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Title: Prefrontal tDCS Demonstrates Superior Efficacy to Mindfulness Training in Improving Motor Skills in Children with ADHD

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Abstract

Mindfulness-based approaches and transcranial direct current stimulation (tDCS) applied to the prefrontal cortex have gained considerable attention as complementary interventions for managing attention-deficit/hyperactivity disorder (ADHD). Despite their growing clinical use, little evidence is available regarding their influence on motor performance among children diagnosed with ADHD. Therefore, the present study was designed to investigate and compare the impact of mindfulness training and prefrontal tDCS on the motor abilities of children with ADHD. A total of 45 children diagnosed with ADHD ($M = 8.48$ years, $SD = 1.18$) were enrolled in the study. Participants were assigned to one of three intervention conditions: a mindfulness-based training group, an active tDCS group, or a sham stimulation control group. The study employed a between-groups design and evaluated outcomes across four time points, including baseline assessment, immediate post-intervention assessment, and two subsequent follow-up evaluations. Outcome measurements were obtained at four separate time points: baseline (pre-intervention), immediately following the intervention, one month after the completion of the final session, and six months after treatment termination. Children assigned to the mindfulness condition participated in fifteen training sessions, each lasting 60 minutes, whereas participants in the prefrontal tDCS condition underwent fifteen stimulation sessions of 30 minutes each. Motor performance was assessed during every evaluation period using the Bruininks–Oseretsky Test of Motor Proficiency, Second Edition (BOT-2).

Repeated-measures ANOVA revealed significant effects of time ($F = 54.98$, $p = .001$, $\eta^2 = .567$), group ($F = 180.90$, $p = .001$, $\eta^2 = .896$), and time × group interaction ($F = 21.78$, $p = .001$, $\eta^2 = .509$) for gross motor skills. Bonferroni tests showed that both prefrontal tDCS ($MD \approx 27.86$–28.86, $p = .001$) and mindfulness training ($MD \approx 12.60$–13.46, $p = .001$) significantly improved motor skills from pre-test to post-test, with effects maintained at one- and six-month follow-ups, while the sham group showed no significant change. Similar significant patterns were observed for fine motor skills ($F = 55.01$, $p = .001$; $F = 88.44$, $p = .001$; $F = 23.77$, $p = .001$) and upper-limb coordination ($F = 16.22$, $p = .001$; $F = 48.50$, $p = .001$; $F = 5.66$, $p = .001$). Subsequent post hoc analyses revealed that participants who received tDCS demonstrated significantly larger gains in performance compared with those in the mindfulness and sham stimulation groups at both the post-intervention assessment and follow-up evaluations ($p < .0125$).

The findings suggest that stimulation of the prefrontal cortex through tDCS may offer superior benefits for enhancing motor functioning in children with ADHD when compared with mindfulness-based interventions.

Keywords: ADHD, Neurodevelopmental Disorders, Prefrontal Transcranial Direct Current Stimulation, Noninvasive Brain Stimulation, Motor Performance, Motor Skill Development.

1. Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is one of the most prevalent neuropsychiatric conditions of childhood and is typically characterized by persistent patterns of inattention, hyperactivity, and impulsive behavior that are inconsistent with a child's developmental level (Kim et al., 2022). Affecting an estimated 3–7% of school-aged children, ADHD often leads to significant difficulties in academic, social, and behavioral functioning (Thapar & Cooper, 2026). In addition to its core symptoms, many children with ADHD exhibit deficits in motor functioning and coordination, although these impairments have received comparatively limited research attention. Motor-related difficulties can adversely affect the performance of activities requiring precise and coordinated movements, such as handwriting and other fine motor tasks, thereby contributing to functional challenges in daily life (Chan, Jang, & Ho, 2022). The prevalence of movement problems in children with ADHD is between 30 and 52% depending on the measurement method (Egeland, Ueland, & Johansen, 2012). A study by Pitcher et al. (2003) reported that approximately 58% of children with ADHD experience motor problems, including impairments in gross and fine motor skills, balance, coordination, and motor planning. Despite the high prevalence of these motor impairments, they often receive less attention in the clinical assessment and treatment of children with ADHD (Fliers et al., 2010).

The reliance on pharmacological interventions for managing ADHD has grown considerably over the past decades. However, concerns regarding medication-related adverse effects, the necessity for prolonged administration to sustain therapeutic benefits, and challenges associated with treatment adherence have increased interest in alternative non-pharmacological approaches (McClintock, Lau, & Miller, 2016). Among these alternatives, Mindfulness-Based Cognitive Therapy (MBCT) has emerged as a widely recognized intervention for individuals with ADHD

(McClintock et al., 2016). Mindfulness-based approaches have gained substantial attention within the mental health field due to their potential to enhance cognitive, emotional, and behavioral outcomes in children with ADHD. Mindfulness is generally defined as the practice of maintaining purposeful awareness of present-moment experiences while adopting an attitude of openness, acceptance, and nonjudgment. Mindfulness meditation typically involves directing and sustaining attention toward a specific anchor, such as breathing, while gently redirecting focus whenever distractions arise (McClintock et al., 2016). Beyond traditional meditation practices, mindfulness-based programs often incorporate movement-oriented activities, including yoga and related exercises. These practices place particular emphasis on cultivating awareness of bodily sensations and movement through interoceptive, proprioceptive, and kinesthetic processes, thereby fostering a deeper connection between attention regulation and physical experience (Schmalzl, Crane-Godreau, & Payne, 2014). A primary objective of mindfulness-based interventions is to strengthen self-awareness and promote a more cohesive sense of self-regulation by improving attentional control processes. Owing to their emphasis on cognitive and behavioral regulation, mindfulness-based approaches have been identified as particularly valuable for addressing the core deficits associated with Attention-Deficit/Hyperactivity Disorder (ADHD) (McClintock et al., 2016). Mindfulness training cultivates the ability to maintain present-moment awareness while enhancing the regulation of attention and emotional responses—domains that are frequently compromised in individuals with ADHD. Consequently, the underlying mechanisms targeted by mindfulness interventions closely correspond to the cognitive and self-regulatory challenges characteristic of the disorder (Cairncross & Miller, 2025; Mak et al., 2026). Whereas children with ADHD often struggle to sustain attention and inhibit impulsive behaviors, mindfulness practices encourage the development of nonreactive awareness, enabling individuals to observe both internal experiences and external events without immediately responding to them (Smalley et al., 2009).

In contemporary psychiatric practice, neuromodulation techniques have become an important complement to conventional psychosocial and pharmacological interventions (Deng et al., 2020). Among these approaches, transcranial direct current stimulation (tDCS) has attracted considerable interest as a non-invasive brain stimulation technique capable of modifying neural functioning through alterations in the resting membrane potential of cortical neurons (Brunoni et al., 2012). Rather than directly eliciting neuronal firing, tDCS influences cortical activity by producing subthreshold changes in neuronal excitability (Stagg et al., 2018). The effects of tDCS depend on the polarity of the stimulation applied. Anodal stimulation is generally used to enhance cortical excitability, whereas cathodal stimulation tends to reduce it. By selectively increasing or decreasing neuronal responsiveness in targeted brain regions, tDCS provides a means of modulating neural activity in accordance with specific therapeutic objectives (Krause et al., 2022). The effects of tDCS are polarity-dependent, either facilitating or inhibiting the neuron's spontaneous firing rate (Kuo, Bikson, & Datta, 2026). These effects vary depending on the duration and intensity of stimulation and may persist beyond the stimulation period, lasting from minutes to hours (Bikson et al., 2026). Emerging evidence indicates that transcranial direct current stimulation (tDCS) can affect large-scale cortical communication by modifying functional connectivity patterns and reorganizing brain network dynamics (Polanía et al., 2025). In addition, research has demonstrated that tDCS is capable of influencing neural oscillatory activity, with particularly notable effects observed in the alpha frequency range both during stimulation and in the period following its application (Kasten & Herrmann, 2024). Changes in alpha-band activity reported across previous investigations (Balconi et al., 2012; Mangia et al., 2014) provide further support for the neuromodulatory effects of tDCS. Given the established association of alpha oscillations with processes such as relaxation, attentional engagement, and executive control, these findings suggest that tDCS may contribute to improvements in cognitive regulation by altering the neural rhythms underlying these functions. Improvements in motor skills might partially result from these neurophysiological changes, as ADHD often involves dysregulation in such neural dynamics. ADHD is associated with impairments in prefrontal cortex activity, including the DLPFC. tDCS targeting this area can enhance activity and connectivity, potentially leading to better motor skill outcomes compared to interventions like mindfulness, which may not directly modulate cortical activity to the same extent (Kuo et al., 2026; Polanía et al., 2025).

Growing attention has been directed toward the application of transcranial direct current stimulation (tDCS) as a tool for enhancing motor learning and optimizing motor performance. Recent investigations have explored the capacity of this non-invasive neuromodulation technique to facilitate the acquisition, refinement, and execution of motor skills by altering cortical excitability and promoting neuroplastic changes within motor-related brain networks. Early reviews suggested that tDCS can facilitate motor skill acquisition; however, the durability of these effects, particularly at follow-up stages, remained uncertain (Bach et al., 2017). Experimental studies have demonstrated that stimulation of motor-related cortical areas can influence motor responses. For example, Molero-Chamizo et al. (2018) reported that a single session of anodal tDCS (1.5 mA for 15 minutes) applied over the left primary motor cortex (M1) improved reaction time in a go/no-go task compared with sham stimulation, indicating that changes in cortical excitability can enhance motor performance.

Research in pediatric populations has also suggested beneficial effects of tDCS on motor learning. Ciechanski and Kirton (2017) showed that repeated tDCS sessions improved sequence reaction time, bimanual coordination, and aiming performance in children, with follow-up assessments demonstrating persistence of these improvements after several months. More recent studies have supported these findings, indicating that non-invasive brain stimulation can enhance motor learning and neuroplasticity by modulating cortical excitability and functional connectivity within motor networks (Kuo et al., 2023; Polanía et al., 2025). Nevertheless, the magnitude of these effects appears to depend on several factors, including task complexity, stimulation parameters, and the participant's baseline skill level (Pixa et al., 2017; Krause & Cohen Kadosh, 2022).

Despite growing interest in the use of tDCS to enhance cognitive and motor functions, relatively limited research has focused specifically on fundamental motor skills, particularly in clinical pediatric populations. This issue is especially important because children with Attention Deficit Hyperactivity Disorder (ADHD) often experience difficulties in both gross and fine motor skills, which may negatively affect their daily functioning and participation in physical activities (Thomas et al., 2015; Kaiser et al., 2024). Therefore, further research is needed to investigate the effectiveness of neuromodulation approaches such as tDCS in improving basic motor skills in children with ADHD.

Despite its therapeutic potential, the physiological and clinical effects of transcranial direct current stimulation (tDCS) are characterized by considerable interindividual variability. This variability arises because tDCS can induce a broad range of neuroplastic changes, which may be either adaptive or maladaptive depending on the stimulation parameters and individual neural characteristics (Nitsche & Paulus, 2000). Factors such as electrode configuration, placement, size, shape, and the specific cortical region targeted can substantially influence whether cortical excitability is enhanced or suppressed (Nitsche & Paulus, 2000). Among the various cortical targets, the prefrontal cortex has emerged as one of the most frequently stimulated regions in tDCS research and clinical applications. As a central hub of executive functioning, the prefrontal cortex is critically involved in cognitive control mechanisms that support goal-directed behavior (Nejati, Alavi, & Nitsche, 2021). Cognitive control encompasses a range of higher-order processes, including attentional regulation, working memory operations, decision-making, conflict monitoring, and the top-down coordination of cognitive resources (Rosen, Stern, Michalka, Devaney, & Somers, 2016). Particularly, the left prefrontal cortex has been identified as a crucial neural substrate underlying cognitive, emotional, and social functioning. Consistent with this role, accumulating evidence suggests that prefrontal tDCS may contribute to reducing symptoms of inattention and hyperactivity in children with Attention-Deficit/Hyperactivity Disorder (ADHD), highlighting its potential as a promising adjunctive intervention for this population (Klomjai et al., 2022; Rosen et al., 2016).

Previous research has demonstrated that the prefrontal cortex plays a critical role in several functions underlying motor performance, including motor planning, attentional regulation, and working memory (Zaehle et al., 2011; Dockery et al., 2009). Although studies investigating the effects of transcranial direct current stimulation (tDCS) on motor performance are still relatively limited, available evidence suggests that prefrontal stimulation can positively influence motor outcomes and facilitate skill acquisition (Grosprêtre et al., 2021; Lee et al., 2020). Given the close interaction between cognitive and motor processes, modulating prefrontal activity through tDCS may represent a promising approach for enhancing motor functioning. It should be noted, however, that conventional tDCS is not entirely focal, and its effects may extend to neighboring cortical regions, potentially influencing both cognitive and motor functions through broader neural network interactions.

Alongside neuromodulation approaches, mindfulness-based interventions have also shown potential benefits for children with Attention-Deficit/Hyperactivity Disorder (ADHD) by targeting attentional and self-regulatory processes that are closely related to motor performance. Despite increasing interest in both interventions, the available literature has primarily examined their effects separately, and little is known about their relative efficacy in improving motor skills among children with ADHD. To our knowledge, no previous study has directly compared the effects of prefrontal tDCS and mindfulness-based interventions on motor skill development in this population. Therefore, the present study was designed to evaluate and compare the effectiveness of these two interventions in enhancing motor skills in children with ADHD.

2. Methodology

2-1. Research type

This study utilized a quasi-experimental pre-test–post-test design with follow-up assessments to evaluate the effects of the interventions over time.

2-2. Participants

The target population consisted of children aged 7–10 years diagnosed with Attention-Deficit/Hyperactivity Disorder (ADHD) who were referred to the Child Psychiatry Clinic in Kermanshah. The sample size was determined based on previous tDCS studies conducted in pediatric ADHD populations, with 15 participants assigned to each experimental condition. Accordingly, 45 eligible boys and girls with ADHD were recruited and randomly allocated to one of three groups: prefrontal transcranial direct current stimulation (tDCS), mindfulness training, or sham stimulation.

ADHD diagnosis was established by a child psychiatrist according to the criteria outlined in the fifth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5). To be eligible for participation, children were required to obtain moderate-to-severe scores on the Conners' Parent Rating Scale (CPRS), have received an ADHD diagnosis at least six months prior to enrollment, be between 7 and 10 years of age, be right-handed, and have parental consent for participation. Additional inclusion criteria included the absence of methylphenidate (Ritalin) use, no current or previous history of epilepsy, seizures, or traumatic brain injury, and a Full-Scale IQ score above 79 as measured by the Wechsler Abbreviated Scale of Intelligence–Second Edition (WASI-II).

Participants were excluded from the study if they missed more than three intervention sessions, chose to discontinue participation, or withdrew consent before completion of the study protocol.

2-2-1. Ethical Considerations

The study protocol adhered to the ethical standards outlined in the most recent revision of the Declaration of Helsinki and received approval from the Ethics Committee of the Research Institute of Sport Sciences, Tehran (Ethics Code: 103741). Before the commencement of data collection, detailed information regarding the study aims, procedures, and requirements was provided to both the participants and their parents. Written informed consent was obtained from the parents or legal guardians, while verbal assent was secured from the children prior to participation. All participants were informed that the confidentiality of their personal data would be strictly maintained and that participation was entirely voluntary, allowing them to withdraw from the study at any time without penalty or adverse consequences.

2-3. Material

A demographic questionnaire was administered to obtain background information about the participants. This researcher-developed form collected essential demographic and clinical data, including age, sex, educational status, and relevant family and medical characteristics. The information obtained was used to describe the study sample and to account for potential demographic factors that could influence the research outcomes.

ADHD symptoms were assessed using the Swanson, Nolan, and Pelham Rating Scale (SNAP-IV), a widely recognized instrument designed to evaluate the core manifestations of Attention-Deficit/Hyperactivity Disorder (ADHD). Developed in accordance with the diagnostic criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders (DSM), the SNAP-IV is extensively employed in both clinical practice and research to measure symptoms of inattention and hyperactivity/impulsivity (Swanson et al., 2001).

The scale comprises 18 items completed by parents or teachers. The first nine items assess inattentive symptoms, whereas the remaining nine evaluate hyperactive and impulsive behaviors. Responses are recorded on a four-point Likert scale ranging from 0 (not at all) to 3 (very much). Scores for each symptom domain are calculated by averaging the responses to the corresponding items. Previous research has demonstrated that the SNAP-IV possesses strong psychometric characteristics, including high levels of internal consistency and reliability (Swanson et al., 2001). Furthermore, studies conducted in Iran have confirmed the validity and reliability of the Persian version, reporting satisfactory Cronbach's alpha coefficients and test–retest reliability indices (Sadrolsadat et al., 2010).

Bruininks–Oseretsky Test of Motor Proficiency (BOTMP). Motor performance was assessed using the Bruininks–Oseretsky Test of Motor Proficiency (BOTMP), a standardized instrument designed to evaluate both gross and fine motor skills in children. Developed by Bruininks (1978), the test is intended for individuals aged approximately 4.5 to 14 years and provides a comprehensive assessment of motor functioning across multiple domains. The BOTMP consists of several subtests that measure key aspects of motor proficiency, including running speed and agility, balance, bilateral coordination, muscular strength, response speed, visual–motor control, and upper-limb speed and dexterity. Administration of the test typically requires between 45 and 60 minutes to complete. Gross motor performance is assessed through subtests evaluating running speed and agility, balance, bilateral coordination, and strength, whereas fine motor performance is measured through tasks involving response speed, visual–motor control, and upper-limb speed and dexterity. The BOTMP is widely used in both clinical and research settings due to its ability to provide a comprehensive profile of children's motor abilities.

tDCS device : The device used in this research is Dose Active and the power source of this device is a 9-volt battery. Electrical stimulation is installed on the scalp through connecting electrodes of different polarity (anode and cathode). These electrodes transmit a constant electric current from the skull to the brain. In this research, the electrodes are placed in the sponge pads of 3.5 cm² and the surface of the pads is smeared with 9% sodium chloride solution in order to increase the conductivity of the electric current and prevent the heat increase. Electrode and duration of stimulation can be controlled.

2-4. Prosedure

Following an initial familiarization session, participants completed the Bruininks–Oseretsky Test of Motor Proficiency (BOT) at baseline under standardized testing conditions. The intervention period consisted of 15 sessions, after which all participants underwent post-intervention assessment using the same motor proficiency measure. The follow-up schedule was established based on previous studies involving pediatric populations, as well as research examining the effects of transcranial direct current stimulation (tDCS) (Grohs, Craig, Kirton, & Dewey, 2020) and mindfulness-based interventions (Lee, Chen, & Lin, 2022). Accordingly, follow-up evaluations were conducted one month and six months after the completion of the intervention.

Participants assigned to the prefrontal tDCS group received 15 stimulation sessions targeting the dorsolateral prefrontal cortex, with the anodal electrode positioned at F3 and the cathodal electrode at F4 according to the international 10–20 EEG system (Soleimani et al., 2022). Each session lasted 30 minutes, during which a constant direct current of 2 mA was delivered. Sessions were administered at three-day intervals throughout the intervention period. All procedures were conducted under the supervision of a licensed clinical psychologist with expertise in neuromodulation and psychological interventions.

The mindfulness intervention group participated in a structured mindfulness training program consisting of 15 sessions, each lasting 60 minutes and delivered every three days. During these sessions, participants engaged in age-appropriate mindfulness exercises and activities designed to enhance attentional control, self-awareness, and self-regulation (Palm et al., 2016).

Participants in the sham stimulation group underwent a procedure identical to that of the active tDCS condition in terms of electrode placement and session duration. However, although a 2 mA current was initially applied to mimic the sensation of active stimulation, the current was automatically discontinued after 30 seconds without the participants' knowledge. This procedure allowed participants to experience the initial tingling sensation associated with tDCS while preventing any meaningful neuromodulatory effects, thereby maintaining the integrity of the control condition.

Mindfulness training program

Mindfulness training was delivered through a structured program including focused attention practices, sensory awareness exercises, development of positive attitudes, and mindful social actions, which are common components of school-based mindfulness interventions for children (Schonert-Reichl & Roeser, 2023; Zenner et al., 2023).

Sessions1 to 3: Focusing:

Session 1 introduced basic concepts of how the brain works, session 2 focused on conscious attention, and session 3 emphasized conscious concentration through core mindfulness exercises. In this unit, children were provided with a simple introduction to brain functioning and the concept of mindful attention. They were taught that mindful attention involves paying attention to the present moment—including other people, the surrounding environment, worries, or challenges—without judgment. In addition, core mindfulness exercises were introduced and practiced daily. Children were also encouraged to engage in brief self-monitoring practices three times a day, each lasting approximately three minutes, to strengthen their awareness and concentration.

Sessions 4-9 :Sharpening the Emotions:

Session 4 focused on mindful listening, session 5 on mindful seeing, session 6 on mindful smelling, session 7 on mindful tasting, and sessions 8 and 9 on mindful movement. This unit aimed to help children experience the relationship between sensory perception, body movement, and thought processes. During these sessions, children were encouraged to focus their attention on specific sensory experiences in order to strengthen concentration and present-moment awareness. The activities included practices such as mindful listening, mindful observation, mindful smelling, mindful tasting, and mindful movement exercises.

Sessions10-12: All about Attitudes:

Session 10 focused on perspective taking, session 11 on choosing optimism, and session 12 on appreciating positive experiences. This unit emphasized understanding the role of mindset in learning and personal development. The module was designed to foster a positive attitude in children by preparing them for learning, promoting positive interpersonal relationships, and encouraging the conscious selection of constructive social activities. Throughout these sessions, children engaged in activities related to perspective taking, optimism, and the appreciation and enjoyment of positive experiences.

Sessions 13 to 15: Acting mindfully:

Sessions 13 through 15 were designed to extend mindfulness practice into interpersonal and social contexts. Session 13 emphasized the cultivation of gratitude, Session 14 focused on engaging in acts of kindness, and Session 15 encouraged the application of mindful awareness in broader social interactions and everyday environments. During these sessions, participants were guided to incorporate mindful attitudes and behaviors into their relationships with others and their engagement with the surrounding community. The overarching aim of this module was to promote prosocial development by providing opportunities for children to practice gratitude, express appreciation, perform acts of kindness, and participate in cooperative classroom and community-oriented activities. In addition, participants were encouraged to consciously observe and reflect upon their thoughts, feelings, and behavioral responses before, during, and after engaging in these experiences, thereby strengthening self-awareness and emotional regulation within social situations.

2-6. Statistical analysis of data

Data analysis was carried out using SPSS version 26. Before conducting the primary statistical procedures, the distribution of the data was assessed for normality using the Shapiro–Wilk test. A mixed-design ANOVA incorporating three experimental groups and four assessment time points was then employed to evaluate the effects of the interventions over time. Following the identification of a significant Group × Time interaction, Bonferroni-corrected pairwise comparisons were performed to investigate within-group differences across measurement occasions. In addition, Tukey post hoc analyses were conducted when necessary to further examine significant effects. Comparisons between groups were evaluated using Bonferroni-adjusted post hoc tests with correction for multiple testing.

3- Results

Table 1 summarizes the demographic characteristics and estimated baseline symptom severity of the three study groups comprising children with ADHD. The groups—Prefrontal tDCS, Mindfulness Program, and Sham Stimulation—were matched on age, height, and weight, with mean ages ranging from approximately 8.2 to 8.9 years. Estimated SNAP-IV scores indicate that all groups exhibited moderate symptom severity at baseline, with the Prefrontal tDCS group showing slightly higher inattention and hyperactivity/impulsivity scores compared to the mindfulness and sham groups. These descriptive statistics provide a comprehensive overview of participant characteristics prior to intervention.

Table 1. Descriptive statistics of demographic variables and estimated SNAP-IV scores by group

Variable	Group	n	Minimum	Maximum	Mean	SD
Age (years)	Prefrontal tDCS	15	7	10	8.20	1.20
	Mindfulness Program	15	7	10	8.93	1.05
	Sham Stimulation	15	7	10	8.33	1.00
Height (cm)	Prefrontal tDCS	15	90	130	113.86	12.86
	Mindfulness Program	15	90	129	108.53	29.12
	Sham Stimulation	15	90	129	114.53	14.11
Weight (kg)	Prefrontal tDCS	15	18	32	24.26	4.66
	Mindfulness Program	15	19	35	25.20	5.34
	Sham Stimulation	15	20	34	26.00	4.86
SNAP-IV Inattention (0–3)	Prefrontal tDCS	15	1.8	2.2	2.0	0.15
	Mindfulness Program	15	1.4	1.8	1.6	0.13
	Sham Stimulation	15	1.6	2.0	1.8	0.14
SNAP-IV Hyperactivity (0–3)	Prefrontal tDCS	15	1.6	2.0	1.8	0.14
	Mindfulness Program	15	1.3	1.6	1.45	0.11
	Sham Stimulation	15	1.5	1.9	1.7	0.13
SNAP-IV Total (0–3)	Prefrontal tDCS	15	1.7	2.1	1.9	0.12
	Mindfulness Program	15	1.35	1.7	1.5	0.12
	Sham Stimulation	15	1.55	1.95	1.75	0.12

In Table No. 2, statistical indicators (mean and standard deviation) related to dependent variables in different groups during different stages of the test are presented.

Table 2. Statistical indicators (mean and standard deviation) related to dependent variables in different groups during different stages of the test

		sham stimulation	Mindfulness	tDCS
Gross motor skills	time	28/40+7/98	30/06+6/83	30/26+7/08
	post test	27/20+5/36	43/46+6/4	59/13+7/47
	1 follow-up	27/20+4/58	43/53+6/52	58/33+5/39
	2 follow-up	27/66+6/05	42/66+6/82	58/13+3/64
Fine motor skills	pre-test	23/66+4/15	22/66+4/96	23/60+3/85
	Post-test	22/20+5/45	32/00+4/67	42/06+5/82
	1 follow-up	22/86+3/50	30/33+3/13	40/40+5/23
	2 follow-up	22/60+3/85	31/00+3/27	42/60+4/74
Upper limb coordination	pre-test	4/86+2/19	4/46+1/45	5/46+1/99
	post test	5/40+1/63	7/46+1/24	10/40+3/33
	1 follow-up	4/26+2/05	7/06+1/38	10/33+3/24
	2 follow-up	4/40+2/35	7/46+1/35	10+60+3/20

The results of the 3 × 4 mixed-design ANOVA, including three experimental groups and four measurement occasions, are summarized in Table 3.

Table 3. The results of the mixed analysis of variance (ANOVA) with three groups and four repeated measurement stages

	Source	Sum of square	df	mean of square	F	P	η²
Gross motor skills	time	6118/32	3	2039/44	54/98	<0/001	0/567
	group	17070/81	2	8535/40	180/90	<0/001	0/896
	Time group	4847/32	6	807/88	21/78	<0/001	0/509
Fine motor skills	time	2446/71	3	815/57	55/01	<0/001	0/564
	group	6203/33	2	3101/66	87/44	<0/001	0/806
	Time group	2114/48	6	352/41	23/77	<0/001	0/531
Upper limb coordination	time	226/81	3	75/60	16/22	<0/001	0/279
	group	603/43	2	301/71	48/50	<0/001	0/698
	Time group	158/44	6	26/40	5/66	<0/001	0/213

Gross motor skills

The results of the repeated-measures ANOVA revealed significant effects of time, $F = 54.98$, $p = 0.001$, $\eta^2 = 0.567$, group, $F = 180.90$, $p = 0.001$, $\eta^2 = 0.896$, and the time × group interaction, $F = 21.78$, $p = 0.001$, $\eta^2 = 0.509$. Given the significance of the interaction effect, Bonferroni-adjusted post hoc comparisons were conducted (adjusted $\alpha = 0.0125$) (see Table 3).

The within-group analyses revealed a marked enhancement in gross motor performance following prefrontal transcranial direct current stimulation (tDCS). Participants in this group exhibited significantly higher gross motor skill scores after the intervention compared with baseline, and these improvements persisted throughout both the one-month and six-month follow-up periods (all $p = 0.001$). A comparable pattern was observed in the mindfulness intervention group, where significant gains in gross motor functioning were detected after treatment and remained evident at subsequent follow-up assessments (all $p = 0.001$). Conversely, participants assigned to the sham stimulation condition did not demonstrate any statistically significant changes in gross motor performance across the study period ($p > 0.0125$).

Comparisons across groups showed that gross motor skill levels were similar prior to the interventions, indicating no significant baseline differences. Following treatment, however, distinct group effects emerged. Children who received prefrontal tDCS achieved significantly better gross motor outcomes than those in both the mindfulness and sham stimulation groups at the post-test, one-month follow-up, and six-month follow-up assessments ($p < 0.0125$). In addition, although the mindfulness intervention was less effective than tDCS, it produced significantly greater improvements in gross motor performance than the sham condition across all post-intervention evaluation points ($p < 0.0125$) (Figure 1).

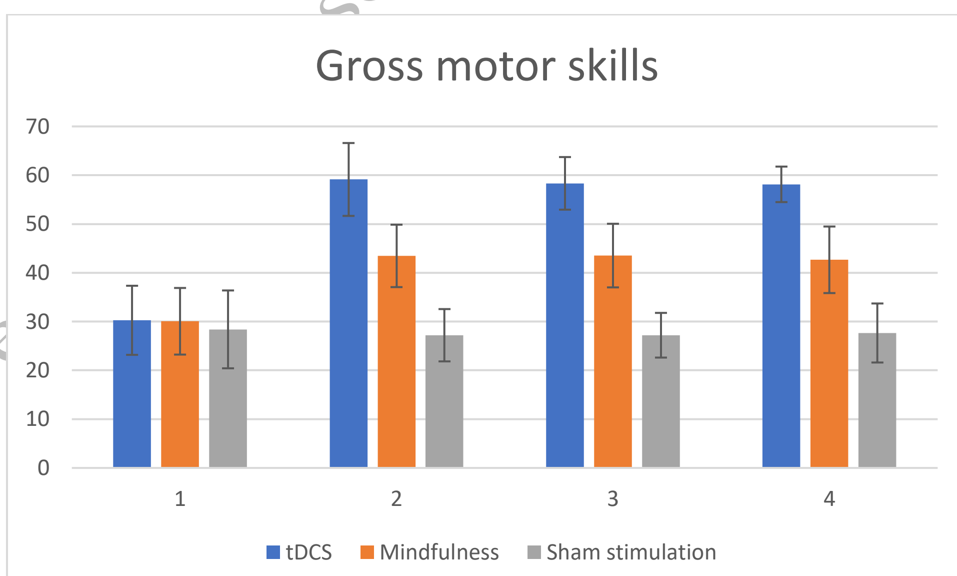

Figure 1. The graph of gross motor skills scores of large groups in different stages of the research

Fine motor skills

The results of the repeated-measures ANOVA demonstrated significant effects of time, $F = 55.01$, $p = 0.001$, $\eta^2 = 0.567$, group, $F = 88.44$, $p = 0.001$, $\eta^2 = 0.806$, and the time × group interaction, $F = 23.77$, $p = 0.001$, $\eta^2 = 0.531$. Given the significant interaction effect, Bonferroni-adjusted post hoc comparisons were performed (see Table 3).

The results of the within-group analyses demonstrated that children who received prefrontal transcranial direct current stimulation (tDCS) showed substantial improvements in fine motor performance following the intervention. These gains were evident at the post-test assessment and were successfully maintained throughout the one-month and six-month follow-up periods (all $p = 0.001$). Likewise, participants in the mindfulness training group exhibited significant enhancements in fine motor skills after treatment, and the benefits remained consistent across subsequent assessments, suggesting sustained intervention effects (all $p = 0.001$). In contrast, the sham stimulation group did not show any statistically meaningful changes in fine motor performance over the course of the study ($p > 0.0125$).

Analysis of between-group differences indicated that the three groups were comparable at baseline, with no significant differences observed prior to the intervention. Following treatment, however, significant group differences emerged. Participants in the prefrontal tDCS condition achieved superior fine motor skill outcomes compared with those in both the mindfulness and sham stimulation groups at post-test as well as at the one-month and six-month follow-up assessments ($p < 0.0125$). Moreover, although the magnitude of improvement was smaller than that observed in the tDCS group, children who participated in the mindfulness program demonstrated significantly better fine motor performance than those in the sham condition across all post-intervention evaluation points ($p < 0.0125$) (Figure 2).

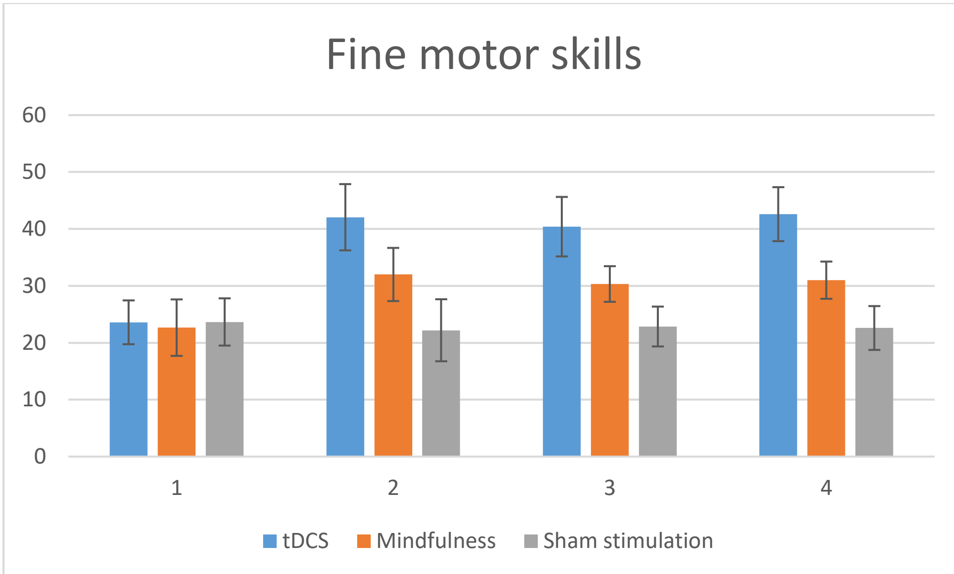

Figure 2. The graph of fine motor skills scores of large groups in different stages of the research

Upper limb coordination

The repeated-measures ANOVA revealed significant effects of time, $F = 16.22$, $p = 0.001$, $\eta^2 = 0.279$, group, $F = 48.50$, $p = 0.001$, $\eta^2 = 0.698$, and the time × group interaction, $F = 5.66$, $p = 0.001$, $\eta^2 = 0.213$. Given the significance of the interaction effect, Bonferroni-adjusted post hoc comparisons were conducted (see Table 3).

The within-group findings revealed that participants who received prefrontal transcranial direct current stimulation (tDCS) experienced significant improvements in upper-limb coordination following the intervention. These gains were observed at the post-test assessment and were preserved at both the one-month and six-month follow-up evaluations (all $p = 0.001$). A similar trend was identified in the mindfulness training group, where upper-limb coordination improved significantly after the intervention and remained unchanged across subsequent assessments, indicating sustained treatment benefits (all $p = 0.001$). By contrast, children in the sham stimulation condition did not exhibit any significant changes in upper-limb coordination throughout the study period ($p > 0.0125$).

The between-group analyses demonstrated that the three groups did not differ significantly in upper-limb coordination at baseline. Following the intervention, however, clear differences emerged among the groups. Participants in the prefrontal tDCS group achieved significantly better upper-limb coordination scores than those in the mindfulness and sham stimulation groups at the post-test, one-month follow-up, and six-month follow-up assessments ($p < 0.0125$). In addition, the mindfulness training group outperformed the sham stimulation group at all post-intervention measurement points, demonstrating significantly higher levels of upper-limb coordination ($p < 0.0125$) (Figure 3).

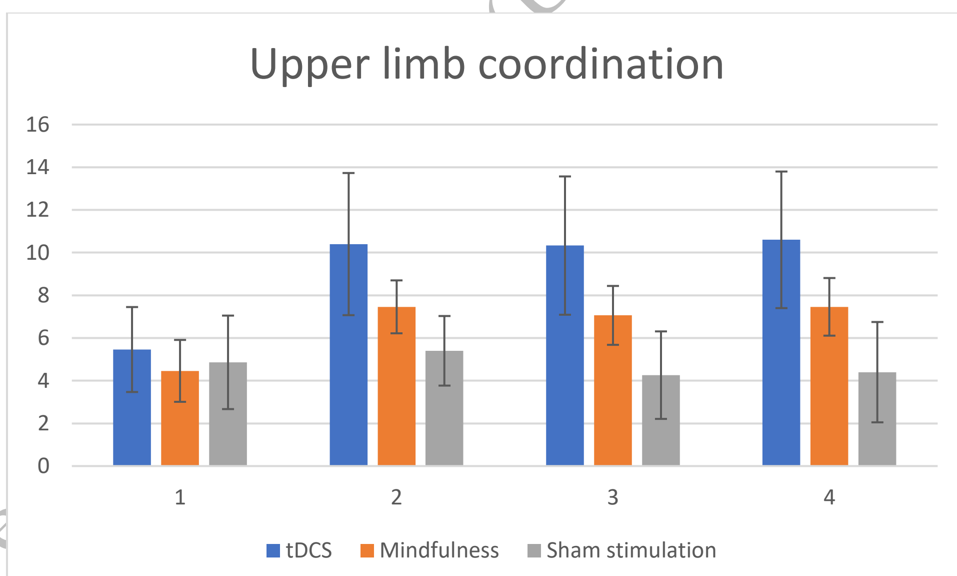

Figure 3. The graph of upper limb coordination scores of large groups in different stages of the research

4- Discussion and conclusion

The primary objective of the present study was to evaluate and compare the effects of mindfulness-based training and prefrontal transcranial direct current stimulation (tDCS) on motor functioning and ADHD-related symptoms in children diagnosed with Attention-Deficit/Hyperactivity Disorder (ADHD). Overall, the findings demonstrated that both interventions produced significant improvements in motor performance and contributed to the maintenance of these gains over time. Specifically, enhancements were observed across multiple domains of motor functioning, including gross motor skills, fine motor skills, and upper-limb coordination. Despite the positive effects associated with both interventions, the results revealed that prefrontal tDCS was more effective than the mindfulness program in promoting motor skill development and sustaining these improvements during the follow-up period. Children who received tDCS exhibited greater gains in gross and fine motor abilities, as well as upper-limb coordination, indicating the superior efficacy of this neuromodulation approach in enhancing motor outcomes among children with ADHD.

A discussion of the impact of the mindfulness program on the improvement and durability of motor skills in children diagnosed with ADHD reveals the potential benefits of this approach. The practice of mindfulness, which emphasizes "being present in the moment" and being non-judgmental and purposeful, has been shown to enhance focus on the activity at hand. Consequently, individuals who engage in this practice experience an improvement in their performance, leading to an increase in their sense of self-efficacy and personal competence. In this case, this finding is consistent with Tarajian et al.'s (2017Tarajian et al. (2017) explored the effects of mindfulness training on the motor and cognitive functioning of children with Attention-Deficit/Hyperactivity Disorder (ADHD). The findings revealed that mindfulness practice was associated with significant enhancements in both motor skill performance and cognitive functioning among children exhibiting symptoms of hyperactivity.

Regarding the effects of transcranial direct current stimulation (tDCS), the findings of the present study demonstrated that prefrontal stimulation significantly enhanced motor performance in children with ADHD. Improvements were observed across several domains of motor functioning, including gross motor skills, fine motor skills, and upper-limb coordination. These results suggest that modulation of prefrontal cortical activity may contribute to better motor outcomes in this population. To the authors' knowledge, few studies have directly investigated the effects of prefrontal tDCS on motor skills in children with ADHD, making direct comparisons with previous research difficult. Nevertheless, the present findings differ from those reported by Harris et al. (2019), who found no significant effect of prefrontal stimulation on golf putting performance. This discrepancy may be attributable to differences in participant characteristics, stimulation protocols, outcome measures, or the specific motor tasks examined across studies. A potential explanation for this difference could be related to the number of stimulation sessions, which was one session in the study by Harris et al. (2019), while it was fifteen sessions in the present study. In this case, it can be stated that multiple sessions of direct anodal current with low intensity show a cumulative effect on the excitability of the cerebral cortex after repeated daily sessions (Martin et al., 2014) (Martin, Liu, Alonzo, Green , & Loo, 2014).

With regard to the effect of DLPFC stimulation, it can be argued that during the performance of motor skills, functional and structural changes occur in some neural networks such as: M1 and DLPFC, and behavioral and neural relationships related to motor performance are changed. (Ungerleider, Doyon, & Karni, 2002) and it is suggested that the beneficial effects of tDCS on motor performance are due to the strengthening of these neural networks and the improvement of cellular-physiological changes that occur with exercise. It is related, especially that it can reduce the amount of inhibitory neurotransmitters (such as gamma aminobutyric acid) or increase the stimulated neurotransmitters, and by improving the parameters that increase the excitability of the motor cortex, it facilitates motor performance. slow (Reis et al., 2009).

An additional finding of the present study was that the two intervention methods differed significantly in their effects on motor performance, with prefrontal transcranial direct current stimulation (tDCS) yielding greater improvements than the mindfulness-based program in children with ADHD. Although no previous research has directly compared these interventions in relation to motor skill development in this population, several neurobiological explanations may account for the observed findings. Neuroimaging evidence has repeatedly shown atypical patterns of activation within prefrontal regions among individuals with ADHD. In particular, reduced activity in the bilateral dorsolateral prefrontal cortex (DLPFC) and decreased activation of the left medial frontal cortex have been reported during tasks requiring attention, inhibitory control, and working memory (Lee et al., 2015; Reis et al., 2009; McCarthy et al., 2014). These functional abnormalities are thought to play a central role in the executive and attentional deficits that characterize the disorder. As a result, increasing cortical excitability within the DLPFC through anodal tDCS has been proposed as a promising strategy for addressing the underlying neural dysfunction associated with ADHD. Because the DLPFC is critically involved in executive processes that support the planning, monitoring, and regulation of behavior, enhancing activity within this region may indirectly facilitate motor functioning. By acting directly on neural circuits implicated in attention regulation and executive control, prefrontal tDCS may produce stronger and more immediate effects on motor performance than interventions that primarily target these functions through behavioral training. This may explain the greater improvements observed in the tDCS group relative to the mindfulness group. Nevertheless, given the limited evidence currently available, future studies are needed to further investigate the mechanisms responsible for these effects and to determine whether similar findings can be replicated in larger and more diverse samples of children with ADHD.

Overall, the results of the present study demonstrated that both prefrontal transcranial direct current stimulation (tDCS) and the mindfulness-based program were effective in enhancing motor performance among children with ADHD. Significant improvements were observed across the assessed domains of motor functioning following participation in either intervention. However, comparative analyses revealed that prefrontal tDCS produced greater gains in motor skills than the mindfulness program. To the best of our knowledge, this study is the first to directly compare the effects of prefrontal tDCS and mindfulness-based training on motor skill development in children with ADHD. The findings suggest that prefrontal tDCS may represent a promising, non-invasive, and well-tolerated intervention for improving motor functioning in this population. Given the magnitude and persistence of the observed benefits, this neuromodulation approach may offer a valuable complement to existing therapeutic strategies aimed at addressing motor deficits in children with ADHD.

Despite providing valuable insights into the effects of prefrontal transcranial direct current stimulation (tDCS) and mindfulness-based training on motor functioning in children with ADHD, several limitations should be considered when interpreting the findings. The study was conducted exclusively among children aged 7–10 years, which may restrict the generalizability of the results to other age groups. Moreover, some of the proposed explanations for the observed effects remain tentative and require further empirical validation. Although the findings offer preliminary support for the effectiveness of both interventions, additional research employing larger and more diverse samples is needed to strengthen the evidence base and clarify the mechanisms underlying these outcomes. Future longitudinal investigations may also provide a more comprehensive understanding of the long-term effects of these interventions. Furthermore, emerging evidence suggests that combining neuromodulation techniques with behavioral interventions may enhance treatment efficacy; therefore, future studies should explore the potential benefits of integrating tDCS and mindfulness-based training either concurrently or sequentially to maximize motor and cognitive improvements in children with ADHD.

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Data Availability

The dataset presented in this study can be requested from corresponding author.

Declarations

The authors declare no conflicts of interest with regards to authorship, sponsorship, and funding.

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