 years. No significant differences were found between the groups in terms of age ($F(1,24)=0.25$, $P=0.120$) or grade level ($F(1,24)=0.19$, $P=0.100$), indicating successful randomization (Table 1).

Table 1. Comparison of demographic characteristics between groups

Demographic Variable	Experimental Group (Mean±SD)	Control Group (Mean±SD)	df	F	Sig
Age (Years)	10.13±2.47	10.54±2.59	1	0.25	0.120
Grade Level	3.03±1.03	3.25±1.25	1	0.19	0.100

Descriptive Findings for Dependent Variables

Table 2 presents the means and standard deviations for cold executive functions and angry/irritable mood across the two groups at pretest and posttest. In the experimental group, cold executive function scores decreased from 75.13±6.47 at pretest to 54.07±7.22 at posttest, while the control group showed minimal change (74.20±5.37 to 75.53±5.73). Similarly, angry/irritable mood scores in the experimental group decreased from 190.00±12.23 to 150.27±19.62, whereas the control group showed virtually no change (188.80±13.09 to 184.87±11.57).

Table 2. Descriptive statistics for cold executive functions and angry/irritable mood across groups and time points

Variable	Group	Pretest (Mean±SD)	Posttest (Mean±SD)
Cold Executive Functions	Experimental	75.13±6.47	54.07±7.22
	Control	74.20±5.37	75.53±5.73
Angry/Irritable Mood	Experimental	190.00±12.23	150.27±19.62
	Control	188.80±13.09	184.87±11.57

To provide a visual representation of the observed changes, Figure 1 illustrates the pre- and post-intervention mean scores for cold executive functions (BRIEF GEC) and angry/irritable mood across both groups. As depicted, the experimental group demonstrated a marked decline in scores following the tDCS intervention, whereas the control group exhibited relatively stable performance over the same period.

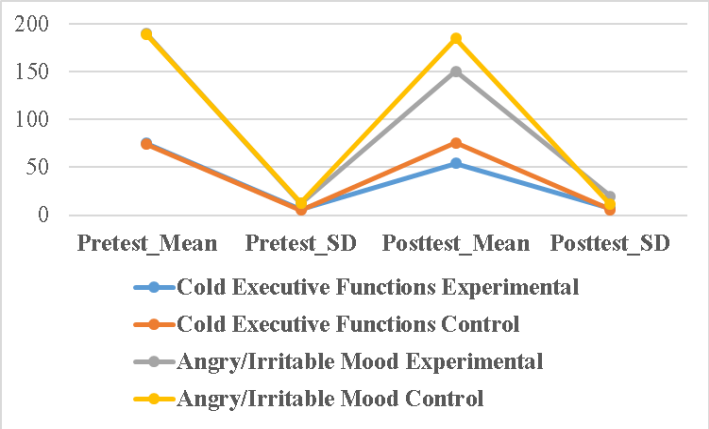


Figure 1. Pre- and post-intervention changes in Cold Executive Functions (BRIEF GEC scores) and Angry/Irritable Mood scores across experimental (tDCS) and control groups. Lower scores indicate improvement in both variables. Error bars represent standard deviations.

Inferential Results

Prior to conducting the main analyses, preliminary assumptions for MANCOVA were examined. The Shapiro-Wilk test confirmed the normality of the data for all dependent variables across both groups ($P>0.05$ for all). Levene's test indicated homogeneity of variances for both cold executive functions ($F(1, 23)=0.136$, $P=0.654$) and angry/irritable mood ($F(1, 23)=0.216$, $P=0.536$). Box's M test confirmed the homogeneity of variance-covariance matrices for cold executive functions (Box's $M=13.87$, $F=1.281$, $P=0.241$) and angry/irritable mood (Box's $M=9.23$, $F=1.145$, $P=0.196$). These results confirmed that the assumptions for MANCOVA were met.

Multivariate Analysis of Covariance (MANCOVA)

A one-way MANCOVA was conducted to evaluate the overall effect of the intervention on the combined dependent variables (cold executive functions and angry/irritable mood), controlling for pretest scores. The results revealed a significant overall difference between the experimental and control groups across the combined dependent variables (Wilks' Lambda=0.055, $F(8,23)=32.005$, $P<0.001$, $\eta^2=0.945$). This indicates that approximately 94.5% of the multivariate variance in the dependent variables was attributable to group membership. (Table 3)

Table 3. Summary of MANCOVA for cold executive functions and angry/irritable mood

Test Statistic	Value	F	df_1	df_2	P	Partial η^2	1-β
Pillai's Trace	0.945	32.005	8	23	<0.001	0.945	1.000
Wilks' Lambda	0.055	32.005	8	23	<0.001	0.945	1.000
Hotelling's Trace	17.069	32.005	8	23	<0.001	0.945	1.000
Roy's Largest Root	17.069	32.005	8	23	<0.001	0.945	1.000

Note: The covariates were the pretest scores for both dependent variables (cold executive functions and angry/irritable mood). Observed power was computed using alpha=0.05. df_1 refers to the hypothesis degrees of freedom and df_2 to the error degrees of freedom (N-k-1=24-2-1=21). All multivariate test statistics were significant ($P<0.001$), confirming the robustness of the multivariate effect.

Univariate Analyses of Covariance (ANCOVA)

Following the significant multivariate effect, univariate ANCOVAs were performed to examine the effect of the intervention on each dependent variable separately, controlling for pretest scores. The results indicated that tDCS significantly improved cold executive functions in the experimental group compared to the control group ($F(1,23)=34.78$, $P<0.001$, $\eta^2=0.613$). Similarly, tDCS significantly reduced angry/irritable mood in the experimental group compared to the control group ($F(1,23)=18.53$, $P<0.001$, $\eta^2=0.457$). (Table 4)

Table 4. Summary of ANCOVA for cold executive functions and angry/irritable mood

Dependent Variable	Sum of Squares	df	Mean Square	F	Sig.	Partial η^2	1-β
Cold Executive Functions	126.796	1	126.796	34.78	0.001	0.613	1.000
Angry/Irritable Mood	26.871	1	26.871	18.53	0.001	0.457	0.984

Statistical Analysis

The MANCOVA and ANCOVA were employed to assess between-group differences while controlling for pretest scores. These analyses confirmed that the observed differences between the experimental and control groups were statistically significant and not attributable to random variation. The effect sizes, as measured by partial eta squared (η^2), were large for both dependent variables (η^2=0.613 for cold executive functions; η^2=0.457 for angry/irritable mood), indicating strong practical significance for the intervention. The observed power (1-β) was high for all analyses (1.000 for cold executive functions; 0.984 for angry/irritable mood), confirming that the sample size was adequate to detect the observed effects.

Summary of Findings

Overall, the results demonstrated that tDCS significantly improved cold executive functions and significantly reduced angry/irritable mood in children with ODD. The experimental group showed substantial improvements from pretest to posttest, while the control group exhibited minimal or no changes across the study period. Both multivariate and univariate analyses confirmed the effectiveness of the intervention, with large effect sizes and high statistical power.

Discussion

The present work examined whether tDCS could improve cold executive functions and reduce angry and irritable mood in children diagnosed with ODD. The findings indicate that children who received active tDCS showed significant gains in executive functioning and noticeable reductions in irritability compared to those in the control group. These results are consistent with earlier work suggesting that tDCS may serve as a useful supplement to existing treatments for cognitive and emotional difficulties in childhood behavioral disorders [16, 21].

Improvement in Cold Executive Functions

The improvement we observed in cold executive functions among children in the experimental group aligns with other researchers' findings. For instance, Gheysari and Mazaheri, in their meta-analysis of Iranian children with neurodevelopmental conditions, found a large overall effect for tDCS on executive tasks [16]. Similarly, work by Sun et al. on children with autism spectrum disorder showed that tDCS, along with repetitive transcranial magnetic stimulation, led to meaningful gains in cognitive flexibility and other executive domains [27]. These parallel findings strengthen our confidence that the improvements seen in our participants were not accidental.

One way to make sense of these results is to consider what tDCS does at the neural level. In our protocol, we placed the anode over the left DLPFC, a region known to be heavily involved in planning, decision-making, and impulse control [10]. By delivering a weak current to this area, tDCS likely increases the excitability of neurons there, making it easier for them to fire and communicate with one another [18]. Over repeated sessions, this enhanced activity may promote lasting changes in synaptic strength, similar to what happens during LTP [28]. In practical terms, this means that the brain circuits responsible for holding information in mind, resisting distractions, and shifting between tasks become more efficient, which could explain why our participants performed better on the executive function measures after the intervention.

The fact that we used 20 sessions, rather than just 1 or 2, may have also contributed to the strength of our findings. Previous studies have reported that multiple sessions produce more durable cognitive gains compared to single-session designs [31]. Children with ODD often struggle with tasks that require planning, organization, and self-monitoring, and these are precisely the kinds of abilities that seemed to improve in our experimental group. From a clinical standpoint, this is encouraging because it suggests that tDCS might help address some of the core cognitive difficulties that make daily life challenging for these children and their families.

Reduction in Angry/Irritable Mood

Perhaps equally important is the finding that tDCS led to a noticeable drop in angry and irritable mood scores. In our experimental group, the average score on the irritability measure fell by about 40 points, whereas the control group demonstrated little change over the same period. This degree of change is clinically meaningful and points to the potential

of tDCS as a tool for managing emotional difficulties in this population.

The connection between improved executive function and better emotional regulation is worth highlighting here. When children become frustrated or angry, their ability to calm down often depends on their capacity to pause, reflect, and choose a different response. This is precisely where executive functions come into play. If a child has difficulty inhibiting impulsive reactions or shifting attention away from a distressing situation, anger is more likely to escalate [36]. In our study, as executive functions improved, irritability decreased. This pattern suggests that the two are closely linked, and that strengthening cognitive control may naturally lead to better emotional control.

From a neurobiological perspective, the DLPFC does not work in isolation. It has strong connections to deeper brain structures such as the amygdala, which is involved in generating emotional responses, and the anterior cingulate cortex, which helps monitor conflicts and adjust behavior [33]. By enhancing activity in the prefrontal cortex, tDCS may strengthen the brain's ability to rein in overactive emotional responses coming from these subcortical areas [34]. This is consistent with work by Moreira et al., who found that tDCS reduced irritability in children with autism [22], and with findings by Vergallito et al., indicating that prefrontal stimulation can modulate negative emotions [35]. Overall, these studies support the idea that tDCS can influence both the cognitive and emotional sides of behavior, which is particularly relevant for a disorder like ODD where both domains are affected.

Mechanisms of Action

Understanding how tDCS produces these effects requires looking at several levels of brain function. At the most basic level, anodal stimulation pushes the resting membrane potential of neurons closer to the firing threshold. This means that neurons are more likely to generate action potentials in response to incoming signals [18]. Over time, this heightened activity triggers molecular changes, including the strengthening of synaptic connections through mechanisms similar to LTP. These changes involve receptors, such as NMDA receptors, and signaling molecules, such as brain-derived neurotrophic factor, both of which play key roles in learning and memory [38].

At a broader network level, tDCS appears to alter how different brain regions communicate. The prefrontal cortex is part of a larger frontoparietal network that supports executive control, and it also connects to limbic regions involved in emotion [30, 39]. By modulating prefrontal cortex activity, tDCS may improve the efficiency of these networks, enabling better coordination between cognitive and emotional systems. This would explain why we observed improvements in both domains simultaneously.

One of the advantages of tDCS over many pharmacological options is its safety profile. In our study, no serious side effects were reported, which is consistent with larger reviews showing that tDCS is well tolerated in children [19]. The most common side effect, mild itching at the electrode site, is temporary and does not interfere with daily activities. This makes tDCS an attractive option for families who are concerned about the side effects of medication or who have not found traditional behavioral interventions to be fully effective [40].

Limitations and Future Directions

While our findings are encouraging, they should be interpreted in light of several limitations. First, our sample size was relatively small, with only 12 children per group. Although our post-hoc power calculations indicated that we had enough participants to detect large effects, smaller effects may have gone unnoticed. Replicating this study with a larger and more diverse sample would help clarify the robustness of the findings [41]. Second, only males were included in the study. This decision was based on the higher prevalence of ODD among males, but it means that we cannot be certain whether the same results would be seen in girls. Given that gender differences in executive function and treatment response have been reported in the literature, future studies should include both male and female participants to explore whether the effects of tDCS differ by gender [42].

Third, we did not include a follow-up assessment; therefore, we do not know whether the improvements we observed persisted over time. It would be valuable to conduct follow-up evaluations at three or six months post-intervention to determine whether the benefits of tDCS are sustained [43]. Fourth, we relied on parent-reported questionnaires for our outcome measures. While these are practical and widely used, they can be influenced by parental expectations or biases. Including objective neuropsychological tests and physiological measures in future studies would provide a more complete picture of treatment effects [11].

Fifth, our study did not include a sham stimulation group. Although our control group received no intervention, a sham-controlled design would have allowed us to rule out placebo effects more confidently [44]. Finally, we did not examine

whether certain child characteristics, such as baseline cognitive ability or symptom severity, influenced the extent of benefit from tDCS. Identifying predictors of response could help clinicians decide which children are most likely to benefit from this approach [45].

Conclusion

In conclusion, the results of the present work suggest that tDCS can improve cold executive functions and reduce angry and irritable mood in children with ODD. These findings add to a growing body of evidence indicating that non-invasive brain stimulation may offer a safe and effective way to address both cognitive and emotional difficulties in childhood behavioral disorders. By targeting the DLPFC, tDCS appears to influence neural circuits that are central to self-control and emotional regulation. Given its favorable safety profile and the limitations of current treatment options, tDCS deserves further attention as a potential complement to therapy and medication. Larger studies with longer follow-up periods and more diverse samples are needed to confirm these early findings and to refine the protocols for clinical use.

Ethical Considerations

The present study was conducted in accordance with the ethical standards outlined in the Declaration of Helsinki. Approval for the research protocol was obtained from the Ethics Committee of Payam Noor University, Iran (IR.RNU.REC.1403.677). Prior to the commencement of the study, all parents or legal guardians of participating children were provided with comprehensive information regarding the purpose of the research, the procedures involved, the anticipated benefits, and any potential risks. Written informed consent was obtained from all parents after they had been given sufficient time to consider their decision and to ask any questions they might have had. Participants were also informed of their right to withdraw from the study at any stage without any negative consequences. All data collected during the study were anonymized to protect participant identity and were stored securely in compliance with data protection regulations. After completing the posttest assessments, the control group was offered two sessions of active tDCS to ensure they could also benefit from the intervention, thereby fulfilling the ethical obligation of beneficence.

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Authors' Contributions

All authors contributed significantly to this work and read and approved the final manuscript

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article. Neither of the authors has any financial or personal relationships with other people or organizations that could inappropriately influence or bias the content of this work.

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