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Effects of Transcranial Direct Current Stimulation on Processing Speed, Life Satisfaction, and Negative Emotional States in Students with Poor Sleep Quality

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Abstract

Background and Objective: This study aimed to investigate the effects of transcranial direct current stimulation (tDCS) on processing speed, life satisfaction, and emotional states in students with poor sleep quality.

Materials and Methods: A semi-experimental pretest-posttest design with a control group was applied. Twenty-seven students with poor sleep quality were selected via convenience sampling. The Pittsburgh Sleep Quality Index (PSQI), the Reaction Time Index (RTI) task from the Cambridge Neuropsychological Test Automated Battery (CANTAB), the Symbol Digit Modalities Test (SDMT), the Satisfaction with Life Scale (SWLS), and Depression, Anxiety, and Stress Scale-21 (DASS-21) were used to collect data. After the pretest, participants were randomly assigned to the intervention (n = 14) or control group (n = 13). The intervention comprised ten 20-minute tDCS sessions at two mA, with the anode over F3 and the cathode over F4. Data were analyzed via analysis of covariance (ANCOVA).

Results: After controlling for pretest scores, the intervention and control groups demonstrated a significant difference in posttest processing speed (computer-based and non-computer-based tests) and the anxiety subscale of the negative emotional states. No significant differences were found regarding sleep quality or life satisfaction.

Conclusion: tDCS improved processing speed and reduced negative emotional states, but did not significantly improve sleep quality or life satisfaction.

Keywords: Transcranial direct current stimulation; Sleep; Processing speed; Life satisfaction; Psychological distress

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Introduction

Sleep quality has recently emerged as an important research variable in the field of sleep medicine (1). Sleep quality is defined by the subjective experience of sleep, feeling refreshed, and the absence of daytime drowsiness (2). It is determined by both subjective factors, such as duration and interruptions, and objective factors, such as sleep depth and restorative quality (3). Sleep problems, including sleep deprivation and poor quality sleep, are increasingly prevalent among students (4), and remain a significant public health concern (5). In academic settings, sleep problems are common and attributed to poor sleep habits (6). A good nighttime sleep is crucial for optimal cognitive functioning, and excessive daytime sleepiness can slow information processing speed (1, 7).

Processing speed is a crucial cognitive ability that significantly impacts academic achievement and daily functioning (8). It refers to the ability to recognize, integrate, decide, and quickly respond to visual and verbal information. Processing speed is crucial for efficient task performance, both in automatic processing and when processing new information (9). Sleep is thought to help rebuild neural restoration, thereby preparing the brain for higher-level cognitive processes, including processing speed. Research indicates that sleep

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deprivation negatively affects cognitive performance, including processing speed, in young individuals (10).

Life satisfaction results from a balance between clear and reasonable wishes and a person's current situation. According to Motevaliyan et al., psychological well-being is characterized by experiencing more pleasant feelings, fewer unpleasant feelings, and overall satisfaction with life (11). Mental well-being comprises two components: a cognitive component, assessed using life satisfaction scales, and an emotional component, including positive and negative emotions. Greater life dissatisfaction is often associated with a greater gap between personal desires and objective life situation (11). Studies have demonstrated that sleep quality positively correlates with life satisfaction (12-14). Negative affect refers to the extent to which an individual feels unhappy and unpleasant. Feeling disappointed and failing to perform pleasurable actions often leads to negative emotions like depression, anxiety, stress, anger, sadness, hatred, humiliation, guilt, and fear (15).

Academic environments can significantly affect students' sleep quality due to educational requirements, tensions, and high psychological pressure. These factors can cause stress, leading to increased arousal and disrupting students' sleep regulation and sleep-wake patterns. Consequently, poor sleep quality among university students is associated with mood disturbances, elevated anxiety and stress levels, and increased symptoms of anxiety and depression (16). Pagan reported a positive relationship between life satisfaction and daily sleep quality, noting that poor sleep quality may decrease brain processing speed and life satisfaction, and increase negative emotional states (17).

Sleeping pills are not recommended as first-line treatment for sleep problems due to concerns regarding safety, efficacy, and side effects (18). These limitations have encouraged research into non-pharmacological approaches to improve sleep hygiene. Among these, non-invasive brain stimulation has received increasing attention, using multiple forms of exogenous stimulation. Non-invasive brain methods such as auditory stimulation, transcranial magnetic stimulation (TMS), and transcranial electrical stimulation (tES) have been increasingly used to target sleep quality and duration (19). Therefore, transcranial direct current stimulation (tDCS) applied to the dorsolateral prefrontal cortex (DLPFC) is a non-invasive, short-term, and painless method for improving sleep quality.

Previous studies confirmed the efficacy of tDCS in improving sleep quality and reducing insomnia (20, 21). In addition, stimulation of the frontal lobe regions (F_3) has been shown to enhance the speed and efficiency of cognitive processes and functions, including processing speed (22). Research also suggests that tDCS effectively reduces anxiety and tension, resulting in increased life satisfaction (23).

Overall, tDCS is a non-invasive and practical intervention improving sleep quality, increasing life satisfaction, and reducing negative emotions. This study investigated the effects of tDCS on sleep quality, processing speed, life satisfaction, and negative emotional states in students with poor sleep quality.

Materials and Methods

Study design, population, and sample size: The semi-experimental study employed a pretest-posttest design with a control group. Participants were students with poor sleep quality who were referred to the Cognitive Science Laboratory of Shahid Bahonar University of Kerman, Kerman, Iran, in 2023. Participants were initially screened using the Pittsburgh Sleep Quality Index (PSQI). Subsequently, all individuals were evaluated according to the Diagnostic and Statistical Manual of Mental Disorders-Fifth Edition (DSM-5) diagnostic criteria by a clinical psychologist to confirm the diagnosis. A total of 27 participants with poor sleep quality were enrolled from the target population after providing informed consent. No participants presented with deficits in visual, auditory, or sensorimotor functions, nor reported any prior neurological or psychiatric conditions or history of substance abuse. Participants were allocated to the intervention or control group using simple randomization based on a random number table. Even numbers were assigned to the intervention group and odd numbers to the control group. Fourteen participants received active tDCS and the 13 participants received sham stimulation. A single-blind method was used to reduce the bias; participants were unaware of their group allocation, whereas the researcher and evaluator were not blinded. Both groups underwent stimulation sessions using the same device (NeuroStim 2 device manufactured by Medina Teb Gostar Com-

pany, Tehran, Iran) with identical session duration and frequency.

Inclusion and exclusion criteria: Inclusion criteria were**:** age ≥ 18 years, being a student, PSQI score ≥ 5, physician-diagnosed sleep disorders, self-reported sleep dissatisfaction, provision of informed consent, and willingness to participate. Exclusion criteria were: dissatisfaction and unwillingness to continue participation, absence from even one intervention session, receipt of other medical services during the intervention, use of addictive substances, history of cardiovascular diseases (CVDs), stroke, epilepsy, seizures, or brain injury, presence of metallic/platinum implants or cardiac pacemakers in the body, and pregnancy.

At baseline, all participants completed the PSQI, Reaction Time Index (RTI) task, Symbol Digit Modalities Test (SDMT), Satisfaction with Life Scale (SWLS), and Depression, Anxiety, and Stress Scale-21 (DASS-21). The tDCS intervention was administered with the anode electrode positioned over F_3 and the cathode over F_4 for 10 sessions of 20 minutes each (3 times per week for 3 weeks) at an intensity of 2 mA. The control group received sham stimulation only.

Ethical approval: This study was approved by Kerman University of Medical Sciences (ethics code: IR.KMU.REC.1402.087), and registered in the Iranian Registry of Clinical Trials (IRCT20221211056780N1). Participation was voluntary and completely free of charge. Written informed consent was obtained from all participants following thorough explanation of the study procedures. Participant confidentiality was strictly maintained throughout the study.

Measurement instruments

PSQI: The PSQI is a 19-item self-report instrument that assesses sleep quality and sleep disturbance over the previous month in clinical and non-clinical populations. Total scores range from 0 to 21, with higher scores indicating poorer sleep quality. A total score > 5 has demonstrated a sensitivity of 98.7% and a specificity of 84.4% for identifying sleep disturbances (24).

RTI: The RTI task assesses attention and motor and cognitive reaction times. During the task, a yellow stimulus appears randomly in one of the circles displayed on the screen, with one circle for the simple task and five circles for the five-choice mode. Participants are instructed to release a response button and select the corresponding circle as quickly as possible, then return their finger to the button. Outcome measures include simple mean reaction time (SMRT) and five-choice mean reaction time (FMRT) (25).

SDMT: We used the SDMT to measure the processing speed. This evaluation employs a series of numbers from 1 to 9, each paired with a unique symbol. Participants have 90 seconds to match numbers with their corresponding symbols. The highest possible score is 93 (26).

SWLS: The SWLS, developed by Diener et al. (27), is a 5-item measure applicable for all ages. Items are rated on a Likert scale from 1 (completely disagree) to 7 (completely agree). The scale has demonstrated internal consistency, with the Cronbach's alpha of 0.87, and acceptable construct validity based on convergent validity with the Oxford Happiness Inventory (OHI) and the Beck Depression Inventory (BDI).

DASS-21: The DASS-21 is a 21-item self-report scale with three 7-item subscales measuring depression, anxiety, and stress. Lovibond and Lovibond reported Cronbach's alpha coefficients of 0.91 for depression, 0.84 for anxiety, and 0.90 for stress, indicating good internal consistency (28).

tDCS: tDCS was administered using a NeuroStim 2 device with two 5 cm × 5 cm saline-soaked sponge electrodes. Stimulation (2 mA for 20 minutes/session, 10 sessions total across 3 weeks, 3×/week) was delivered with the anode over F3 and the cathode over F4. In the control (sham) group, electrode placement was identical; however, the current was applied for only 30 seconds at the beginning and end of each session, then ramped down, producing a transient tingling experience without any neural effects. All participants completed outcome assessments before the intervention (pretest) and after the intervention (posttest) using the same instruments (PSQI, RTI, SDMT, SWLS, and DASS-21).

Statistical analysis: Data were analyzed using SPSS software (version 24, IBM Corporation, Armonk, NY, USA). Descriptive statistics included means, standard deviations (SDs), and frequencies. Inferential analyses were performed using analysis of covariance (ANCOVA) and multivariate ANCOVA (MANCOVA). Assumptions for ANCOVA, including normality of distribution and homogeneity of variances, were evaluated using Levene's test. Statistical significance was set at P-value < 0.05.

Table 1. Demographic characteristics of participants in the intervention and control groups

Variables		Intervention group (n = 14)	Control group (n = 13)	Total (n = 27)
Gender [n (%)]	Men	8 (57.14)	10 (76.92)	18 (66.70)
	Women	6 (42.86)	3 (23.08)	9 (33.30)
Education [n (%)]	Bachelor's	5 (35.71)	6 (46.15)	11 (40.70)
	Master's	8 (57.14)	4 (30.77)	12 (44.40)
	PhD	3 (7.15)	1 (23.08)	4 (14.80)
Marital status [n (%)]	Single	14 (100)	13 (100)	27 (100)
	Married	0 (0)	0 (0)	0 (0)
Age (year) (mean ± SD)		23.21 ± 2.91	22.62 ± 2.02	22.93 ± 2.09

SD: Standard deviation

Results

Participants (n = 27) were randomly assigned to the intervention (n = 14) or control (n = 13) groups.

Table 1 presents the comparison of demographic characteristics between the intervention and control groups.

Table 2 presents the means and SDs of the study variables at the pretest and posttest for both the intervention and control groups. Before performing ANCOVA, the required assumptions were examined. The assumption of normality was satisfied as skewness and kurtosis values for all variables were within the acceptable range (± 2.58). Homogeneity of variances was assessed using Levene's test. A univariate ANCOVA analysis was performed to investigate the effect of tDCS on sleep quality, non-computer-based processing speed, and life satisfaction at posttest, while controlling for pretest scores (Table 3). For non-computer-based processing speed (coding or SDMT), ANCOVA revealed a significant between-group difference at posttest after controlling for pretest scores (F = 4.539, P = 0.044). In contrast, no significant between-group differences were observed for sleep quality (F = 1.963, P = 0.174) or life satisfaction (F = 0.075, P = 0.786), after controlling for baseline values (Table 3).

In addition, we employed MANCOVA to examine the effect of tDCS on computer-based processing speed and subscales of negative emotional states (depression, anxiety, and stress), controlling for pretest scores (Table 4). All assumptions for MANCOVA, including homogeneity of regression slopes and the absence of significant interactions between the independent variable and covariates, were met (P < 0.05). Regarding computer-based processing speed (computer-RTI), significant between-group differences were found for both SMRT (F = 6.416, P = 0.019) and FMRT (F = 7.735, P = 0.012) at posttest (Table 4). Among the negative emotional state subscales, a significant difference between groups was observed only for anxiety (F = 4.320, P = 0.05). No significant posttest differences were found between the intervention and control groups for depression (F = 0.284, P = 0.559) or stress (F = 0.102, P = 0.752) (Table 4).

Discussion

This study investigated the effects of tDCS on processing speed, life satisfaction, and negative emotional states (psychological distress) in students with poor sleep quality. The findings showed that tDCS did not produce a significant improvement in sleep quality in the intervention group compared to the control group.

Table 2. Descriptive statistics of study variables in the intervention and control groups at pretest and posttest

Variables	Intervention group (mean ± SD)		Control group (mean ± SD)		P-value
	Pretest	Posttest	Pretest	Posttest	
Sleep	9.29 ± 3.42	4.79 ± 1.80	7.85 ± 2.30	5.85 ± 2.79	0.17
SMRT	300.52 ± 94.37	268.04 ± 38.97	339.00 ± 131.71	347.18 ± 119.84	< 0.01
FMRT	283.32 ± 69.29	259.75 ± 24.62	316.34 ± 100.94	336.11 ± 98.50	0.01
SDMT	58.00 ± 12.37	65.07 ± 10.55	54.54 ± 8.84	58.38 ± 8.67	0.04
Life satisfaction	20.00 ± 6.12	22.14 ± 6.13	19.54 ± 6.89	22.31 ± 6.79	0.78
Depression	14.43 ± 10.55	9.57 ± 8.81	18.77 ± 10.66	14.15 ± 11.23	0.59
Anxiety	13.14 ± 10.22	6.71 ± 7.21	13.54 ± 8.64	11.85 ± 7.32	0.05
Stress	20.29 ± 10.07	15.29 ± 9.91	21.85 ± 6.90	18.31 ± 10.70	0.75

SMRT: Simple mean reaction time; FMRT: Five-choice mean reaction time; SDMT: Symbol Digit Modalities Test; SD: Standard deviation

Table 3. Analysis of covariance (ANCOVA) results for Pittsburgh Sleep Quality Index (PSQI), Symbol Digit Modalities Test (SDMT), and Satisfaction with Life Scale (SWLS) scores

Source	Dependent variables	SS	df	MS	F	P-value	Eta
Group	PSQI	10.648	1	10.648	1.963	0.174	0.076
	SDMT	103.409	1	103.409	4.539	0.044	0.159
	SWLS	1.621	1	1.621	0.075	0.786	0.003

SS: Sum of squares; df: Degree of freedom; MS: Mean squares; PSQI: Pittsburgh Sleep Quality Index; SDMT: Symbol Digit Modalities Test; SWLS: Satisfaction with Life Scale

These findings are consistent with previous research by Frase et al. (29), and Cody et al. (10), both of which showed that stimulating the prefrontal areas with tDCS did not significantly affect sleep continuity, architecture, or overall sleep quality. In contrast, other studies have reported beneficial effects of tDCS on improving sleep and sleep quality (30, 31).

These discrepancies may be attributed to several factors. Sleep quality is difficult to assess objectively, and the PSQI is a subjective instrument that may be influenced by underreporting or overreporting of symptoms. In addition, pretest exposure may have affected participants' responses. The small sample size in this study likely reduced statistical power and limited the generalizability of the findings.

Another key finding was that tDCS had a significant positive effect on processing speed (both non-computer-based and computer-based tests). These findings are consistent with the study by Cody et al. (10), which demonstrated improvements in processing speed following tDCS in patients with human immunodeficiency virus (HIV). However, inconsistent results have also been reported. For example, despite stimulation of the F_3 region, some studies have found no significant effects of tDCS on social-cognitive measures and processing speed (32). These findings may be explained by the small sample size and potential differences in tDCS effects between healthy individuals and clinical populations, as well as variability across different neurological or psychiatric conditions (32).

The study also showed that tDCS did not have a significant effect on life satisfaction in the intervention group compared to the control group. This finding contrasts with some studies reporting improved life satisfaction following anodic stimulation of F_3 and cathodic stimulation of F_4 (33). The Satisfaction with Life Scale (SWLS) is a subjective measure of life satisfaction, and participants' current life conditions may have influenced responses.

Regarding negative emotional states, tDCS significantly reduced anxiety levels in the intervention group compared to the control group, while no significant effects were observed for depression or stress. This finding is consistent with previous studies demonstrating the effectiveness of tDCS in reducing negative emotional states (34-36). The DLPFC cortex plays a central role in emotional processing, particularly in regulating negative emotional conditions (37). Although tDCS was effective in reducing anxiety in the present study, it was not significantly effective in reducing depression and stress, inconsistent with some reports suggesting that tDCS influences stress reactivity (37, 38). It has been proposed that stimulation of the left DLPFC enhances positive emotions, whereas stimulation of the right DLPFC reduces negative emotions, reflecting that right hemisphere handles negative emotions, while the left hemisphere handles positive ones (38).

Several limitations should be considered, including a small sample size, the absence of follow-up assessments due to limited participant cooperation, and the extended duration of the intervention.

Table 4. Summary of multivariate analysis of covariance (MANCOVA) for Reaction Time Index (RTI) and Depression, Anxiety, and Stress Scale-21 (DASS-21) scores

Source	Dependent variables	SS	df	MS	F	P-value	Eta
Group	SMRT	24250.590	1	24250.590	6.416	0.019	0.218
	FMRT	23213.219	1	23213.219	7.375	0.012	0.243
	Depression	19.021	1	19.021	0.284	0.559	0.013
	Anxiety	135.331	1	135.331	4.320	0.050	0.164
	Stress	6.411	1	6.411	0.102	0.752	0.005

SS: Sum of squares; df: Degree of freedom; MS: Mean squares; SMRT: Simple mean reaction time; FMRT: Five-choice mean reaction time

Future studies are recommended to examine the effects of tDCS on sleep quality across different age groups and to assess sleep quality at multiple time points during the intervention (e.g., first, fifth, and tenth sessions), to improve measurement accuracy. Additionally, individualized tDCS protocols based on the unique neural mapping and involved brain regions may enhance treatment efficacy.

Conclusion

The findings of this study indicate that tDCS improves processing speed and reduces anxiety among students with poor sleep quality. However, tDCS did not significantly enhance sleep quality or overall life satisfaction. These results suggest that tDCS may exert selective effects, highlighting its nuanced effects on specific facets of cognitive and emotional well-being among students with sleep-related difficulties.

Conflict of Interests

Authors have no conflict of interests.

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