DOI 10.47176/sjmshm.6.4.1

Original Article

SRPH

SJMSHM, 2024; 6(4): 1-7

Effectiveness of Transcranial Direct Current Stimulation (TDCS) on Short-Term Memory and Academic Performance Enhancement in Adolescents

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Received: 10 October, 2024
Revised: 22 November, 2024
Accepted: 10 December, 2024
Published: 28 December, 2024

ABSTRACT
The main objective of the present study was to investigate the effectiveness of transcranial direct current stimulation (tDCS) on short-term memory and the enhancement of academic performance in adolescents. This research employed a single-group experimental design and a case study approach. The statistical population consisted of all second-grade high school students in the year 1403 (Iranian calendar), totaling 8 individuals. Through convenience sampling, 4 students were selected and divided into experimental and control groups (2 individuals each). They responded to the working memory questionnaires developed by Daneman and Carpenter (1980) and the academic performance questionnaire by Pham and Taylor (1994). Subsequently, the experimental group underwent tDCS. Based on Cohen's d index, the effect size for the two experimental subjects was very large, whereas it was low for the control group, indicating that brain stimulation with direct electrical current (tDCS) effectively improves working memory and academic performance. Based on the results, it was concluded that brain stimulation with direct electrical current and other psychological interventions had more significant and effective therapeutic effects.

Keywords: Brain stimulation, transcranial direct current stimulation (tDCS), working memory, and academic performance.

Introduction

Transcranial direct current stimulation (tDCS) is a neurotherapeutic technique that applies a weak, continuous electrical current to cortical areas, thereby facilitating or inhibiting spontaneous neural activity. Over the past decade, tDCS has been extensively studied as a non-invasive, cost-effective, and safe method for modulating cortical excitability by altering the resting membrane potential of cortical neurons [1]. This weak direct current was delivered via two electrodes of opposite polarity—typically one anode and one cathode—placed on specific scalp regions, stimulating underlying neurons. Cathodal stimulation reduced cortical excitability, whereas anodal stimulation enhanced it [2].

Some electrode montages used configurations such as one anode with two cathodes or two anodes with two cathodes. In certain studies, one electrode was placed outside the skull (e.g., on the upper arm) to address ambiguities in interpreting tDCS effects when using two cranial electrodes [3]. tDCS was applied to study various cognitive domains in both healthy individuals and clinical populations. Several studies evaluated its effects on attention subtypes (selective, sustained, and divided) [4], while others focused on working memory, verbal memory, and related functions. Research investigating the effects of tDCS on cognitive functions has reported both facilitatory and inhibitory outcomes [5]. Electrode positioning was identified as critical to tDCS efficacy. Stimulation intensities up to 2 mA and durations of approximately 20 minutes were considered safe, with mild side effects, such as electrode-site itching and transient headaches, observed during or after sessions (real or sham). These effects were observed across diverse brain regions in both healthy subjects and patients with neurological disorders [6]. Studies examining the effects of tDCS on cognitive performance have consistently demonstrated its capacity for both inhibition and facilitation [3].

Publisher: Scientific Research Publishing House (SRPH), Shirvan, Iran
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As mentioned, tDCS treatment was found to be very effective for disorders such as attention deficit hyperactivity disorder (ADHD), learning disabilities, autism, intellectual disability, major depression, and cravings for substances, including amphetamines and alcohol [7]. Ahmadi et al. (2023) compared the efficacy of transcranial electrical stimulation and cognitive rehabilitation for eye-hand coordination in children aged 7–13 with specific learning disabilities (dyslexia). Their findings revealed that cognitive rehabilitation had a greater impact on improving eye-hand coordination in dyslexic students compared to transcranial electrical stimulation [8]. Narimani et al. (2023) investigated the effects of tDCS on selective attention and auditory perception in visually impaired individuals, and their results indicated that tDCS significantly increased mean scores in both selective attention and auditory perception [9]. Li et al. (2022), in their study on tDCS targeting the dorsolateral prefrontal cortex (DLPFC) for neuropsychiatric disorders, demonstrated that tDCS over the DLPFC alleviated clinical symptoms of schizophrenia, depression, substance addiction, ADHD, and other mental disorders. The DLPFC remains a promising target for non-invasive stimulation in psychiatric conditions, and tDCS, a safe and cost-effective neuromodulation approach, holds significant clinical potential [10].

tDCS is a non-invasive brain stimulation technique that applies a weak electrical current to the scalp, inducing temporary changes in cortical excitability [11]. Key physical parameters included current intensity, electrode size, stimulation duration, and polarity (anode/cathode), each influencing outcome differently. tDCS modulated neuronal excitability by altering membrane potentials, leading to depolarization or hyperpolarization of superficial neurons, thereby increasing or decreasing neural firing [12]. While the primary effects of tDCS were localized beneath the electrodes, functional impacts extended to connected neural networks. Early tDCS research focused on the motor and visual cortices, though recent studies increasingly explored its effects on the dorsolateral prefrontal cortex (DLPFC) [13].

One relevant domain examined in the context of tDCS was working memory. The term "working memory" refers to a system responsible for temporarily manipulating and storing information. Its function was like a mental workspace that could flexibly support daily cognitive activities requiring both processing and storage. This memory was identified as one of the important cognitive processes underlying thinking and learning. Working memory was defined as a system that temporarily processes and stores information and was also considered essential for higher cognitive functions [14]. Working memory was conceptualized as the ability to hold information in mind while performing complex tasks. The ability to use prior experiences for the current situation and to employ problem-solving strategies for the future was also related to working memory [15].

Students' academic progress is recognized as an important indicator for evaluating education, and all efforts and endeavors of educational systems are aimed at achieving this goal. In other words, society, and especially the education system, was interested and concerned about the fate, successful growth, development, and social position of the individual, and expected the individual to progress and excel in various aspects, including cognitive dimensions, skill acquisition, as well as personal, emotional, and behavioral dimensions [16]. Given that academic progress and decline were among the criteria for assessing the efficiency of the educational system, identifying and examining variables affecting academic performance improved understanding and prediction of influential factors in schools. People's beliefs about their abilities were found to affect the level of psychological stress and depression they experienced in threatening or stressful situations. Those who could control potential threats or psychological pressures did not allow disruptive cognitions to affect them. In contrast, a lack of self-efficacy beliefs led to experiencing stress and anxiety arousal when facing potential threats [17].

This study addressed a critical gap: adolescents constitute a significant population segment, yet limited research exists on tDCS applications in this group. The main objective of the present research was to determine the effectiveness of transcranial direct current stimulation (tDCS) on short-term memory and on students' academic performance. The research hypothesis was as follows: Transcranial direct current stimulation (tDCS) had a positive and significant effect on students' short-term memory and academic performance enhancement.

Method

The data in this study were collected using a single-group experimental design and a single-subject study. A single-subject study, sometimes called a single-case experiment or time-series experiment, involves intensive research on a limited number of individuals, considered individually or as a single group. In this study, there was an experimental group and a control group. Before the intervention, both groups took a pretest measuring academic performance and working memory.

[DOI: 10.47176/sjmshm.6.4.1]

Then, the experimental group underwent transcranial direct current stimulation (tDCS), while the control group received no intervention. After completing the treatment period, both groups took a posttest.

The statistical population of this research included second-grade high school students (Grades 10-12) from the Tabadkan district of Mashhad city who were studying in the academic year 1403 (2024-2025). The sample consisted of 4 individuals who were randomly divided into two groups: control (2 people) and experimental (2 people). Based on convenience sampling and the research objective, after obtaining the necessary permissions from the education department and coordinating with school management, participants were selected. The age range of participants was 15 to 18 years. Before the intervention, screening questionnaires were completed in person by the participants. Members of both experimental and control groups completed the questionnaires before the intervention and immediately after the treatment sessions.Ethical Considerations: This research was conducted in accordance with ethical principles for research involving human participants. All participants provided written informed consent before starting the sessions, after being fully informed about the study objectives, procedures, potential benefits, and possible side effects of tDCS. Participants were assured of the confidentiality of their personal information and their right to withdraw from the study at any time without penalty. The study protocol was approved by the relevant institutional ethics committee, and all procedures complied with the Helsinki Declaration guidelines.

A: Pham and Taylor Academic Achievement Questionnaire (1994):

This questionnaire was adapted from the studies of Pham and Taylor (1990) in the field of academic achievement and was developed for the Iranian population (38). It contained 48 items. Each item was scored on a 5-point Likert scale: None = 1, Low = 2, Moderate = 3, High = 4, Very High = 5. For 11 negatively worded questions, scoring was reversed. The maximum possible score was 240, and the minimum was 48. Moradian (2013) confirmed the content validity of this questionnaire through expert evaluation. The validity coefficient obtained in that study was 0.91. Moradian (2013) reported the questionnaire's reliability using Cronbach's alpha as 0.82 [18]. In the present study, reliability was assessed with Cronbach's alpha and found to be 0.92, indicating good reliability. Albert and Harper (2010) reported the questionnaire's validity by correlating it with the Test Anxiety Scale ($r = 0.51$, $p < 0.001$) and reliability coefficients of 0.80 and 0.81 using Cronbach's alpha and split-half methods, respectively, confirming high reliability [19].

B: Daneman and Carpenter Working Memory Questionnaire (1980):

This questionnaire was developed by Daneman and Carpenter (1980) and consisted of 27 sentences . These sentences were divided into six sections: two-sentence, three-sentence, four-sentence, five-sentence, six-sentence, and seven-sentence sections. Each section of this test was read to the subjects in order, from the two-sentence section to the seven-sentence section, and they were asked to listen to these sections, each of which contained relatively difficult and unrelated sentences, and then perform the following two tasks:

1.Determine whether the sentence was semantically correct or not.

2.Write down the last word of each sentence.

To score the working memory test, the number of correct answers in each section was divided by the total number of sentences, and then the numbers obtained from each section were added together and divided by 2. The resulting number indicated the working memory capacity of each subject. Daneman and Carpenter (1980) calculated the reliability coefficient of this tool using its correlation with the Verbal Academic Aptitude Test as 0.59. Also, in the study by Ashouri (2016), the reliability of the aforementioned tool was calculated as 0.87 using Cronbach's alpha method [20].

C: Transcranial Direct Current Stimulation (tDCS) Device:

To create electrical stimulation, the Neurostim device, manufactured by Medina Teb Gostar Company, was used. This device was launched in 2015 and was designed to provide transcranial stimulation with electrical currents. It could provide 5 different types of stimulation, including transcranial electrical stimulation with direct current, transcranial electrical stimulation with alternating current, transcranial electrical stimulation with pulsed current, transcranial electrical stimulation with oscillating direct current, and transcranial electrical stimulation with random noise. The device had two completely separate channels, and each channel could be adjusted independently.

Various stimulation parameters, such as current intensity, time, and frequency, could be adjusted in this device.

The device could adjust the current intensity from 0.1 to 2 milliamps and could also apply sham stimulation.

Electrical stimulation of the brain was performed as follows:

1.First, two electrodes with positive and negative poles were placed on the head through a sponge pad moistened with a conductive solution.

2.These electrodes passed the current through various areas such as the scalp, skull, etc., and finally reached the surface of the cerebral cortex.

3.This current caused the neurons to be charged and created positive and negative poles, thereby changing the activity of that area.

4.This action caused calcium to enter the cell and increase cellular activity.

5.This process also increased the amount of glucose and oxygen in that area and facilitated brain repair. This action increased functional capacity in that area by creating connections between damaged cells and healthy cells, leading to rehabilitation, repair, and improvement.

In this study, a weak direct current of 1.5 mA was applied by placing a 5 × 5 cm anode electrode in the left posterolateral frontal region (Fz), and a 5 × 7 cm cathode electrode was placed on the forearm with a current of 1 mA.

Procedure

After obtaining the necessary permissions from clinic management, participants were selected from the center's records. The research objectives and confidentiality of the results were discussed with the participants. Subsequently, among individuals who met the inclusion criteria and were willing to participate, 4 were selected via convenience sampling and randomly assigned to experimental and control groups (2 per group). Before the intervention, participants in both groups completed the Daneman and Carpenter Working Memory Questionnaire (37) and the Pham and Taylor Academic Achievement Questionnaire (38) as the pretest.Then, the experimental group underwent 10 tDCS sessions (each lasting 20 minutes) administered every other day for three weeks, following the standard tDCS protocol (1). The control group received no intervention. After completing the stimulation sessions, participants in both groups again completed the same questionnaires as in the posttest. Finally, the data obtained from the pretest and posttest stages were prepared for statistical analysis. The results were analyzed in SPSS version 26 at the descriptive level using means and standard deviations, and at the inferential level using Cohen's d effect size.

Finding

The demographic characteristics of the participants were as follows: the sample consisted of 4 individuals (2 male, 2 female) with a mean age of 16.5 years (SD = 1.2, range: 15-18 years). In the experimental group, there was one male (age 16) and one female (age 17); in the control group, there was one male (age 15) and one female (age 18). All participants were second-grade high school students (Grades 10-12) from the Tabadkan district of Mashhad.

Table 1. Results of Transcranial Direct Current Stimulation (tDCS) on Working Memory Improvement

Group	Participant	Baseline M	Intervention M (SD)	Improvement Percentage (MPI)	Reduction Percentage (MPR)	Cohen's d
Experimental	1	45	34 (6.24)	32.35	24.44	2.49
Experimental	2	38	30 (4)	26.66	21.05	2.82
Control	3	42	45.66 (1.15)	-8.01	-8.71	-4.50
Control	4	39	42 (1)	-7.14	-7.69	-4.24

According to the results in Table 1, it was observed that the mean scores of the experimental group participants showed a significant increase after the intervention compared to the baseline phase. In contrast, the control group exhibited the opposite pattern, indicating a decrease in scores compared to the baseline. Based on Cohen's d index (where effect sizes less than 0.2 were considered small, 0.3 to 0.5 medium, and above 0.8 large), it was inferred that the effect size for the two experimental participants was very high, while for the control group it was low. This indicated the effectiveness of transcranial direct current stimulation (tDCS) in improving working memory. As Figure 1 shows, the scores of the two subjects in the experimental group increased, whereas those of the two subjects in the control group decreased. According to the results of Table 2, it was observed that the average of the subjects in the experimental group after the intervention had a significant increase compared to the baseline stage, but for the control group, the opposite was true, indicating a decrease in the average scores of the intervention stages compared to the baseline. Based on Cohen's index, it was also inferred that the effect size for the two subjects in the experimental group was very high and that of the control group was low, which indicated the effectiveness of brain stimulation with direct current (tDCS) on improving academic performance.

[DOI: 10.47176/sjmshm.6.4.1]

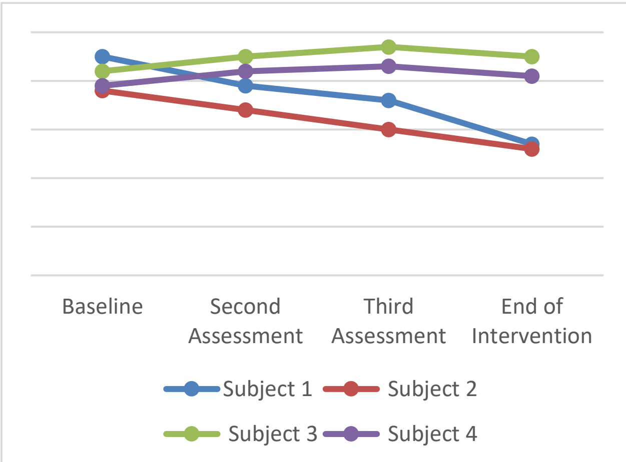

Figure 1. The Process of Changing Working Memory at Different Stages of Assessment

Table 2. Results of Transcranial Direct Current Stimulation (tDCS) on Improvement of Academic Performance

Group	Participant	Baseline M	Intervention M (SD)	Improvement Percentage (MIP)	Reduction Percentage (MPR)	Cohen's d
Experimental	1	27	22 (2.64)	22.72	18.51	2.67
Experimental	2	25	17.66 (2.51)	41.56	29.36	4.13
Control	3	25	26 (2)	-3.84	-4.00	-0.70
Control	4	24	25 (1)	-4.00	-16.41	-1.41

As shown in Figure 2, it was observed that the trend in academic performance scores for the two subjects in the experimental group was increasing, while for the two subjects in the control group it was accompanied by relative decreases.

Discussion

As mentioned, the present study aimed to evaluate the effectiveness of transcranial direct current stimulation (tDCS) on short-term memory and the enhancement of academic performance in adolescents. The data analysis showed that tDCS led to an increase in working memory and academic performance in the experimental group at the posttest. These findings were consistent with the research of Ahmadi et al. [8], Narimani et al. [9], Li et al. [10], and Zaehle et al. [21]. To explain this finding, researchers noted that the concept of working memory helped them understand how brain function affects cognitive skills. For example, some individuals with amnesia performed well on working memory tasks but struggled with long-term memory tasks, while others had normal long-term memory abilities but performed poorly on working memory tasks.

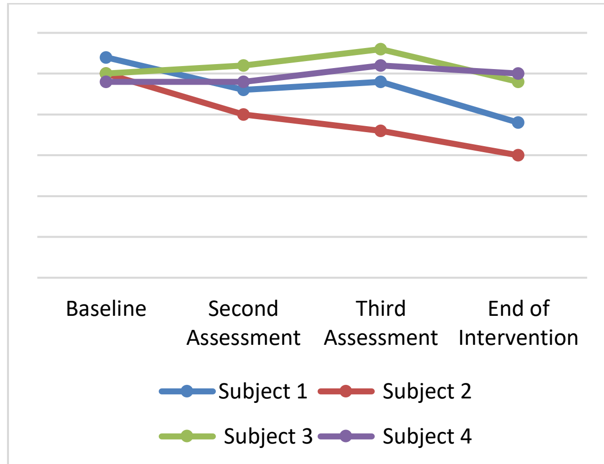

Figure 2. The Trend of Change in Academic Performance at Different Stages of Assessment

The results of this study showed that transcranial electrical stimulation had a significant effect on attention processing, accuracy in working memory tests, and academic performance. This intervention significantly improved cognitive function in these individuals [5].

Overall, for individuals who had difficulty understanding the logical sequence of cognitive tasks, this treatment was effective in improving working memory. One hypothesis was that increased dopamine in the frontal region improved working memory, and another was that increased cortical excitability in the left prefrontal cortex occurred via neuronal depolarization [22].

Therefore, anodal brain electrical stimulation produced facilitatory effects that might increase glutamate levels related to memory and learning. In any case, brain stimulation combined with other treatments such as medication and cognitive-behavioral therapy was identified as a non-invasive, side-effect-free, and fast-acting method that could have positive effects for individuals with cognitive difficulties [23].

The human brain was capable of self-repair; it could learn or relearn self-regulation mechanisms of neural activity, which were essential for normal brain function. This stimulation protocol strengthened the underlying self-regulatory mechanisms, improving function and reducing symptom severity.

This system provided feedback to the brain about the individual's recent actions and the state of natural bioelectrical rhythms, encouraging the brain to adjust, modulate, and maintain appropriate activity. Consequently, the brain was prompted to optimize

[DOI: 10.47176/sjmshm.6.4.1]

various neural processes, thereby enhancing cognitive function [24].

The findings of the present study indicated that tDCS was an effective method for improving working memory and academic performance and had practical applicability in educational settings. By helping students increase their use of this method, there was hope for improvement in academic outcomes.

The results of the present study showed that neurocognitive functions in higher brain regions (e.g., processes supported by the prefrontal cortex and brain regions related to self-regulation, behavior, cognition, and emotion) were influenced by the beneficial effects of brain stimulation [25]. The use of electrical stimulation could enhance cognitive performance and reduce negative cognitive patterns. Ultimately, regarding the effectiveness of transcranial direct current stimulation (tDCS) for brain stimulation, it was concluded that stimulating the left dorsolateral prefrontal cortex with direct electrical current improved cognition, working memory, and academic performance [26].

Every research had limitations, and this study was no exception. Limitations included: due to the implementation of the research on a small sample, generalizing the results should be done with caution; exclusive use of measurements based on self-report scales; the implementation of treatment and evaluations related to the intervention by the researcher might introduce bias into the findings; also, subjects might have been affected by the test conditions due to repeated responses to the same questionnaire (pretest and posttest), potentially reducing their accuracy in responding. Additionally, the absence of a follow-up phase limited the ability to assess the intervention's long-term effects.

Finally, since the present study used self-report instruments, future research should also employ other data collection methods, such as interviews and objective cognitive assessments. One of the influential factors in the effectiveness of tDCS was individual differences in response to stimulation. It was suggested that future researchers examine demographic variables such as age, gender, and baseline cognitive abilities as potential moderators. The present study had a small sample size; future researchers should use larger samples and longitudinal designs to examine the dimensions of working memory and academic performance more precisely.

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Citation: Darbani F.Effectiveness of Transcranial Direct Current Stimulation (TDCS) on Short-Term Memory and Academic Performance Enhancement in Adolescents.SJMSHM, 2024; 6(4): 1-7.

https://doi.org/10.47176/sjmshm.6.4.1

[DOI: 10.47176/sjmshm.6.4.1]