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Investigation of the Effect of Transcranial Direct Current Stimulation on Inhibitory Control Deficits and Tendency Toward Stimulant Substance Use in Students

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A B S T R A C T

Objective: This study aims to examine whether transcranial direct current stimulation can effectively improve inhibitory control deficits and reduce students' tendency toward stimulant substance use.

Methods and Materials: This research employed a quasi-experimental design with a pretest-posttest format. The study population included all 12th-grade students with stimulant substance use attending the Atieh Roshan Addiction Treatment Center in Shahriar in 2024. A total of approximately 100 12th-grade students were present at this center. From this population, 40 individuals were selected as the sample, based on inclusion and exclusion criteria, to conduct a targeted study. The statistical population consisted of all 12th-grade students aged 15 to 19 years with stimulant substance use in addiction treatment centers in Shahriar. Multivariate analysis of variance and SPSS26 software were used for data analysis.

Findings: The results indicated the effectiveness of transcranial brain stimulation on emotional inhibition, aggression inhibition, mental rumination, benign inhibition, and the tendency toward stimulant substance use in students.

Conclusion: It can be concluded that transcranial direct current stimulation can be effective in improving the psychological problems of individuals with substance use disorders.

Keywords: *Students, Transcranial Direct Current Stimulation, Inhibitory Control, Stimulants, Addiction.*

1. Introduction

Substance use disorder is a major social concern and is defined as the dependence on substances that affect the central nervous system and brain function, resulting in changes in behavior, perception, judgment, and emotions. The effects of substances vary depending on the type, amount, or frequency of use. They can cause physiological and psychological disorders, impaired self-control and social relationships, and poor academic and work performance

(Momeni et al., 2021). Problems arising from substance abuse are considered a global concern and one of the serious risk behaviors threatening adolescents (Farhadi-Nasab et al., 2007). Substance abuse is one of the most widespread and costly health problems in modern societies, and conventional medical treatments often prove ineffective, with relapse being common (Bari et al., 2018). Despite a slow decline over the past decade, the prevalence of substance use among adolescents remains high (Brown, 2013). Substance abuse often begins during high school, highlighting the necessity of implementing prevention measures from adolescence (Yaqoubi et al., 2015).

One of the variables that play a crucial role in individuals' relapse into substance use is craving and inhibitory control deficits. Recent studies have indicated that craving, as one of the core clinical symptoms of substance abuse, can be considered a manifestation of impaired inhibitory control. Brain imaging findings have demonstrated that dysfunction of the prefrontal cortex leads to impaired inhibitory control in substance abuse, characterized by an excessive allocation of importance to substances and substance-related cues, reduced sensitivity to non-substance rewards, and decreased ability to inhibit maladaptive behavior (Barati et al., 2023; Goldstein & Volkow, 2012). Repeated exposure to substances reinforces habitual action circuits and alters associative learning behaviors, indicating impaired top-down inhibitory control. Poor top-down control may result from diminished prefrontal regulation over goal-directed behaviors, which brings about habitual response strategies (McKim et al., 2021). Impaired inhibitory control due to substance use may drive behavior governed by conditioned or dominant responses inappropriate for the current context (Jentsch & Taylor, 1999).

The treatment options for stimulant substance use disorder are very limited, and currently, there are no FDA-approved pharmacotherapies (Pandey et al., 2016). Current evidence points to the potential of various neuromodulation techniques as promising treatment methods. Some researchers suggest that therapeutic stimulation, such as transcranial direct current stimulation (tDCS), could prevent substance addiction (Gay et al., 2022). Given that studies have shown that deep brain stimulation can effectively modulate reward circuits and treat addiction, there is a growing interest in noninvasive deep brain stimulation techniques (Edinoff et al., 2023). Among these methods, transcranial stimulation is a noninvasive approach for modulating the excitability of the central nervous system (Abdullah & et al., 2020). This method is one of the innovative treatments that can improve symptoms of various psychological disorders, particularly in managing or controlling substance use cravings. Transcranial direct current stimulation is a noninvasive, advanced, and simple technique for modulating brain activity (Dotta et al., 2009).

In recent years, due to the increasing prevalence of substance dependence and craving, researchers have implemented various interventions both individually and, for cost and time efficiency, in group settings. They have compared the effectiveness of these interventions in reducing substance use symptoms between experimental and control groups. Nevertheless, due to the limited number of such studies, experts' opinions on the efficacy of these treatment approaches remain mixed. Moreover, despite the presence of some studies investigating transcranial direct current stimulation's effect on addiction treatment, research on this approach has been mostly conducted among young adults and adults, neglecting the necessity of examining its effects on adolescents and students, who are increasingly at risk of addiction. Therefore, the present study seeks to address whether transcranial direct current stimulation can effectively improve inhibitory control deficits and reduce students' tendency toward stimulant substance use.

2. Methods and Materials

2.1. Study Design and Participants

The present study utilized a quasi-experimental method with a pretest-posttest design. The statistical population consisted of all 12th-grade students with stimulant substance use at the Atieh Roshan Addiction Treatment Center in Shahriar in 2024. In total, approximately 100 12th-grade students were present at the center. From this population, 40 individuals were selected as the sample, based on inclusion and exclusion criteria, for a targeted study. The inclusion criteria were as follows: students had to be diagnosed with stimulant substance use disorder (e.g., methamphetamine, cocaine, or cannabis derivatives); they must have had a history of stimulant use for at least six months; they should be in 12th grade; they had to provide informed consent for the research procedures and demonstrate a willingness to participate; they must be under treatment at the Shahriar Addiction Treatment Center; they had to be between 15 and 19 years old; they must not have physical illnesses such as diabetes, epilepsy, or kidney problems, as per their medical records; they must not have other psychological diagnoses based on their medical records; and they must not have received psychological interventions in the last six months.

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The exclusion criteria included: having a history of using addiction treatment medication; having participated in similar intervention programs; being absent for more than three sessions; and withdrawing or expressing unwillingness to participate in the sessions.

This study included an experimental group and a control group, both consisting of students diagnosed with substance use disorder. However, only the experimental group received transcranial direct current stimulation treatment, while the control group did not receive any treatment. The intervention involved 12 sessions, conducted weekly over 12 weeks, each lasting 30 minutes and administered by a specialist. Ethical considerations, such as obtaining informed consent and ensuring confidentiality of personal and treatment information, were observed. Both groups were assessed using the Inhibitory Control Questionnaire and the Relapse Prediction Scale (RPS) before and after the intervention to compare the effects of tDCS on the dependent variables. If significant differences were found, the researcher could confirm the efficacy of the independent variable.

2.2. Measures

2.2.1. Inhibitory Control

To measure this variable, the standard Inhibitory Control Questionnaire developed by Roger and Nesshoever (1987) was used. This questionnaire consists of 56 items and four dimensions: emotional inhibition, aggression inhibition, rumination or mental rehearsal, and benign control. Roger and Nesshoever (1987) developed the original structure, which was later revised by Roger and Najarian (1989). The revised version, used in this study, contains 56 items and four subscales, each comprising 14 items scored on a binary scale (0 or 1). Thus, an individual's score for each subscale ranges from 0 to 14, with a total score ranging from 0 to 56. Cronbach's alpha coefficients for the overall scale and the subscales of emotional inhibition, aggression control, rumination, and benign control were 0.68, 0.70, 0.76, 0.77, and 0.58, respectively. Roger and Najarian reported internal consistency for emotional inhibition, aggression control, rumination, and benign control subscales as 0.77, 0.81, 0.86, and 0.79, respectively. Additionally, their research showed a significant positive correlation between the rumination subscale and the neuroticism factor of the Eysenck Personality Questionnaire (EPQ), a significant negative correlation between the aggression control subscale and Buss-Durkee Hostility Inventory, a significant negative correlation between the emotional inhibition subscale and the extraversion factor of the EPQ, and a significant negative correlation between the benign control subscale and the psychoticism factor of the EPQ (Akrami-Nejad, 2019; Soltaninejad et al., 2019).

2.2.2. Substance Use Tendency

The Relapse Prediction Scale (RPS), developed by Wright et al. (1993), was used to assess the tendency toward substance use. This 45-item self-report scale measures craving and the likelihood of substance use disorders in addicts. It comprises two dimensions: craving intensity and probability of use, scored on a 5-point Likert scale, yielding a total score ranging from 0 to 180. Higher scores in the first part indicate greater craving, while higher scores in the second part indicate a higher probability of use. Cronbach's alpha coefficients calculated for craving intensity and probability of use subscales were 0.94 and 0.97, respectively. Convergent validity was 0.91 for craving intensity and 0.93 for probability of use (Wright et al., 1995). In Firouzabadi et al.'s (2009) study, reliability for the RPS was calculated using Cronbach's alpha on 40 substance-dependent patients in early recovery, yielding 0.90 for craving intensity and 0.93 for craving probability. The overall scale's reliability coefficients were 0.58 for craving intensity and 0.63 for probability of use. Pearson's correlation between these subscales was 0.85, indicating a statistically significant relationship (Ghivi Qamari & Mojarad, 2016; Sadri Demirchi et al., 2019).

2.3. Intervention

2.3.1. Transcranial Direct Current Stimulation (tDCS)

tDCS is the rediscovery of an old technology, and numerous studies are currently exploring its therapeutic potential across a range of disorders. Essentially, tDCS is a tool that enhances the brain's ability to process incoming information. While it enhances the efficacy of other treatments, it does not eliminate the need for them. The application of brain stimulation, which includes both invasive and noninvasive methods, is now a topic of interest in cognitive neuroscience. tDCS is a noninvasive method that applies a constant, low-intensity electrical current to the scalp, effectively modulating cortical excitability and influencing human behavior and perception. During tDCS, a weak direct current is applied to the scalp, creating long-term changes in cortical excitability. Depending on the research

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or therapeutic goals, specific areas are targeted with low electrical currents. The basic mechanism involves placing two electrodes, one anode and one cathode, on the scalp using a conductive solution-soaked sponge pad. The electrical current travels through various tissues (scalp, skull, etc.) to reach the cortical surface, polarizing neurons and altering activity in the targeted brain region. Specific parameters, such as the intensity, duration, and direction of the current, as well as the placement of each electrode and the size of the sponge pads, need to be defined based on the disorder being studied. This noninvasive method is safe and involves applying a very weak electrical current (about 2 mA) continuously and directly to the target cells, promoting neuroplasticity (Akrami-Nejad, 2019; Amini-Masooleh et al., 2019; Baher Talari, 2022; Dehghanian, 2023; Hassan Zadeh, 2023; Helmzadeh, 2016; Rigi-Kouteh et al., 2021; Sasani & Mazhami-Goudarzi, 2019a, 2019b)s In this study, 12 treatment sessions were conducted weekly over 12 weeks, with each session lasting 30 minutes and administered by a specialist in the field.

2.4. Data Analysis

Data analysis was performed in two stages. Descriptive statistics, including percentages, frequencies, means, and standard deviations, were calculated first. Inferential statistics were then used to test the research hypotheses. Shapiro's test was used to check data normality. If normal, Levene's test for homogeneity of variances and multivariate analysis of variance (MANOVA) were applied using SPSS version 26.

3. Findings and Results

Table 1 presents the descriptive statistics for the research variables.

Table 1

Mean and Standard Deviation of Research Variables by Group

Variable	Time	Control (M)	Experiment (M)	Control (SD)	Experiment (SD)	Skewness (Control)	Kurtosis (Control)	Skewness (Experiment)	Kurtosis (Experiment)
Emotional Inhibition	Pretest	3.432	3.428	0.278	0.240	-1.332	-1.207	-0.017	-0.620
	Posttest	3.214	3.507	0.273	0.185	-0.727	-0.514	-1.248	1.834
Aggression Inhibition	Pretest	3.446	3.445	0.340	0.271	-1.853	-1.287	-0.201	-0.058
	Posttest	3.357	3.725	0.289	0.147	0.243	0.196	-0.124	0.228
Rumination	Pretest	3.396	3.390	0.319	0.213	-0.889	0.167	-0.787	1.205
	Posttest	3.397	3.042	0.368	0.206	-0.070	1.067	0.793	1.009
Benign Control	Pretest	3.460	3.467	0.281	0.219	0.429	-0.361	-0.315	1.119
	Posttest	3.461	3.592	0.380	0.129	-0.789	1.984	0.864	-0.079
Craving Intensity	Pretest	3.273	3.271	0.258	0.376	-0.556	0.585	-0.871	-0.108
	Posttest	3.241	2.610	0.252	0.121	-0.455	1.053	1.064	1.412
Craving Likelihood	Pretest	3.370	3.374	0.227	0.261	-1.788	-1.782	-1.528	-1.811
	Posttest	3.638	2.572	0.287	0.329	-0.066	-0.991	-0.423	-0.311

Normality of the data was assessed, and given that the z-statistics were within ±1.96 at a 95% confidence level ($p > 0.05$), the data were considered normally distributed. The assumptions of multivariate analysis of variance (MANOVA), including Box's test, were satisfied, indicating homogeneity of variance-covariance matrices ($p > 0.01$). Levene's test was also used to assess the equality of error variances for the variables across groups. Since the F-statistic's p-values were greater than 0.05, the assumption of equal variances was accepted, meaning error variances were statistically homogenous between the control and experimental groups.

The Wilks' Lambda test ($p < 0.05$) indicated a significant difference between the experimental and control groups in at least one dimension of inhibitory control, with a large effect size ($\eta^2 = 0.473$), suggesting a substantial difference in group means.

Based on the data, the mean scores for emotional ambivalence in expression, self-control, and impulsivity are 39.40, 48.51, and 52.11, respectively. Furthermore, since the

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skewness and kurtosis values range between -2 and +2, the data are considered normally distributed at the 0.05 level.

Table 2

MANOVA Results for Inhibitory Control

Test	Value	F	Hypothesis df	Error df	Sig.	Eta Squared
Pillai's Trace	0.273	6.944	4	31	0.000	0.473
Wilks' Lambda	0.727	6.944	4	31	0.000	0.473
Hotelling's Trace	0.896	6.944	4	31	0.000	0.473
Roy's Largest Root	0.896	6.944	4	31	0.000	0.473

Table 3 shows significant differences between the control and experimental groups across the dimensions of inhibitory control. Emotional inhibition (F = 17.858, p = 0.000), aggression inhibition (F = 10.418, p = 0.000), rumination (F = 10.411, p = 0.001), and benign control (F = 15.917, p = 0.000) all demonstrated significant differences. The effect sizes for each variable indicate substantial differences in group means.

Table 3

ANCOVA Results for Inhibitory Control

Dependent Variable	Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Emotional Inhibition	1.970	1	1.970	17.858	0.000	0.344
Error	1.846	34	0.054			
Aggression Inhibition	1.458	1	1.458	10.418	0.003	0.235
Error	1.494	34	0.044			
Rumination	1.690	1	1.690	10.411	0.010	0.179
Error	1.166	34	0.093			
Benign Control	1.100	1	1.100	15.917	0.000	0.319
Error	1.350	34	0.069			

Since Wilks' Lambda's p-value was less than 0.05, there were significant differences between the groups in at least one of the variables related to craving intensity and likelihood of use. The effect size ($\eta^2 = 0.493$) indicated a substantial difference between group means.

Table 4

MANOVA Results for Substance Abuse Tendency

Test	Value	F	Hypothesis df	Error df	Sig.	Eta Squared
Pillai's Trace	0.193	16.995	2	35	0.000	0.493
Wilks' Lambda	0.807	16.995	2	35	0.000	0.493
Hotelling's Trace	0.971	16.995	2	35	0.000	0.493
Roy's Largest Root	0.971	16.995	2	35	0.000	0.493

The results indicates significant differences in craving intensity (F = 34.089, p = 0.000) and likelihood of use (F = 17.323, p = 0.003) between the control and experimental groups.

Table 5

ANCOVA Results for Substance Abuse Tendency

Dependent Variable	Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Craving Intensity	1.381	1	1.381	34.089	0.000	0.486
Error	1.458	36	0.041			
Likelihood of Use	1.031	1	1.031	17.323	0.003	0.209
Error	1.425	36	0.095			

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4. Discussion and Conclusion

The results of testing this study's hypothesis indicate that transcranial (cathodal-anodal) stimulation is effective in reducing inhibitory control deficits among students. The hypothesis is confirmed based on the analysis of the research data, as the Wilks' Lambda test's significance value is less than 0.05, indicating a statistically significant difference between the experimental and control groups in at least one of the dimensions of inhibitory control.

According to the findings, there is no significant difference between the pretest and posttest phases in emotional inhibition, aggression inhibition, rumination, and benign control in the control group. However, the experimental group showed significant differences between the pretest and posttest phases in these variables. These findings demonstrate the effectiveness of transcranial brain stimulation in improving inhibitory control among students. Thus, emotional inhibition, aggression inhibition, rumination, and benign control significantly changed in students undergoing transcranial stimulation. Notably, rumination decreased, while the other variables increased in the experimental group.

It can be inferred that transcranial stimulation influences the reduction of inhibitory control deficits in students by altering neuronal excitability and shifting membrane potential towards depolarization or hyperpolarization. This change causes neurons to fire more or less, and it is likely that anodal stimulation increases brain excitability and normalizes the nervous system's function. Specifically, anodal stimulation of the left dorsolateral prefrontal cortex may enhance the efficiency of this brain region, which governs inhibitory control mechanisms.

Rumination involves the central executive and the default mode network of the brain. High activity in the default mode network is associated with increased rumination, while lower activity corresponds to more adaptive thought styles. Stimulation of the right hemisphere moderates the processing of negative emotional and cognitive information, while stimulation of the left hemisphere increases cognitive control over positive emotional stimuli, thereby affecting rumination.

Studies suggested that if the behavioral inhibition system suppresses behavior and emotions, individuals may struggle to recognize and manage their emotions, contributing to negative outcomes over time. Emotion suppression in the inhibition system can disrupt individuals' ability to focus on their thoughts and assess situations, possibly leading to a higher risk of addiction in adolescents (Babaei et al., 2016).

Overall, the results suggest that problems in emotional regulation and inhibition, as immature developmental mechanisms, drive students toward maladaptive strategies like substance use when facing life challenges and difficulties. The hypothesis that transcranial (cathodal-anodal) stimulation affects students' inhibitory control deficits is confirmed. Since the Wilks' Lambda test's significance value is less than 0.05, a significant difference between the experimental and control groups is evident in at least one variable, such as craving intensity and likelihood of use.

Adjusted means of craving intensity and likelihood of use during transcranial stimulation indicate a significant difference between the control and experimental groups. The experimental group's mean scores in these variables were significantly lower than those of the control group, demonstrating the effectiveness of transcranial stimulation in reducing craving intensity and the likelihood of substance use.

Neuroimaging studies have highlighted the dorsolateral prefrontal cortex's critical role in craving and cognitive-emotional disorders. Research has identified changes in the prefrontal regions, particularly the lateral prefrontal cortex, in addiction disorders. These brain alterations, linked to substance cravings, are exacerbated by intense cravings and impaired inhibitory control. Transcranial stimulation is used to modulate dorsolateral prefrontal cortex activity and reduce cravings and associated cognitive deficits. The rationale for using transcranial stimulation to treat addiction and cravings is that the dorsolateral prefrontal cortex, crucial for inhibitory control and reward mechanisms, exhibits dysfunction in these disorders (Amini-Masooleh et al., 2019; Baher Talari, 2022; Hassan Zadeh, 2023; Sasani & Mazhami-Goudarzi, 2019a, 2019b).

Although the exact mechanism of this method is unclear, evidence suggests that repeated magnetic stimulation may influence neurotransmission and neuronal plasticity. Repeated magnetic stimulation, affecting cortical excitability and dopaminergic transmission, has been identified as a tool in addiction research and treatment. Previous animal studies have shown that anodal stimulation increases neuronal firing, while cathodal stimulation has the opposite effect. Thus, increased activity in the right or left prefrontal areas may reduce cravings. Research suggests that altering activity in either hemisphere can disrupt overall brain function, and stimulation of the left and right

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dorsolateral prefrontal cortex may reduce substance cravings.

5. Limitations & Suggestions

Challenges in accessing addiction treatment centers and selecting students from these centers limited sample diversity. The study's restriction to Shahriar students complicates generalizing the findings to other populations. The field of transcranial electrical stimulation is relatively new in Iran, with limited research, especially on students. This scarcity results in a lack of Persian resources and findings. Future studies should include more diverse age and educational groups and consider long-term follow-ups to understand the intervention's sustainability. Developing culturally appropriate assessment tools could also enhance research accuracy and validity. Given the limitations of current research on brain stimulation, future studies should focus on various age groups and contexts. Researchers are encouraged to conduct longitudinal or mixed-method (quantitative and qualitative) studies on students prone to substance use.

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Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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This article is derived from the first author's doctoral dissertation. All authors equally contributed to this article.

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