DOI: 10.48305/jrrs.2026.42721.1092 Published by Vesnu Publications

The Effect of Optimized Electrode Placement Protocols for Transcranial Direct Current Stimulation on the Cold and Hot Executive Functions of Children with Attention Deficit Hyperactivity Disorder: A Scoping Review

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Review Article

Abstract

Introduction: Attention deficit/hyperactivity disorder (ADHD) is a chronic neurodevelopmental disorder characterized by complex and heterogeneous clinical manifestations, including disruptive and inappropriate levels of inattention, hyperactivity, and impulsivity, which cause significant dysfunctions in the mechanisms related to hot and cold executive functions. This disorder directly affects processes such as working memory, attention, response inhibition, emotional self-regulation, planning, cognitive flexibility, reaction time manipulation, preference for immediate rewards, and decision-making. Given the significance of executive functions in essential daily living skills and their prominent role in neurodevelopmental disorders, many studies have examined the effectiveness of various approaches, such as neuromodulation strategies, in improving these functions. Therefore, the present review was conducted to investigate the effect of transcranial direct current stimulation (tDCS) on cold and hot executive functions of children with ADHD.

Materials and Methods: This study was conducted as a scoping review. To identify relevant studies, a comprehensive search was performed across several international databases, including Web of Science, ScienceDirect, Scopus, PubMed, and Google Scholar, using English keywords such as 'Transcranial Direct Current Stimulation', 'tDCS', 'Hot and Cold Executive Functions', 'Attention-Deficit/Hyperactivity Disorder', 'ADHD', and 'Brain Neuromodulation'. Additionally, the Persian Scientific Information Database (SID) was searched using equivalent Persian keywords to identify relevant local studies. Ultimately, 15 studies met the inclusion criteria and underwent full-text analysis.

Results: tDCS generally demonstrates significant potential for improving executive functions in children with ADHD. Numerous studies suggest that this method works by modulating the excitability of brain regions associated with executive functions, particularly the prefrontal cortex (PFC). tDCS appears to enhance aspects of cold executive functions, such as working memory and cognitive flexibility, by increasing activity or altering the excitation/inhibition balance in these areas. Regarding hot executive functions, evidence also supports the impact of tDCS on emotional regulation and impulse control. However, results in this area may be more variable due to differences in electrode placement protocols and targeted regions. Some research emphasizes the importance of precise tDCS protocol selection, including current intensity, stimulation duration, and electrode placement (especially on prefrontal areas), for achieving optimal efficacy.

Conclusion: Utilizing appropriate protocols for electrode placement across a variety of brain neuromodulation methods, including tDCS, can be a promising treatment for improving symptoms in children with ADHD.

Keywords: Transcranial direct current stimulation; Cold executive functions; Hot executive functions; Children; Attention deficit-hyperactivity disorder

Citation: Erfaninasab M, Faramarzi S. **The Effect of Optimized Electrode Placement Protocols for Transcranial Direct Current Stimulation on the Cold and Hot Executive Functions of Children with Attention Deficit Hyperactivity Disorder: A Scoping Review.** J Res Rehabil Sci 2024; 20.

Received date: 31.12.2023 Accept date: 04.02.2024 Published: 03.04.2024

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Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is a prevalent neurodevelopmental disorder characterized by a pervasive constellation of clinical symptoms, including inattention, hyperactivity, and impulsivity, which result in functional impairments in social, academic, or occupational domains (1). In essence, ADHD is a clinically complex and chronic condition often marked by highly heterogeneous diagnostic signs and pathophysiological factors. Nevertheless, it is frequently associated with deficits across a broad range of cognitive domains, such as arousal, working memory, behavioral inhibition, planning, cognitive flexibility, attention, and delay discounting (2–4). In other words, children and adolescents with ADHD exhibit deficiencies in high-level cognitive processes—collectively known as executive functions—which play a fundamental role in the initiation and management of goal-directed behaviors (5).

Researchers have yet to reach a consensus over the conceptualization of executive functions. It could still be argued that executive functions include a set of cognitive abilities associated with controlled information processing in the human brain (6). There is currently a consensus among experts and scholars that cold executive functions, such as working memory, attention, planning, and cognitive flexibility, are more likely to be impaired in patients with specific learning and attention-deficit/hyperactivity disorders (7). In their attempts to confirm the role of executive functions as an integral component of students' academic performance, many researchers have suggested that academic success entails the use of brain regions associated with executive functions, thereby strengthening these regions automatically (8). Overall, recent research indicates that executive functions can be enhanced through training and specialized interventions.

In recent years, advancements in brain imaging techniques have largely attributed the pathophysiological basis of ADHD to anomalies in brain structure and function, particularly within cortical and subcortical regions. These include the Dorsolateral Prefrontal Cortex (DLPFC), Orbitofrontal Cortex (OFC), Ventrolateral Prefrontal Cortex (VLPFC), Cerebellum, and Basal Ganglia. These abnormalities lead to deficits in both cold and hot executive functions in individuals with the disorder (9, 10).

Broadly, cold executive functions primarily encompass skills acquired under relatively abstract, logical, and non-emotional conditions. These include aspects such as working memory, planning, problem-solving, response inhibition, and attention. In contrast, hot executive functions pertain to motivational and emotional decision-making and involve elements such as delay discounting, theory of mind, emotion regulation, and interpersonal/social behaviors (9).

In line with this understanding, and given the significance of executive functions in fundamental daily-life skills and their prominent role in neurodevelopmental disorders, numerous studies have investigated the efficacy of various approaches, such as Brain Neuromodulation techniques, in enhancing these functions. Findings from recent interventions suggest that activity within circuits associated with cognitive processes can be modulated using Transcranial Direct Current Stimulation (tDCS) (10).

Transcranial Direct Current Stimulation (tDCS) is a non-invasive, superficial, and non-convulsive technique capable of modulating brain function. It typically involves applying weak currents, ranging from 0.5 to 2 milliamperes, between an anode and a cathode. These electrodes, often sponge pads soaked in saline solution or rubber electrodes enclosed in conductive gel, are placed on selected locations on the scalp. In this method, the weak electrical current stimulates brain neurons by connecting two electrodes with different polarities, usually an anode and a cathode (the anode, or negative electrode, is where electricity enters the brain, and the cathode, or positive electrode, is where it exits) at various points on the skull surface. Cathodal stimulation reduces brain excitability, while anodal stimulation increases it (11).

Studies on the human brain indicate that tDCS alters the action potential mechanism and synaptic relaxation in neurons. This mechanism can be up to four times more impactful than potential changes within the neuronal cell body. Essentially, tDCS can shift the polarity of the axon terminal to a level at which significant changes in action potential dynamics and neuronal relaxation can occur (12). Furthermore, despite findings suggesting that only twenty-five to fifty percent of the current applied by tDCS reaches the brain due to the high resistance of the skull, tDCS exerts its most significant influence on neural brain circuits indirectly by affecting peripheral nerves (13).

Another point regarding the efficacy of this method is that cellular and molecular studies, predominantly conducted in animal models, provide evidence of plasticity mechanisms that underlie the after-effects of tDCS. Therefore, these findings justify and support the therapeutic potential of this method for treating neurological disorders by improving impaired synaptic plasticity (14). This treatment is among the safe and painless techniques; in most cases, its side effects are limited to a burning and itching sensation in the first

few seconds of stimulation, localized to the area beneath the electrodes (14). Considering these factors, tDCS can be regarded as a novel therapeutic technique that may offer a suitable, side-effect-free alternative to pharmacological treatment for ADHD (15).

Numerous studies have investigated the cognitive effects of Transcranial Direct Current Stimulation (tDCS) across various patient groups. For instance, Salehi and Souri Qaramaleki (1402) conducted a systematic review examining the efficacy of tDCS in treating mental disorders. Based on the findings of this research, the use of tDCS can be effective in improving various psychological disorders (16).

Most studies involving tDCS on individuals with ADHD have targeted the Dorsolateral Prefrontal Cortex (DLPFC), particularly the left DLPFC, using anodal stimulation. The efficacy of this therapeutic protocol is unsurprising, given the significant and well-documented role of this region in the regulation of several cognitive processes, including working memory, planning, and cognitive flexibility (17). However, one of the most consistent findings from Functional Magnetic Resonance Imaging (fMRI) studies is the reduced activity in the orbito-frontal-cortico-striato-thalamo-cortical (OFCSTO) circuit, also known as the impulse/force loop. This reduction has been identified as another cause for other negative symptoms in individuals with ADHD, such as impulsivity, emotional processing deficits, and lack of impulse control (18). Furthermore, the cortical thickness of the OFC in individuals with ADHD is significantly reduced compared with that of healthy individuals, with reduced gray matter volume in the right OFC. This region plays a crucial role in controlling goal-directed behavior (19). Therefore, it can be concluded that, in addition to the DLPFC therapeutic protocol, stimulating other areas, including the OFC, can lead to significant improvements in cognitive processes (20). Consequently, there is insufficient evidence to support the use of various brain electrical stimulation protocols for this population. Hence, this study aims to investigate the effect of optimal Transcranial Direct Current Stimulation (tDCS) therapeutic protocols on the executive functions of individuals with Attention-Deficit/Hyperactivity Disorder through a scoping review.

Materials and Methods

Through this scoping review, the effects of optimized electrode placement protocols for Transcranial Direct Current Stimulation (tDCS) on cold and hot executive functions in children diagnosed with Attention-Deficit/Hyperactivity Disorder (ADHD) were examined. Based on this approach, by analyzing findings from relevant prior studies published between 2016 and 2024, we first investigated the diverse objectives and therapeutic protocols of tDCS for addressing executive functions in children with ADHD. Subsequently, the significance of employing this therapeutic modality was explored. Initially, to identify pertinent studies, research indexed in reputable English-language databases, including Web of Science, ScienceDirect, Scopus, PubMed, and Google Scholar, was systematically searched. (To ensure comprehensiveness and complete coverage of domestic studies, the Scientific Information Database (SID) was selected as the sole Persian database. This decision was made because SID is one of the most extensive repositories of Iranian scientific articles, indexing a substantial volume of research published in the country's reputable journals in the medical and psychological sciences. In essence, an initial review confirmed that SID comprehensively covers a significant portion of relevant domestic studies, rendering further searches in other Persian databases largely unproductive. The keywords utilized were: Transcranial Direct Current Stimulation, tDCS, Hot executive functions, Cold executive functions, Attention deficit/hyperactivity disorder, ADHD, and brain neuromodulation.

The inclusion criteria for this study encompassed research published between 2016 and 2024 that focused on children and adolescents diagnosed with ADHD. Eligible studies were required to utilize transcranial Direct Current Stimulation (tDCS) protocols—irrespective of electrode type, intensity, or duration—as the primary intervention and assess executive functions (cool and/or hot) as either primary or secondary outcomes. Furthermore, only studies published in English or Persian were included. Conversely, the exclusion criteria comprised research written in languages other than English or Persian, as well as studies involving adult populations or mixed-age groups where results were not reported separately by age category. Additionally, studies characterized by methodological ambiguities, significant flaws, or insufficient sample sizes were excluded from the current analysis.

Following the initial search, all articles were screened based on their titles and abstracts. Subsequently, the full text of the selected articles underwent a more rigorous review to ensure their adherence to the inclusion and exclusion criteria. The quality of the included studies was assessed qualitatively, and key points regarding study design, sample size, tDCS protocol, and reported outcomes

were extracted. Ultimately, 56 articles were identified. After reviewing each of these articles and considering their degree of alignment with the primary objective of the research and the inclusion/exclusion criteria, 15 articles were deemed eligible for use in the present study.

Results

After completing the search and using the targeted keywords, 56 articles and dissertations related to the research topic were identified. Based on the inclusion and exclusion criteria, 14 studies have investigated the effectiveness of transcranial direct current stimulation on cold and hot executive functions in children with attention-deficit/hyperactivity disorder. In all studies conducted, except those by Guimarães et al. (21) and Westwood et al. (28), the effectiveness of this method on the cold and hot executive functions of students with attention-deficit/hyperactivity disorder was reported. In other words, it can be said that in most of the studies conducted with a stimulation protocol targeting the dorsolateral prefrontal cortex, cold executive functions such as working memory, cognitive flexibility, planning, attention, and response inhibition had improved and been enhanced (26, 25, 23), and in studies with protocols related to stimulation of the ventromedial prefrontal cortex, hot executive functions in children with attention-deficit/hyperactivity disorder had improved (28, 39) (Table 1).

Discussion

The present study aimed to investigate research related to the effects of transcranial direct current stimulation (tDCS) on cool and hot executive functions in children with attention deficit/hyperactivity disorder (ADHD). Overall, in recent years, numerous studies have explored the efficacy of tDCS in improving symptoms in children with other neurodevelopmental disorders such as autism and specific learning disorder (40, 42). Nevertheless, regarding the effectiveness of this method on the cool and hot executive functions of children with ADHD, there are conflicting results. Some studies have reported improvements in cool executive functions (22, 26), while others have reported enhancement and promotion of hot executive functions following tDCS interventions (25). Alongside these findings, some researchers, such as Westwood et al., have not reported tDCS as an effective method for improving the executive functions of this group of children (28). This discrepancy can be attributed to the use of different electrode placement protocols.

To provide further explanation regarding the efficacy of protocols, a large and compelling body of evidence from brain imaging studies in recent years indicates that cortical and subcortical brain regions, including the medial prefrontal cortex, parietal cortex, particularly the orbitofrontal cortex, ventrolateral prefrontal cortex, amygdala, insula, limbic system, and striatum, play a role in executive functions related to reward, emotions, motivation, and social evaluation. Conversely, regions such as the lateral prefrontal cortex, especially the dorsolateral prefrontal cortex (dlPFC) and ventrolateral prefrontal cortex, hippocampus, basal ganglia, and anterior cingulate cortex are crucial for the activation of cool executive functions. In other words, despite convincing evidence of the prefrontal cortex's key role in managing and supporting executive functions, this region is not the sole cortical area involved. It is considered part of a larger neural network (the Fronto-Cingulo-Parietal network) that supports executive functions through interactions among various cortical and subcortical brain structures. Essentially, executive functions are mediated by a complex cognitive network, with the PFC serving as a key region (37-40). Ultimately, all these factors can justify the effectiveness of tDCS on the cool and hot executive functions of children with ADHD, provided that an appropriate electrode placement protocol is used.

In summary, Cool Executive Functions (CEFs) can be categorized into working memory and attention, inhibition, and cognitive flexibility. Regarding working memory and attention, several studies (25, 27, 34) have demonstrated that anodal stimulation of regions associated with these functions—specifically the dorsolateral prefrontal cortex (dlPFC)—leads to significant improvements in the performance of children with ADHD. In the domain of inhibition, evidence suggests that tDCS, particularly through anodal stimulation of areas related to inhibitory control such as the dlPFC, can enhance impulse control and the ability to suppress inappropriate responses in children with ADHD (29, 33). Furthermore, some research indicates that stimulating specific prefrontal regions can strengthen cognitive flexibility, thereby improving these children's ability to shift approaches and adapt to new situations (33). On the other hand, Hot Executive Functions (HEFs) primarily encompass emotional regulation. The relationship between tDCS and emotional regulation in the ADHD pediatric population remains less explored. However, given the neuroanatomical overlap between regions involved in emotion regulation and executive functions, certain stimulation protocols—particularly those targeting prefrontal areas—may indirectly contribute to improved emotional regulation (28, 39).

Table 1. Summary of the reviewed articles

References	Study Design and Sample Size	Measures of Cold and Hot Executive Functions	Location of Electrodes	Intervention Protocol (Session Description)	Results
Wang et al. (23)	Semi – blind sham- controlled/ N = 16	Stroop and Go/No-Go	Experiment 1: Anodal over DLPFC (posterolateral), cathodal over rOFC. Experiment 2: Cathodal over DLPFC (posterolateral), anodal over lOFC. Experiment 3: Sham stimulation.	A twenty-minute session, with 1 mA current intensity	Anodal stimulation of the dorsolateral prefrontal cortex can improve inhibitory control in children with ADHD.
Guimarãe et al. (24)	Triple-blind sham- controlled/ N = 15	Wechsler Digit Span Subtest / Corsi Block-Tapping Task / NEPSY Visual Attention Task	Anode: left DPFC; Cathode: right OFC (FP2)	Five thirty-minute sessions, with 1 mA current intensity	Participants derived no benefit from the intervention, and no significant effect was found.
D'Aiello et al. (25)	Semi–blind sham- controlled	N-back Working Memory Task / Stop-Signal Task (SST)	Anode: left DLPFC; Cathode: right OFC (FP2)	A twenty-minute session with 1 mA current intensity	The mechanism of effect of a single session of tDCS is comparable to a single dose of methylphenidate on working memory and inhibitory control in children with ADHD.
Wang et al. (26)	Semi–blind sham-controlled/ N = 56	Tower of Hanoi/ Stroop /IVA/CPT	Anode: right OFC (FP2); Cathodes: FPz, F4, AF8, AF4	Ten twenty-minute sessions with 1 mA current intensity	This protocol is effective on the sustained attention of children with attention deficit/hyperactivity disorder; however, it does not affect other components.
Nejati et al. (27)	Semi–blind sham- controlled/ N = 22	Go/No-Go / N-back Working Memory Task / Wisconsin Card Sorting Test (WCST) / Stroop	Trial 1: Anode: left DLPFC; Cathode: right DLPFC. Trial 2: Anode: left DLPFC; Cathode: right OFC. Trial 3: Anode: right OFC; Cathode: left DLPFC.	A fifteen-minute session with 1.5 mA current intensity	Anodal stimulation of the dorsolateral prefrontal cortex improves working memory and interference inhibition in children with attention deficit/hyperactivity disorder, whereas cathodal stimulation of this area improves inhibitory control. Finally, cognitive flexibility and task switching are also possible with the combined protocol of the orbitofrontal cortex and dorsolateral prefrontal cortex.
Nejati et al. (28)	Semi – blind sham- controlled/ N = 20	Balloon Analog Risk Task (BART) / Delay Discounting Task	Trial 1: Anode: right vPFC; Cathode: left lPFC. Trial 2: Reversed protocol.	A fifteen-minute session per trial with 1 mA current intensity	Stimulation of the dorsolateral and ventromedial prefrontal cortices is effective at improving reward processing in children with attention-deficit/hyperactivity disorder.
Salehinejad et al. (29)	Semi – blind sham- controlled/ N = 22	N-back Working Memory Task / Wisconsin Card Sorting Test (WCST) / Go/No-Go / Flanker Task	Bilateral Anodal: left & right DLPFC.	A fifteen-minute session with 1.5 mA current intensity	Bilateral anodal modulation of the dorsolateral prefrontal cortex has a more beneficial effect on improving executive functions in children with attention-deficit/hyperactivity disorder.

Table 1. Summary of the reviewed articles (continue)

References	Study Design and Sample Size	Measures of Cold and Hot Executive Functions	Location of Electrodes	Intervention Protocol (Session Description)	Results
Breitling et al. (30)	Semi–blind sham- controlled/ N = 42	Flanker Task	Trial 1: Anode: right IFG; Cathode: left Mastoid. Trial 2: Reversed protocol.	A twenty-minute session with 1 mA current intensity	The stimulation protocol used in this research improves interference control in children with attention deficit/hyperactivity disorder.
Westwood et al. (31)	Double – blind Sham–controlled/N = 50	Electroencephalography (EEG)	Anode: right IFG; Cathode: left vmPFC.	Fifteen one-minute sessions with 1 mA current intensity	The results indicated the treatment protocol was ineffective.
Soff et al. (32)	Double–blind Sham–controlled/ N = 16	N-back Working Memory Task	Anode: left DLPFC; Cathode: Central.	A twenty-minute session with 1 mA current intensity	The results of this research indicated that a single session of anodal stimulation of the left dorsolateral prefrontal cortex not only activated this region but also significantly increased activity in other areas related to working memory, including the left premotor cortex, left supplementary motor cortex, and precuneus.
Erfani nasab et al. (33)	Semi – blind sham- controlled/ N = 24	Brief Questionnaire	Anode: left DLPFC; Cathode: right DLPFC.	Fifteen twenty-minute sessions with 1 mA current intensity	The results of this study indicate improved executive functions in the experimental group following the intervention.
Amouzadeh et al. (34)	Semi-experimental (with experimental and control groups)/N = 45	Continuous Performance Test (CPT)	Anode: left DLPFC; Cathode: right DLPFC.	Ten fifteen-minute sessions with 1 mA intensity	Improvements in cognitive abilities and working memory in children with attention-deficit/hyperactivity disorder were among the results of this research.
Ayatnia Mirzaie (35)	Semi-experimental (with experimental and control groups /N = 32	N-back Working Memory Task / Nejati's Cognitive Abilities Questionnaire	Anode: left DLPFC; Cathode: right DLPFC	Eighteen thirty-minute sessions with 1.5 mA current intensity	The results indicated the effectiveness of this method in improving working memory and response inhibition in children with attention-deficit/hyperactivity disorder.
Fattahi Andebil et al. (36)	Semi-experimental (with experimental and control groups)/N = 36	N-back Working Memory Task / Go/ No-Go	Anode: left DLPFC; Cathode: right DLPFC	Ten ten-minute sessions with 1 mA current intensity	Improvement in executive functions, except for response inhibition, following participation in transcranial direct current stimulation intervention sessions.
Estaji et al. (38)	Semi – blind sham- controlled/ N = 24	N-back Working Memory Task / Stroop and Go/No-Go	Anode: left DPFC; Cathode: right DlPFC	Three different and combined stimulation sessions in the dorsolateral prefrontal cortex, ventromedial prefrontal cortex, left frontal cortex and orbital gyrus, and right frontal cortex and orbital gyrus.	Improvements in emotion regulation were observed in both combined protocols.

IVA: Integrated Visual and Auditory; WCST: Wisconsin Card Sorting Test; BRIEF: Behavior Rating Inventory of Executive Function; CPT: Continuous Performance Test; tDCS: Transcranial direct current stimulation; ADHD: Attention deficit hyperactivity disorder

Limitations

It is also necessary to note that, similar to other studies, the present research has certain limitations alongside its achievements. By taking these limitations into account and addressing them in future studies, more reliable and well-supported results can be obtained. One limitation of this study was the small number of available articles examining the efficacy of transcranial direct current stimulation (tDCS) for improving hot executive functions in children with attention deficit/hyperactivity disorder. Therefore, further research in this area is recommended. In addition to the aforementioned points, other limitations include searching only within a limited scope (e.g., the absence of comprehensive searching across a Persian database), the lack of a unified standard for the number of sessions and current intensity, differences in the assessment tools used for executive functions, and limitations in generalizing the findings to different populations.

Furthermore, it can be argued that multi-session tDCS protocols (10–20 sessions or more) may produce more stable and stronger effects on the executive functions of children with ADHD than single-session protocols. Single-session studies have generally shown short-term, transient effects that may not be sufficient to assess long-term effectiveness. Therefore, the use of single-session protocols is also a limitation of this study.

Recommendations

Based on recent research, it is recommended that, by conducting more in-depth reviews of new brain imaging studies and implementing studies with more precise electrode placement protocols, interventions be designed and implemented to treat symptoms related to attention deficit/hyperactivity disorder in children.

Conclusion

In conclusion, considering the weaknesses of children with attention deficit/hyperactivity disorder (ADHD) in components related to executive functions, and its association with their poor performance in academic-related abilities, as well as research findings indicating the efficacy of transcranial direct current stimulation (tDCS) in improving executive functions in these children, it can be stated that, based on the results obtained from previous years' research, the use of brain neuromodulation methods such as tDCS can have a positive impact on executive functions, and consequently, on the academic performance and progress of this group of children. Ultimately, while the results are promising, further research with a broader scope, larger sample sizes, and standardized protocols appears necessary to achieve more conclusive results and enhance generalizability.

Acknowledgments

The authors would like to express their sincere gratitude to all those who contributed to the completion of this review study.

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Project Design and ideation: Mohadeseh Erfani Nasab
Providing financial resources for the project: This research was developed without financial support
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Funding

This research received no specific grant from any funding agency and was conducted at the authors' personal expense. The University of Isfahan had no involvement in the study design, data collection and analysis, manuscript preparation, or the decision to publish.

Conflict of Interest

The authors did not have a conflict of interest.

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