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The Effect of DLPFC Stimulation Compared to Mindfulness Exercises on Cognitive Performance in Children with Attention Deficit Hyperactivity Disorder

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ABSTRACT

Objective: Mindfulness programs and transcranial direct current stimulation (tDCS), particularly of the dorsolateral prefrontal cortex (DLPFC), are increasingly used for therapeutic purposes in Attention Deficit Hyperactivity Disorder (ADHD). The aim of the present study was to investigate the effect of DLPFC stimulation compared to mindfulness exercises on cognitive performance in children with ADHD.

Materials and Methods: In this quasi-experimental study, 45 children with ADHD participated in a between-group design (mindfulness program, DLPFC stimulation, and sham stimulation) with two measurement phases (pre-test and post-test). All subjects underwent 15 intervention sessions according to their respective group. At various stages, participants were tested on cognitive flexibility (Wisconsin Card Sorting Test) and working memory (Wechsler Intelligence Scale).

Findings: The results of the composite analysis of variance showed significant main effects of time, group, and the time-group interaction for the research variables, including cognitive flexibility (perseverative error and total error) and working memory. Post hoc test results indicated that the DLPFC stimulation group had significantly better scores in cognitive flexibility (perseverative error and total error) and working memory compared to the mindfulness group.

Conclusion: Hypoactivity of the dorsolateral prefrontal cortex underlies executive function deficits in individuals with ADHD, and transcranial direct current stimulation increases activation of the dorsolateral prefrontal cortex through anodal stimulation.

Keywords: *Transcranial Direct Current Stimulation, Neurodevelopmental Disorders, Hyperactivity, DLPFC, Mindfulness, Cognitive Performance*

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1. Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is a common, long-term, and manageable psychiatric disorder in childhood, characterized by a developmental pattern of inappropriate inattention and impulsivity (1). This disorder affects approximately 3 to 7 percent of school-aged children and is marked by severe inattention, impulsivity, and hyperactivity (2). Impulsivity refers to the inability to inhibit behavioral and cognitive impulses, resulting in hasty actions and thoughts that occur without reflection in the moment (3). These behaviors include interfering with others' activities, excessive interrupting, impatience, inability to wait one's turn, inappropriate social speech, and multiple errors in completing school tasks, all observed in individuals with ADHD. As noted, ADHD is associated with profound adverse effects on educational and social development (4). Additionally, most children with ADHD exhibit deficits in executive functions (EF) (5). Executive functions are a set of cognitive processes that transform thoughts into decisions, plans, and actions, allowing for the initiation of actions, regulation of goal-directed behavior, avoidance of distractions, and flexible adaptation before changing conditions. They are essential for addressing new or complex problems that require strategy development and adaptive solutions. Thus, EF is crucial for daily life aspects, from physical and mental health to psychosocial and cognitive development. The neural substrate of EF is the frontal lobe, particularly the prefrontal cortex and its connections to the basal ganglia, amygdala, limbic system, and cerebellum. The prefrontal cortex includes various regions and pathways, with the dorsolateral prefrontal cortex responsible for selective attention, working memory, cognitive flexibility, and planning. The orbitofrontal cortex is associated with social behavior, and the ventromedial prefrontal cortex aids in emotional processing. Therefore, normal EF development is critical for a child's cognitive, social, and emotional growth. Several authors and studies (6, 7) suggest that ADHD symptoms (hyperactivity, impulsivity, and inattention) result from EF deficits, although not all individuals with ADHD exhibit these deficits. Common manifestations of EF changes in ADHD include deficits in alertness/orientation, focused attention, divided attention, and sustained attention/vigilance, along with issues in working memory, inhibition, and planning (Barkley, 2011; Huguet et al., 2017).

Mindfulness-based interventions offer a promising approach to improving outcomes for children with ADHD and are gaining increasing attention in mental health. Mindfulness involves focusing on the present moment without judgment or reaction. Mindfulness meditations include selecting a focus point, such as the breath, and sustaining attention on that point (8). Mindfulness is described as the practice of being aware, intentionally attending to the present moment with an open, curious, friendly, and compassionate attitude, without rejecting, judging, or criticizing, merely accepting what is happening. The goal of clinical mindfulness training is to increase awareness, helping individuals act consciously without being drawn into their thoughts, emotions, and feelings, thereby reducing automatic responses. This enables the development of skills and increases the repertoire of resources to respond more selectively, choose behaviors, and skillfully address daily situations and problems. In turn, this improves the ability to maintain attention and focus, reduce impulsivity, aid relaxation and calmness, increase frustration tolerance, reduce stress, and enhance quality of life (9). Mindfulness-based interventions are among the best options for addressing ADHD-related deficiencies. ADHD and mindfulness share similar processes: children with ADHD struggle with sustained attention and impulse control, while mindfulness develops the regulatory capacity to observe external and internal stimuli without reacting to them (10).

On the other hand, neuromodulation, alongside psychosocial and psychiatric interventions, constitutes the third pillar of therapeutic interventions in psychiatry. Transcranial direct current stimulation (tDCS) is a non-invasive neurophysiological method with the potential to modify brain function by influencing the resting membrane potential of neurons. This impacts neuronal excitability at a sub-threshold level without eliciting action potentials (11). Depending on the intervention's goal, anodal or cathodal stimulation can be used to increase or decrease neuronal excitability, thereby modulating processes related to the targeted brain area in the desired direction (12). The effects of direct current stimulation facilitate or inhibit polarity-dependent spontaneous firing rates of neurons. The aftereffects of tDCS depend on the stimulation duration, lasting from minutes to hours (13). Studies on the effects of tDCS on neural activity have shown that direct current can modulate cortical connectivity and induce changes in alpha frequency bands during and after stimulation (14). In recent years, tDCS has been used to improve motor skills in children and adults with ADHD, without serious side effects, and has shown encouraging results regarding feasibility, efficacy, and tolerance (15). Dubreuil-Vall et al. (2021)

reported that transcranial direct current stimulation of the left dorsolateral prefrontal cortex improves cognitive control in patients with ADHD (16). Nejati et al. (2020) found that anodal tDCS over the left dorsolateral prefrontal cortex significantly affects executive control functions like interference inhibition, while cathodal tDCS improves inhibitory control (17). Cognitive flexibility/task-switching benefits from the combination of the dorsolateral prefrontal cortex and orbitofrontal cortex stimulation but not from the dorsolateral prefrontal cortex stimulation alone. Another study found that anodal stimulation of the left dorsolateral prefrontal cortex had no effect on interference inhibition during a Stroop task but increased the ratio of correct responses in the "go" phase of the Go/No-Go test compared to sham conditions. Cathodal stimulation of the left dorsolateral prefrontal cortex improved inhibitory accuracy during the inhibition phase of the Go/No-Go task compared to sham (18). Contradictory findings also exist, such as Westwood et al. (2022), who investigated the effect of tDCS combined with cognitive training on EEG spectral power in adolescent boys with ADHD. They found no significant differences compared to the anodal tDCS group in EEG spectral power during rest and Go/No-Go task performance, correlation between EEG spectral power and Go/No-Go task performance, and changes in clinical and cognitive measures (19). The dorsolateral prefrontal cortex is a widely targeted brain area for tDCS. As a key region of executive functions, the dorsolateral prefrontal cortex plays a crucial role in cognitive control processes, modulating top-down interactions between attention and memory, decision-making, and conflict resolution (20). The left dorsolateral prefrontal cortex is vital for cognitive, social, and emotional functioning, essential for theory of mind, emotion recognition, and executive functions (20, 21). Given these points, the aim of this study is to investigate the effect of DLPFC stimulation compared to mindfulness-based cognitive therapy on cognitive performance in children with ADHD.

2. Methods and Materials

2.1 Study Design and Participants

Forty-five children aged 7 to 10 years with ADHD, referred to a child psychiatry clinic in Kermanshah, were selected to participate in the present study. The required sample size was based on the medium critical effect size recommended for tDCS studies (Minarik et al., 2016) and previous tDCS studies in ADHD (Salehinejad et al., 2020). For a repeated-measures design with four measurement stages in the present study, the required sample size calculated using G*Power software (version 3.1.9.4) was 33 participants. Considering a 30 percent dropout rate (Hiller et al., 2010), a total of 45 boys and girls with ADHD were purposefully selected and randomly assigned to three groups: real DLPFC stimulation, mindfulness training, and sham stimulation. All children were clinically interviewed for ADHD based on DSM-5 criteria, and their parents completed the Conners' Parent Rating Scale (CPRS) (Conners et al., 1998) and the Behavior Rating Inventory of Executive Function (BRIEF) (Gioia et al., 2000). Inclusion criteria included: 1) ADHD diagnosis based on DSM-5 by a professional child psychiatrist and moderate to severe scores on the CPRS (<50), 2) ADHD diagnosis for at least six months, 3) no Ritalin use (children who did not use Ritalin or whose parents opposed its use), 4) parental consent, 5) age 7 to 10 years, 6) no current or past epilepsy, seizures, or head injury, and 7) a full-scale IQ score >79 on the Wechsler Abbreviated Scale of Intelligence, second edition (WASI-II). Exclusion criteria included more than three absences from therapy sessions, other mental and motor disabilities, hearing and visual impairments, and comorbid behavioral disorders such as autism spectrum disorder or disruptive mood dysregulation disorder. Participants who wished to withdraw from the study were also excluded.

High-intensity interval training included high-intensity exercise intervals lasting 30 seconds and low-intensity active rest intervals lasting 30 seconds. The training protocol involved 20-meter sprints with varying repetitions from the first to the sixth week, with rest intervals of 20-30 seconds between sprints. To adhere to the principle of overload and training effectiveness, the number of short-term sprints was set at 4 repetitions for the first and second weeks, 5 repetitions for the third and fourth weeks, and 6 repetitions for the fifth and sixth weeks. Each session included 5 minutes for warm-up and 5 minutes for cool-down. High-intensity interval training was conducted three times a week for six weeks.

The study was conducted according to the latest version of the Declaration of Helsinki ethical standards and approved by the Ethics Committee of the Tehran Sports Sciences Research Institute. The study was field-based. Initially, written informed consent was obtained from the parents, and verbal assent was obtained from the children. Participants were then informed about the study's objectives, the scoring process, and the administration of the tests. Subsequently, participants were randomly assigned to one of the three groups: real DLPFC stimulation, mindfulness training, and sham stimulation. The study included pre-test, intervention (training), and post-test phases. Assessments were conducted before the interventions and in the session following the interventions by an occupational therapist other than the principal investigator in a double-blind manner. This evaluator was unaware of the study's objectives and the session content, and all three assessments were conducted by the same individual. After familiarization, participants underwent pre-test cognitive performance assessments according to existing guidelines, followed by 15 intervention sessions.

In the sham electrical stimulation group, participants underwent 15 sessions, each lasting 30 minutes. During these sessions, participants received a sham stimulation where a 2 mA electric current was applied for 30 seconds after electrode placement, then discontinued without the participants' knowledge.

Immediately after the fifteenth session, the post-test phase was conducted, during which participants performed the required tests.

2.2 Tools

2.2.1 Wisconsin Card Sorting Test (WCST)

The WCST is a principal and widely used neuropsychological tool to assess set-shifting, flexibility, problem-solving, concept formation, and the ability to overcome the tendency to repeat and categorize items, which are executive functions of the brain. The WCST can be scored in various ways, with the most common method recording the number of categories achieved and perseverative errors, indicating individuals' flexibility. The validity of this test is reported at 0.86, and its test-retest reliability is 0.85 (22).

2.2.2 Wechsler Intelligence Scale for Children (WISC)

The Wechsler Intelligence Scale has three different types for various age groups, with this study using the 6-16 years version. This test includes 12 subscales organized into verbal and performance scales, yielding verbal IQ, performance IQ, and full-scale IQ scores. To measure working memory, the digit span subscale of the Wechsler Intelligence Scale was used, with a test-retest reliability coefficient of 0.68 reported by Shahim (2008) (17).

2.3 Interventions

2.3.1 Transcranial Direct Current Stimulation Device

In the DLPFC stimulation group, participants received 15 sessions of tDCS, with each session lasting 30 minutes. The anodal stimulation was applied to F3 and the cathodal to F4, with a 2 mA direct current administered throughout the session. Sessions were held every three days. The device used in this study was the Dose Active device, with a 9-volt battery as the current source. The maximum current intensity was 4 mA DC, delivered through electrodes with different polarities (anode and cathode) attached to the scalp. The electrodes were placed in 3.5 cm^2 sponge pads soaked in 9% saline solution to enhance electrical conductivity and prevent heat buildup. The device allowed control of current intensity, electrode size, and stimulation duration. In the DLPFC stimulation group, electrodes were placed at F3 and F4 using the 10-20 international system for locating points. The study was conducted under the supervision of a licensed clinical psychologist with certification from the Psychology Organization (11, 15, 19, 23, 24).

2.3.2 Mindfulness Training

In the mindfulness training group, participants engaged in the relevant exercises for 15 sessions, with each session lasting 60 minutes, held every three days (7, 10, 25-31).

Unit One: Focusing (Sessions 1 to 3)

Session 1: How the Brain Works

In the first session, children are introduced to basic brain physiology and the concept of mindful attention. The session focuses on helping children understand how their brain functions, particularly in relation to attention and mindfulness. Activities include simple explanations of brain parts and functions, and the introduction of mindful attention as "paying attention to the here and now without judgment."

Session 2: Mindful Attention

The second session builds on the concept introduced in the first session by focusing on mindful attention. Children practice exercises that help them become aware of their surroundings, thoughts, and feelings without judgment. These exercises include guided mindfulness practices that encourage paying attention to breathing and immediate sensory experiences.

Session 3: Core Mindful Focus Exercises

In the third session, core mindfulness exercises are introduced. Children practice three-minute self-monitoring exercises three times a day. These exercises involve focusing attention on breathing, bodily sensations, or immediate environment to develop sustained mindful awareness.

Unit Two: Sharpening the Senses (Sessions 4 to 9)

Session 4: Mindful Listening

In this session, children practice mindful listening. Activities include listening to various sounds and focusing on the quality of each sound without forming judgments. This exercise aims to enhance their auditory awareness and concentration.

Session 5: Mindful Seeing

The fifth session introduces mindful seeing. Children engage in activities that involve observing objects or scenes in detail, noting colors, shapes, and textures. The goal is to improve visual awareness and concentration.

Session 6: Mindful Smelling

This session focuses on mindful smelling. Children are given different scents to smell and describe their experiences. The exercise aims to enhance olfactory awareness and bring attention to the present moment through the sense of smell.

Session 7: Mindful Tasting

In the seventh session, children practice mindful tasting. They are given small samples of food to taste slowly and attentively, noting flavors and textures. This activity helps them develop a greater appreciation and awareness of the sense of taste.

Session 8: Mindful Movement I

The first session on mindful movement involves simple, slow movements such as stretching or yoga. Children are guided to focus on their bodily sensations during each movement to cultivate body awareness and present-moment focus.

Session 9: Mindful Movement II

The second session on mindful movement continues to build on the previous session. Children practice more complex movements or sequences, maintaining their focus on bodily sensations and the quality of each movement.

Unit Three: All About Attitudes (Sessions 10 to 12)

Session 10: Perspective-Taking

In this session, children learn about perspective-taking. Activities include exercises that help them understand different viewpoints and consider how others might feel or think in various situations. The goal is to enhance empathy and social understanding.

Session 11: Choosing Optimism

The eleventh session focuses on cultivating a positive mindset. Children practice identifying positive aspects of their experiences and expressing gratitude. Activities include discussions and journaling about things they are thankful for and looking at the bright side of situations.

Session 12: Appreciating Joyful Experiences

In this session, children learn to recognize and appreciate joyful experiences. They engage in activities that encourage them to recall and savor happy moments, enhancing their ability to focus on positive experiences and build emotional resilience.

Unit Four: Acting Mindfully (Sessions 13 to 15)

Session 13: Expressing Gratitude

The thirteenth session encourages children to express gratitude. Activities include writing thank-you notes and sharing what they are grateful for with the group. This practice aims to foster a sense of appreciation and connection with others.

Session 14: Performing Kind Acts

In this session, children plan and perform acts of kindness. Activities include brainstorming kind actions they can take in their daily lives and carrying out these actions, such as helping a peer or complimenting someone. The goal is to promote prosocial behavior and empathy.

Session 15: Mindful Action in the World

The final session focuses on applying mindful behavior in broader social contexts. Children are encouraged to reflect on their feelings before, during, and after engaging in mindful actions. Activities include participating in a community service project or a class collaborative effort, reinforcing the practice of mindfulness in everyday interactions and community involvement.

2.4 Data Analysis

All analyses were performed using SPSS version 26. Analysis of variance (ANOVA) for three groups with repeated measurements (two measurement stages) was used for the analyses. If the interaction effect of measurement stages in the group was significant, Bonferroni post-hoc tests were used for within-group and between-group analyses.

3. Findings and Results

Forty-five children with ADHD were divided into three groups of 15 each: DLPFC stimulation (age: 8.20 ± 1.20 years; height: 113.86 ± 12.86 cm; weight: 24.26 ± 4.66 kg), mindfulness program (age: 8.93 ± 1.05 years; height: 108.53 ± 12.29 cm; weight: 25.20 ± 5.34 kg), and sham stimulation (age: 8.33 ± 1.23 years; height: 114.53 ± 14.11 cm; weight: 26.00 ± 4.86 kg).

Table 1. Descriptive Statistics for All Research Variables by Group and Stage

Variable	Group	Pre-Test Mean (SD)	Post-Test Mean (SD)
Perseverative Errors	DLPFC Stimulation	12.60 (3.20)	8.20 (2.50)
	Mindfulness Program	13.00 (3.10)	9.89 (2.80)
	Sham Stimulation	12.80 (3.00)	12.70 (2.90)
Total Errors	DLPFC Stimulation	20.50 (4.50)	13.07 (3.60)
	Mindfulness Program	21.00 (4.20)	15.91 (3.80)
	Sham Stimulation	20.80 (4.10)	20.60 (4.20)
Digit Memory	DLPFC Stimulation	14.80 (3.60)	20.38 (3.90)
	Mindfulness Program	15.00 (3.40)	17.58 (3.70)
	Sham Stimulation	14.90 (3.50)	14.92 (3.60)

3.1 *Perseverative Errors*

Results of the repeated measures ANOVA indicated significant main effects of measurement time ($\eta^2 = 0.567$, $P = 0.001$, $F = 54.98$), group ($\eta^2 = 0.652$, $P = 0.001$, $F = 180.90$), and the interaction between measurement time and group ($\eta^2 = 0.509$, $P = 0.001$, $F = 21.78$). Bonferroni post-hoc tests showed that DLPFC stimulation significantly improved perseverative errors from pre-test to post-test ($P = 0.001$, mean difference = 4.40). Similarly, mindfulness training significantly improved perseverative errors from pre-test to post-test ($P = 0.001$, mean difference = 3.11). No significant differences were found between stages in the sham stimulation group ($P > 0.05$). Between-group differences showed no significant differences in pre-test scores ($P > 0.05$). In the post-test stage, the DLPFC stimulation group had significantly fewer perseverative errors compared to the sham stimulation group ($P < 0.05$, mean difference = 4.388) and the mindfulness group ($P < 0.05$, mean difference = 1.05).

3.2 *Total Errors*

Repeated measures ANOVA results indicated significant main effects of measurement time ($\eta^2 = 0.567$, $P = 0.001$, $F = 55.01$), group ($\eta^2 = 0.806$, $P = 0.001$, $F = 88.44$), and the interaction between measurement time and group ($\eta^2 = 0.531$, $P = 0.001$, $F = 23.77$). Bonferroni post-hoc tests revealed that DLPFC stimulation significantly improved total errors from pre-test to post-test ($P = 0.001$, mean difference = 7.429). Mindfulness training also significantly improved total errors from pre-test to post-test ($P = 0.001$, mean difference = 5.09). No significant differences were found between stages in the sham stimulation group ($P > 0.05$). Between-group comparisons showed no significant differences in pre-test scores ($P > 0.05$). In the post-test stage, the DLPFC stimulation group had significantly fewer total errors compared to the sham stimulation group ($P < 0.05$, mean difference = 6.17) and the mindfulness group ($P < 0.05$, mean difference = 2.95).

3.3 *Digit Memory*

Repeated measures ANOVA results indicated significant main effects of measurement time ($\eta^2 = 0.279$, $P = 0.001$, $F = 16.22$), group ($\eta^2 = 0.698$, $P = 0.001$, $F = 48.50$), and the interaction between measurement time and group ($\eta^2 = 0.213$, $P = 0.001$, $F = 5.66$). Within-group comparisons using Bonferroni post-hoc tests showed that DLPFC stimulation significantly improved digit memory from pre-test to post-test ($P = 0.001$, mean difference = 5.58). Mindfulness training also significantly improved upper limb coordination from pre-test to post-test ($P = 0.001$, mean difference = 2.58). No significant differences were found between stages in the sham stimulation group ($P > 0.0125$). Between-group comparisons showed no significant differences in pre-test scores ($P > 0.0125$). In the post-test stage, the DLPFC stimulation group had significantly better upper limb coordination compared to the sham stimulation group ($P < 0.0125$, mean difference = 5.00) and the mindfulness group ($P < 0.0125$, mean difference = 2.93). Additionally, the mindfulness group had significantly better upper limb coordination compared to the sham stimulation group ($P < 0.0125$, mean difference = 2.06).

Table 2. ANOVA Table for All Measures

Source	Measure	SS	df	MS	F	p	η²
Time	Perseverative Errors	137.02	1	137.02	54.98	0.001	0.567
Group		450.78	2	225.39	180.90	0.001	0.652

Time * Group		54.65	2	27.32	21.78	0.001	0.509
Error		95.50	40	2.39			
Time	Total Errors	402.05	1	402.05	55.01	0.001	0.567
Group		324.72	2	162.36	88.44	0.001	0.806
Time * Group		72.22	2	36.11	23.77	0.001	0.531
Error		94.50	40	2.36			
Time	Digit Memory	135.62	1	135.62	16.22	0.001	0.279
Group		819.25	2	409.63	48.50	0.001	0.698
Time * Group		48.92	2	24.46	5.66	0.001	0.213
Error		334.05	40	8.35			

Table 3. Bonferroni Post-Hoc Tests for All Measures

Measure	Comparison	Mean Difference	p
Perseverative Errors	DLPFC Stimulation (Pre-Post)	4.40	0.001
	Mindfulness Program (Pre-Post)	3.11	0.001
	Sham Stimulation (Pre-Post)	Not Significant	> 0.05
	DLPFC vs. Sham (Post-Test)	4.388	< 0.05
	DLPFC vs. Mindfulness (Post-Test)	1.05	< 0.05
Total Errors	DLPFC Stimulation (Pre-Post)	7.429	0.001
	Mindfulness Program (Pre-Post)	5.09	0.001
	Sham Stimulation (Pre-Post)	Not Significant	> 0.05
	DLPFC vs. Sham (Post-Test)	6.17	< 0.05
	DLPFC vs. Mindfulness (Post-Test)	2.95	< 0.05
Digit Memory	DLPFC Stimulation (Pre-Post)	5.58	0.001
	Mindfulness Program (Pre-Post)	2.58	0.001
	Sham Stimulation (Pre-Post)	Not Significant	> 0.0125
	DLPFC vs. Sham (Post-Test)	5.00	< 0.0125
	DLPFC vs. Mindfulness (Post-Test)	2.93	< 0.0125
	Mindfulness vs. Sham (Post-Test)	2.06	< 0.0125

4. Discussion and Conclusion

This study aimed to compare the effectiveness of mindfulness interventions and transcranial direct current stimulation (tDCS) on the cognitive performance of children with ADHD. Overall, the results indicated that both tDCS and mindfulness programs significantly improved cognitive performance in children with ADHD. Additionally, the results showed that tDCS had a superior effect compared to mindfulness programs in enhancing cognitive performance in these children.

The results of this study demonstrated that DLPFC stimulation significantly impacts cognitive performance in children with ADHD, leading to a significant reduction in their attention deficits. Consistent with these findings, Leffa et al. (2022) examined tDCS versus sham stimulation for treating inattention in adults with ADHD in a randomized clinical trial. This trial found that daily home-based tDCS for four weeks improved attention in adults with ADHD not using stimulant medications. Similarly, Dubreuil-Vall et al. (2021) showed that tDCS of the left dorsolateral prefrontal cortex improves cognitive control in patients with ADHD. In contrast, a study by Jacoby and Lavidor (2018) found no significant effect of tDCS on sustained attention in children with ADHD. A possible explanation is the existence of a compensatory activity pattern in the brains of individuals with ADHD, which does not benefit from positive regulation of both hemispheres. Some tDCS studies on ADHD have shown that cathodal stimulation of the left DLPFC might increase activity in the right DLPFC through connections.

Regarding attention and focus components in ADHD, it is necessary to refer to different types of attention. All three types of attention (sustained, selective, and divided attention) are generally impaired in individuals with ADHD. Specific studies on the effects of stimulation on different types of attention have shown improved attentional abilities {Coffman, 2012 #31658}. These studies suggested that stimulation of the DLPFC can balance over-arousal and vigilance, improving attention performance. Notably, these improvements are only observed when the anodal electrode is placed on the right hemisphere and the cathodal electrode on the left hemisphere. Therefore, the direction of stimulation is crucial for activating the region {Brevet-Aeby, 2016 #31659}. Recent meta-analyses of neuroimaging studies on functional abnormalities in ADHD populations have shown bilateral hypoactivity of the DLPFC {Lee, 2022 #31660} and reduced activation of the left medial prefrontal cortex {McCarthy, 2014 #31661} during inhibitory control, working memory, and attention tasks. It is hypothesized that this hypoactivity underlies attention deficits, inhibitory control issues, and executive dysfunctions in individuals with ADHD, providing a pathophysiological rationale for using tDCS to increase DLPFC activation through anodal stimulation.

Additionally, the "cognitive dysfunction or inhibition-based model" of ADHD supports the idea that inhibitory executive function deficits are a core impairment in ADHD. Furthermore, one potential mechanism through which DLPFC stimulation might improve attention is by increasing the P300 amplitude. Salehinejad et al. (2022) showed that faster reaction times in incongruent trials in ADHD patients were significantly correlated with increased P300 amplitude following left and right anodal tDCS {Salehinejad, 2019 #31662}.

The present study also found that mindfulness programs significantly improved ADHD symptoms, including hyperactivity and inattention. Consistent with these findings, Siebelink et al. (2022) demonstrated that mindfulness-based interventions significantly improved ADHD symptoms in children {Siebelink, 2022 #31663}. The study's results also indicated that mindfulness training improved cognitive performance in children with ADHD. Enhanced cognitive functions resulting from mindfulness might be due to mindfulness-induced brain flexibility. For example, mindfulness training has been reported to increase N2 amplitudes, an electrophysiological index in event-related potentials, during the Go/No-Go task, indicating better inhibitory control. Additionally, increased activation of the medial prefrontal cortex, anterior cingulate, and insula has been observed following mindfulness training, which are brain regions likely involved in inhibitory control (Haase et al., 2015). Mindfulness training also increases sustained attention by enhancing the ability to return attention to a specific focus after noticing mind-wandering. Over time, increased mindfulness cultivates higher levels of meta-awareness and self-regulation, allowing individuals to ignore distractions and refocus attention, leading to improvements in sustained attention {Nien, 2020 #31667}. Moreover, mindfulness might impact other executive functions (such as memory, planning, and organization) through a bottom-up effect by improving sustained attention.

Mindfulness-based interventions have been associated with changes in gray matter concentration in brain regions involved in learning and memory, emotion regulation, self-referential processing, and perspective-taking {Hölzel, 2011 #31668}. This suggests a neural basis for cognitive and executive changes resulting from mindfulness training. Considering the impact of emotional states on decision-making and the role of mindfulness in understanding and recognizing emotional states, it can be concluded that mindfulness training also influences decision-making. One mechanism through which mindfulness may affect cognitive performance is its role in emotion regulation. Studies have shown that mindfulness training reduces emotional regulation difficulties, distractions, and rumination. Researchers have identified six primary processes in mindfulness that increase cognitive flexibility: acceptance, self-awareness, contact with the present moment, value clarification, cognitive defusion strategies, and committed action {Jankowski, 2014 #31666}.

Given the significant difference in cognitive performance improvement between the two interventions, with DLPFC stimulation showing greater efficacy compared to mindfulness programs in children with ADHD, it can be inferred that recent meta-analyses of neuroimaging studies on ADHD populations have shown bilateral DLPFC hypoactivity {Lee, 2022 #31660;Reis, 2009 #31669} and reduced activation of the left medial prefrontal cortex {McCarthy, 2014 #31661} during inhibitory control, working memory, and attention tasks. This hypoactivity is thought to underlie attention deficits, inhibitory control issues, and executive dysfunctions in ADHD, providing a rationale for using tDCS to increase DLPFC activation through anodal stimulation. Therefore, stimulating this area, which directly addresses the underlying attention deficits and executive dysfunctions in ADHD, is likely to result in greater improvements compared to other interventions, as supported by the results of this study.

Overall, the findings of this study demonstrated that DLPFC stimulation and mindfulness programs significantly improved cognitive performance in children with ADHD. Furthermore, the results indicated that DLPFC stimulation was superior to mindfulness programs in enhancing cognitive performance in these children. To our knowledge, this is the first study comparing the effects of DLPFC stimulation and mindfulness programs on cognitive performance in children with ADHD, suggesting that DLPFC stimulation is a practical, safe, and effective method for improving cognitive performance in children with ADHD.

This study aimed to provide a better understanding of the cognitive performance associated with DLPFC stimulation and mindfulness programs during the intervention. However, it was limited to the device and protocol tested, conducted solely among children aged 7 to 10 years with ADHD, making it difficult to generalize the results to children of other ages. Additionally, some arguments in this study lacked concrete evidence and can only be considered preliminary findings. Therefore, further in-depth research is needed for exploration and clarification. Moreover, the cross-sectional design of this study prevents any causal inferences. A future longitudinal study could better elucidate the effects of tDCS and mindfulness programs. Recently, it has been hypothesized that these techniques (mindfulness intervention and tDCS) may have greater feasibility and efficacy when combined simultaneously or sequentially. Therefore, future studies should consider combined interventions.

Authors' Contributions

R.O.G. conceptualized the study, designed the research methodology, and supervised the overall project implementation. R.S., the corresponding author, conducted the data analysis using paired t-test and Mixed ANOVA, interpreted the results, and led the drafting and revising of the manuscript. H.M. assisted with the recruitment of participants, facilitated the administration of the exercise programs, and contributed to the literature review. A.H. supported the biochemical measurements and helped with data collection and analysis. All authors participated in discussing the findings, critically reviewed the manuscript for important intellectual content, and approved the final version for publication.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants. In conducting this research, ethical considerations were adhered to in accordance with the guidelines of the Ethics Committee of the Sports Sciences Research Institute. The ethical approval code obtained is IR.SSRI.REC.1401.1504.

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