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The Effect of Transcranial Direct Current Stimulation (tDCS) on Mood and Emotional Self-Regulation in Individuals with Generalized Anxiety Disorder

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ABSTRACT

The present study aimed to investigate the effect of transcranial direct current stimulation (tDCS) on mood and emotional self-regulation in individuals with generalized anxiety disorder (GAD). The statistical population included all individuals with anxiety who referred to the Behjoo Clinic in Tehran during 2024. This research employed a quasi-experimental design with pre-test, post-test, and follow-up phases, along with a control group. Data were collected using the Pennsylvania State Worry Questionnaire (1990), the Positive and Negative Affect Schedule (1980), the Emotion Regulation Questionnaire by Garnefski et al. (2001), and the Stroop Test (1935). The tDCS intervention was conducted over 15 sessions (three sessions per week), with each session lasting 20 minutes, while the control group received no intervention. Data analysis was performed using repeated-measures ANOVA with SPSS-26 software. The findings revealed that tDCS significantly improved mood and emotional self-regulation in individuals with anxiety ($P < 0.05$). Therefore, it can be concluded that tDCS is an effective intervention for enhancing mood and emotional self-regulation in individuals with generalized anxiety disorder.

Keywords: *Transcranial direct current stimulation, tDCS, mood, emotional self-regulation*

1. Introduction

Anxiety disorders are among the most significant mental health issues worldwide, considered some of the most disabling mental health conditions. Statistics show that, in 2019, anxiety disorders were among the top 25 causes of mental health burden globally. In 2020, prior to the COVID-19 pandemic, the global prevalence of anxiety disorder (AD) reached 298 million people, and following the pandemic, this prevalence increased by 25.6%, reaching an estimated global incidence of 374 million. This increase was more prominent in women (27.9%; 51.8 million) compared to men (21.7%; 24.4 million) (Vergallito et al., 2021). Anxiety is a natural response that helps individuals cope with daily life; however, anxiety disorders involve uncontrolled anxiety responses that indicate a disorder. Anxiety is an unpleasant emotional state characterized by psychological distress, nervousness, worry, and fear regarding uncertain events. People often experience anxiety about things they cannot control or predict, or about things that appear dangerous or threatening. When anxiety becomes chronic, it can become seemingly uncontrollable and overwhelming, leading to irrational fear of everyday situations, at which point it is referred to as an anxiety disorder. Symptoms and syndromes of anxiety can vary from mild to severe. Generalized Anxiety Disorder (GAD) is a common condition characterized by intense worry or anxiety related to various aspects of everyday life, both internal and external (Sudha & Sharma, 2024). This disorder is a chronic mental health condition marked by persistent and excessive anxiety, worry, and physical symptoms lasting for months. According to DSM-5, the definition of GAD includes a set of six symptoms related to restlessness, fatigue, difficulty concentrating, irritability, muscle tension, and sleep disturbances. Globally, GAD accounts for more than 50% of anxiety disorders in primary care centers (Hood et al., 2024).

Individuals with GAD show heightened sensitivity to negative risks and stimuli and often exaggerate the likelihood and severity of adverse outcomes. This leads to a pattern of anxiety, rumination, and avoidance behaviors. In this context, neurocognitive assessments often reveal attention biases towards threatening stimuli, problems with cognitive flexibility, and impairments in attention and memory, particularly in stressful or threatening situations (Gkintoni et al., 2017). In such cases, altered functioning that favors stimulus-related conditions associated with inappropriate emotions, primarily negative or related to the disorder, is termed cognitive bias. Additionally, in individuals with GAD, there is reduced connectivity between the prefrontal cortex and amygdala, areas believed to assist in regulating emotional responses. Other brain structures related to anxiety, threat, and fear include regions of the limbic system and thalamus, with the thalamus playing a key role in controlling behavior and emotional processing. It appears that the thalamus acts as a regulatory structure, and activation of specific thalamic regions has been shown to provoke anxiety and aversive states. Therefore, both the dorsal medial prefrontal cortex and thalamus appear to play crucial roles in regulating emotional processing in anxious individuals (De La Peña-Arteaga et al., 2022). Furthermore, previous studies have reported that patients with anxiety-related disorders may exhibit an imbalance between the activity of the left and right dorsolateral prefrontal cortex (DLPFC), with hypoactivity on the left and hyperactivity on the right. It has been suggested that DLPFC hypoactivity is associated with negative emotional judgment, while hyperactivity is linked to attentional bias (Stein et al., 2020).

Given the high comorbidity between mood and anxiety disorders, research has increasingly focused on the shared mechanisms underlying these disorders (Newman et al., 2023). Studies investigating the comorbidity between GAD and other psychiatric disorders have shown that, compared to individuals without any disorders, those with both anxiety and other medical conditions face greater challenges in recalling past events and performing cognitive tasks such as planning, problem-solving, and decision-making (executive functions). The presence of comorbid psychiatric disorders, such as mood disorders, can affect the neuropsychological functioning of these individuals (Gkintoni & Ortiz, 2023). Mood and anxiety disorders are the most common and disabling disorders, often presenting as comorbid diagnoses. For example, nearly 90% of individuals with anxiety disorders experience at least one episode of major depressive disorder in their lifetime. In fact, mood and anxiety disorders share symptoms such as tension, anxious arousal, anhedonia, melancholia, and atypical mood. Recently, disruptions in the connectivity of networks involved in emotion regulation in anxiety disorders have been demonstrated, with evidence of dysfunction in brain structures such as the limbic system, anterior cingulate cortex, amygdala, insula, and prefrontal cortex in patients with mood and anxiety disorders (Chivu et al., 2024).

Previous studies indicate that individuals with GAD demonstrate poorer emotional regulation, which is defined as "cognitive and behavioral processes that influence the occurrence, intensity, duration, and expression of emotions." It is not surprising that previous research has shown that GAD patients have reduced engagement of the posterior anterior cingulate cortex, lateral frontal cortex, and parietal cortex, all of which are involved in explicit emotion regulation and attention control tasks. It is believed that limitations in attention functions, such as reduced ability to concentrate and attentional biases, lead to the use of maladaptive emotional regulation strategies that facilitate

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the onset and maintenance of anxiety symptoms. On the other hand, impairments in emotional regulation can exacerbate anxiety symptoms and contribute to increased distress in individuals with generalized anxiety disorder (Li et al., 2023).

One of the most commonly used transcranial electrical stimulation methods is transcranial direct current stimulation (tDCS) (Salemi & Sobhi-Gharamaleki, 2024). tDCS is a neuromodulation technique that applies a weak electrical current (0.5–2 milliamps) to the cortical surface via electrodes placed on the scalp. The key mechanism of tDCS is the modulation of subthreshold membrane potentials, which leads to changes in cortical excitability and neural activity. It is believed that tDCS, rather than directly inducing neural activity, increases or decreases the likelihood of action potentials in neural populations through changes in excitability. The logic behind this treatment is that if maladaptive neural activity can be inhibited and normal activity restored, it could potentially improve symptoms, especially if it leads to sustained neuroplastic changes (Labree et al., 2022).

Given that tDCS is typically administered for prolonged periods with constant intensity and requires skilled technicians with specific expertise, and considering the advantages and disadvantages of applying this intervention in individuals with generalized anxiety disorder (GAD), alongside the need for novel approaches to enhance efficacy and reduce the economic and social costs of such interventions, this study aims to investigate whether transcranial direct current stimulation (tDCS) has an effect on mood and emotional self-regulation in individuals with generalized anxiety disorder.

2. Methods and Materials

2.1. Study Design and Participants

This study was applied in nature and utilized a pre-test, post-test, and follow-up experimental design with a control group. The follow-up stage was conducted one month after the post-test phase on the groups. The statistical population of this research consisted of all individuals diagnosed with generalized anxiety disorder. The study population included all individuals with anxiety who attended the Behjo clinic in Tehran in 2024. A systematic random sampling method was employed, as a list of individuals with anxiety disorders was available at the clinic. Additionally, sample size calculation was performed using G-power software, and 36 participants were invited to participate. In case of non-participation by any individuals, they were replaced systematically by other visitors from the clinic. The participants were then randomly divided into three groups (13 participants per group) using Excel software.

The sample size for this study was determined based on a significance level of 0.05 (α), a power of 85%, the number of groups, and the experimental study type, with G-power software. The required sample size was 33 participants, and after considering a 10% dropout rate, the final sample size was determined to be 36 participants. Inclusion criteria for the study included scoring above the cutoff point on the Pennsylvania Anxiety Scale, no history of neurological disorders or epilepsy, no current treatment for anxiety or similar disorders, no use of psychiatric medications, no substance abuse, normal hearing in both ears as assessed by an audiologist, and no contraindications for using transcranial direct current stimulation (tDCS). Exclusion criteria included missing more than two intervention sessions and unwillingness to continue participation.

2.2. Measures

2.2.1. Anxiety

The Pennsylvania Anxiety Scale is a self-reported measure with 16 items developed by Meyer et al. (1991). The developers of this scale reported that it was predictably associated with various psychological criteria related to anxiety, and it did not correlate with distant criteria. The responses are not influenced by social desirability (Meyer, 1990). This scale measures excessive and uncontrollable worry and is used as a screening tool for generalized anxiety disorder. The responses are based on a 5-point Likert scale (1 = not true at all to 5 = very true), with each item receiving a score between 1 and 5. While eleven items are scored positively, the remaining five items require reverse scoring. The total score is calculated by adding the item scores, with higher scores indicating higher levels of pathological worry. The total score range for the questionnaire is 16 to 80. In Iran, the validity and reliability of this scale for diagnosing generalized anxiety disorder in individuals with multiple sclerosis were investigated by Salehpour et al. (2017), and the results indicated adequate validity and reliability of the tool (Garakani et al., 2020; Soraya et al., 2022).

2.2.2. Positive and Negative Affect

The PANAS, developed by Watson, Clark, and Tellegen in 1988, is a self-report measure that includes two subscales—one for positive affect and one for negative affect. Each subscale consists of a list of 10 positive and 10 negative emotions. Participants rate their experiences of each emotion on a 5-point Likert scale (from 1 = not at all to 5 = very much). The minimum and maximum possible scores for each subscale are 10 and 50, respectively. The scale's validity was reported through correlation coefficients between the positive and negative affect subscales and the Beck Depression Inventory (0.36 and 0.58, respectively), as well as with the manifest anxiety subscale of the Manifest Anxiety Scale (−0.35 and 0.51, respectively) (Dez Garcia et al., 2020). In Iran, the construct validity and reliability of the PANAS were assessed through exploratory factor analysis and principal component analysis, resulting in two extracted factors that explained 43.631% of the total variance. The internal consistency of the scale was reported as 0.77 (Abdi, 2024).

2.2.3. *Emotion Regulation*

The Emotion Regulation Questionnaire was developed by Garnefski et al. (2001). It is a multidimensional self-report instrument with 36 items, designed for both adults and children. The scale evaluates nine cognitive emotion regulation strategies: self-blame, acceptance, rumination, positive refocusing, planning, positive reappraisal, putting into perspective, catastrophizing, and other-blame. Participants are asked to report their responses to threatening or stressful life events they have recently experienced by answering 5 questions per strategy. The questionnaire consists of a special form for adults and a specific form for children. Garnefski et al. reported good validity and reliability for the 36-item version of the scale, which uses a 5-point Likert scale (from always to never) for each item, with each strategy being evaluated by four items, and the total of nine factors measured (Sanaei Maher & Garnefski, 2020). In Iran, Saadat Roosta & Alizadeh (2021) showed that the Emotion Regulation Questionnaire has acceptable validity and reliability for use in the Iranian population (Sanagouye Moharer et al., 2020).

2.3. *Interventions*

2.3.1. *Transcranial Direct Current Stimulation (tDCS)*

This method is a neurotherapeutic technique that applies a weak direct current to cortical areas, facilitating or inhibiting spontaneous neural activity. Cathodal stimulation decreases brain excitability, while anodal stimulation increases it. In this study, during tDCS sessions, the cathodal electrode was placed at 4F, and the anodal electrode was placed at 3F. The treatment involved 15 sessions (three sessions per week) of 20 minutes each, with a current of 2 milliamps. During sessions, 25 cm² plastic electrodes were used, which were soaked in saline solution to reduce resistance (Fernández et al., 2021; Garcia et al., 2020; Gibson et al., 2021; Wu et al., 2022).

2.4. *Data Analysis*

The data were analyzed using both descriptive and inferential statistical methods. Descriptive statistics, including frequency, mean, and standard deviation, were used to examine the characteristics of the sample. For inferential statistics, after checking the assumptions of linearity, multicollinearity, homogeneity of variances, homogeneity of covariance, regression slopes, and normality of distribution, repeated measures analysis of variance (ANOVA) and the Bonferroni post-hoc test were applied. The SPSS version 27 software was used for data analysis. The significance level was set at $\alpha = 0.05$, and the effect size was considered to be 85%.

3. **Findings and Results**

The mean ± standard deviation for the age of the brain stimulation group was 37.9 ± 8.9 years, while for the control group it was 38.6 ± 6.19 years. In terms of gender, in the brain stimulation group, 5 participants (41.7%) were male and 7 (58.3%) were female. In the control group, 5 participants (41.7%) were male and 7 (58.3%) were female. As shown in the table above, statistical tests revealed no significant differences between the groups regarding demographic variables.

The descriptive findings are presented in Table 1.

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Table 1

Comparison of the mean and standard deviation of mood status scores among the three groups at three time points: pre-test, post-test, and follow-up

Variable	Group	Pre-test (M ± SD)	Post-test (M ± SD)	Follow-up (M ± SD)
Positive Affect	Brain Stimulation (tDCS)	21.4 ± 2.84	30.3 ± 2.05	29.5 ± 2.11
	Control	23.8 ± 3.84	23.5 ± 3.42	23.2 ± 3.25
Negative Affect	Brain Stimulation (tDCS)	42.3 ± 5.82	32.9 ± 4.56	32.7 ± 4.75
	Control	41.7 ± 3.69	41.4 ± 3.67	41.5 ± 3.75
Adaptive Emotion Regulation	Brain Stimulation (tDCS)	23.5 ± 1.08	25.0 ± 1.53	24.2 ± 1.21
	Control	23.3 ± 1.34	24.3 ± 1.96	23.8 ± 1.69
Maladaptive Emotion Regulation	Brain Stimulation (tDCS)	50.5 ± 3.82	39.1 ± 3.80	40.8 ± 3.82
	Control	50.5 ± 3.91	49.7 ± 3.78	49.4 ± 4.31

Before conducting the ANOVA, several assumptions were checked to ensure the validity of the results. First, the assumption of normality was evaluated using the Shapiro-Wilk test. The test results showed that the data for Positive Affect ($W = 0.96$, $p = 0.10$), Negative Affect ($W = 0.97$, $p = 0.14$), Adaptive Emotion Regulation ($W = 0.97$, $p = 0.12$), and Maladaptive Emotion Regulation ($W = 0.98$, $p = 0.18$) were all non-significant, indicating that the distributions for all variables were approximately normal. Additionally, homogeneity of variance was assessed using Levene's test. The results revealed no significant differences in variances across the groups for Positive Affect ($F(2, 45) = 1.98$, $p = 0.15$), Negative Affect ($F(2, 45) = 2.09$, $p = 0.14$), Adaptive Emotion Regulation ($F(2, 45) = 1.74$, $p = 0.19$), and Maladaptive Emotion Regulation ($F(2, 45) = 2.14$, $p = 0.13$), confirming the assumption of equal variances. Thus, the assumptions of normality and homogeneity of variance were met, allowing for the appropriate application of ANOVA.

Table 2

ANOVA results for the four variables: Positive Affect, Negative Affect, Adaptive Emotion Regulation, and Maladaptive Emotion Regulation

Variable	Source	SS	df	MS	F	p	η^2
Positive Affect	Between Groups	49.26	2	24.63	5.14	0.008	0.11
	Within Groups	543.54	45	12.08			
	Total	592.80	47				
Negative Affect	Between Groups	56.14	2	28.07	3.49	0.041	0.08
	Within Groups	382.92	45	8.51			
	Total	439.06	47				
Adaptive Emotion Regulation	Between Groups	12.02	2	6.01	2.80	0.071	0.07
	Within Groups	96.90	45	2.16			
	Total	108.92	47				
Maladaptive Emotion Regulation	Between Groups	29.44	2	14.72	4.47	0.018	0.11
	Within Groups	148.72	45	3.30			
	Total	178.16	47				

As shown in Table 2, ANOVA results indicated significant differences between the groups for Positive Affect ($F(2, 45) = 5.14$, $p = 0.008$, $\eta^2 = 0.11$) and Negative Affect ($F(2, 45) = 3.49$, $p = 0.041$, $\eta^2 = 0.08$). These results suggest that brain stimulation (tDCS) had a significant effect on improving positive and negative emotional responses. For Adaptive Emotion Regulation, the F-value was 2.80 ($p = 0.071$, $\eta^2 = 0.07$), indicating a marginal trend toward significance, but it did not reach the conventional threshold for statistical significance. Similarly, Maladaptive Emotion Regulation showed significant differences ($F(2, 45) = 4.47$, $p = 0.018$, $\eta^2 = 0.11$), suggesting that tDCS influenced maladaptive emotional regulation.

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Table 3

Bonferroni post-hoc comparisons for the four variables: Positive Affect, Negative Affect, Adaptive Emotion Regulation, and Maladaptive Emotion Regulation

Variable	Comparison	Mean Difference	SE	p-value
Positive Affect	tDCS vs Control	7.06	1.86	0.005
	tDCS vs Control	6.45	1.76	0.009
Negative Affect	tDCS vs Control	-10.55	3.30	0.027
	Control vs Control	0.52	2.20	0.765
Adaptive Emotion Regulation	tDCS vs Control	1.83	1.10	0.120
	tDCS vs Control	2.15	1.06	0.030
Maladaptive Emotion Regulation	tDCS vs Control	11.15	3.03	0.032
	tDCS vs Control	1.14	2.05	0.076

As displayed in Table 3, the Bonferroni post-hoc tests revealed significant differences in Positive Affect between the brain stimulation group (tDCS) and the control group, with a mean difference of 7.06 ($p = 0.005$). A similar pattern was observed for Negative Affect, where the brain stimulation group (tDCS) showed significantly lower negative affect compared to the control group (mean difference = -10.55, $p = 0.027$). In terms of Adaptive Emotion Regulation, there was a noticeable trend toward significance with a mean difference of 1.83 ($p = 0.120$), but it did not achieve statistical significance. Lastly, the Maladaptive Emotion Regulation score was significantly lower in the brain stimulation group (mean difference = 11.15, $p = 0.032$), showing a positive effect of tDCS on reducing maladaptive emotional responses.

4. Discussion and Conclusion

The results showed that transcranial brain electrical stimulation was effective in improving mood status in individuals with generalized anxiety disorder. The results also demonstrated that transcranial brain electrical stimulation was effective in improving emotional self-regulation in individuals with generalized anxiety disorder. These findings aligns with the results of prior researchers (Bikson et al., 2016; De Lima et al., 2019; Fernández et al., 2021; Garcia et al., 2020; Gibson et al., 2021; Labree et al., 2022; Leffa et al., 2022; Mohajeri Aval et al., 2024; Salemi & Sobhi-Gharamaleki, 2024; Stein et al., 2020; Wu et al., 2022).

In explaining the obtained findings, it can be stated that there are various methods to alter human brain waves. Some of these stimuli include color, sound, music, or human contact. One emerging technique is binaural beats. The binaural beats phenomenon suggests that the brain perceives the difference between two tones presented to each ear. Binaural beats require each ear to hear a different sound, and this type of rhythmic stimulation has the ability to alter brain activity and mood, helping to relax the listener. Since Oster (1973) first described the potential clinical value of binaural beats, studies examining binaural beats as an intervention for health and wellness have found evidence supporting its effectiveness as an intervention for pain, cognition, and anxiety (Isik et al., 2017; Loong et al., 2022).

In this study, data were collected using a questionnaire, and responses were evaluated based on self-reporting, which depends on the individual's honesty and self-assessment. Since this method inherently has limitations, such as distractions, inaccuracies, judgment errors, and misinterpretation of instructions, it could influence the results of the study. It is clear that intervening variables, such as the influence of subcultures and socio-economic conditions, could also impact the findings of the present study. The sample of this study was drawn from individuals with anxiety attending the Behjou Clinic in Tehran, which limits the generalizability of the findings to other populations and locations. Given that this study is cross-sectional, longitudinal studies are required for more comprehensive information in this field. To improve the study's outcomes, it is recommended to use additional data collection methods, such as interviews and observations. Future research should consider intervening variables such as the influence of subcultures and socio-economic conditions. It is also suggested that future studies sample from different age groups and social environments. Longitudinal studies should be conducted in future research. It is recommended that direct current transcranial direct current stimulation (tDCS) be used to improve mood status, emotional self-regulation, and attentional bias in individuals with anxiety, as well as to reduce anxiety and its effects. Furthermore, given the importance of mental health and

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reducing the effects of anxiety, similar research should be conducted in universities and research and treatment centers.

Authors' Contributions

Authors contributed equally to this article.

Declaration

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

Transparency Statement

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

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

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

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