Negative affective traits moderate transcranial direct current stimulation effects on memory

Marko Živanović[1*], Jovana Bjekić[2*], Carlo Miniussi[3], Walter Paulus[4], & Saša R. Filipović[2]

[1]*Institute of Psychology, Department of Psychology, Faculty of Philosophy, University of Belgrade, 11000 Belgrade, Serbia (marko.zivanovic@f.bg.ac.rs)*

[2]*Human Neuroscience Group, Center for Neuroscience and Neuromodulation, Institute for Medical Research, University of Belgrade, 11000 Belgrade, Serbia (jovana.bjekic@imi.bg.ac.rs, sasa.filipovic@imi.bg.ac.rs)*

[3]*Center for Mind/Brain Sciences - CIMeC, University of Trento, Rovereto (TN), Italy (carlo.miniussi@unitn.it)*

[4] *Department of Neurology, Ludwig Maximilians University, Munich, Germany (walter.paulus@med.uni-muenchen.de)*

Corresponding author: Jovana Bjekić
Institute for Medical Research, University of Belgrade
Dr Subotica 4, 11000 Belgrade, Serbia
jovana.bjekic@imi.bg.ac.rs

Author contributions (CRediT): MŽ – Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft; JB – Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft; CM – Conceptualization, Funding acquisition, Writing – review and editing; WP – Conceptualization, Funding acquisition, Writing – review and editing; SRF – Conceptualization, Funding acquisition, Methodology, Writing – review and editing

Abstract

The cognitive effects of transcranial direct current stimulation (tDCS) show considerable inter-individual variability, prompting the need to identify moderators of responsiveness. This study examined whether negative affectivity (such as depressiveness, anxiety, and stress level), conceptualized as both transient states and stable traits, moderates the effects of tDCS on working memory (WM) and associative memory (AM). We pooled data from six sham-controlled experiments involving 144 healthy young adults (351 tDCS sessions) using within-subject crossover designs. Participants completed WM and AM tasks following active anodal tDCS or sham, as well as Depression, Anxiety, and Stress Scale (DASS-21) before each session. We found that trait-level negative affectivity, but not state-level emotional fluctuations, moderated WM. Individuals with higher levels of depression, anxiety, or stress demonstrated greater tDCS-induced WM gains. In contrast, AM benefits were consistent and unaffected by affective traits or states. These findings indicate that psychological traits can shape the variability of tDCS effects. In particular, negative affectivity influences susceptibility to tDCS effects on cognitively demanding tasks that rely heavily on executive control. This effect may stem from negative affectivity's association with downscaled baseline cortical excitability in prefrontal networks, crucial for WM performance, thereby opening the possibility of greater tDCS-induced improvement. These findings provide further support to our growing understanding of the complex interplay between emotional and cognitive processes in shaping individual responses to tDCS and point out that negative affectivity should be taken into consideration when evaluating individual variability of the tDCS (and other non-invasive brain stimulation techniques) effects on memory and cognition.

Keywords: transcranial direct current stimulation (tDCS), emotion, depression, anxiety, stress, cognition, DASS, working memory, associative memory, dorsolateral prefrontal cortex (DLPFC), posterior parietal cortex (PPC)

Introduction

Over the past two decades, interest in non-invasive brain stimulation techniques has grown significantly due to their potential for probing and modulating cognitive functions. Among these techniques, low-intensity transcranial direct current stimulation (tDCS) has significantly advanced our knowledge of the neural mechanisms underpinning cognitive functions. The underlying premise of applying tDCS for cognitive neuromodulation is that delivering electrical current through scalp electrodes can influence cortical excitability, promote targeted circuit activity and neuroplasticity, ultimately modulating cognitive performance, either facilitating or attenuating it [1,2]. The high usability and favorable safety profile [3], coupled with the ability of tDCS to enhance cognitive functions, has led to its investigation in both healthy individuals and clinical populations, with studies reporting improvements in attention [4,5], executive functions [6], learning, and memory [7,8] among other cognitive domains. However, evidence for tDCS efficacy in cognitive enhancement, especially in healthy young adults, remains controversial, with some early meta-analyses showing little to no reliable evidence of behavioral and neuropsychological effects (e.g., [9]), while other subsequent works depicted a more granulated picture of functions that are more or less susceptible to tDCS effects as well as conditions that either promote or impede neuromodulatory effects of tDCS on cognition in healthy adults [10–12].

Among the cognitive domains investigated, associative memory (AM) and working memory (WM) have been of particular interest due to their fundamental roles in learning, problem-solving, decision-making, and overall daily functioning [13,14]. WM supports the temporary storage and manipulation of information [15], while AM refers to the ability to link previously unrelated pieces of information into complex representations [16]. Since the first study on tDCS effects on WM in healthy adults [17], more than a hundred studies have assessed these effects. One high-quality meta-analysis found overall weak but significant effects of tDCS on WM, attributing inconsistent and seemingly conflicting findings to various factors, including publication bias and low statistical power [18]. More recent meta-analyses on tDCS and WM emphasize the relevance of more specific methodological, neuroanatomical, and measurement-related factors, such as electrode placement, tDCS protocol (online/offline, duration, intensity), electric field distribution, and the type of outcome measures employed, in shaping cognitive outcomes [6,10,19]. Similarly, initial tDCS studies aiming to facilitate AM reported positive effects [20,21], but these were soon followed by experiments that failed to conceptually replicate such findings and reported no

significant effects [22,23]. The first meta-analysis of tDCS impact on episodic memory, including AM in healthy adults [24], reported small to negligible overall benefits, highlighting that these outcomes might be largely obscured by substantial methodological heterogeneity. The most recent systematic review specifically focusing on AM [25] found that targeted brain area (i.e., parietal *vs* frontal) and type of outcome measure (recognition *vs* cued-recall paradigm) may be the most important differentiators between null and positive results presented in the literature. Overall, positive results are more likely when the stimulation is applied over the parietal cortex, and the effects are assessed in cued recall paradigms.

The effects of tDCS are known to show high variability, meaning that they can vary depending on the specific stimulation parameters such as duration, intensity, electrode montage [26], characteristics of the study participants including neuroanatomical [27], neurochemical [28], genetic [29], and sex differences [30], but also factors such as, the neural excitability state [31], or properties of the outcome measures relative to the study population, such as task difficulty [32,33]. Furthermore, the tDCS effects have been argued to be dependent on certain experimental conditions, such as successfulness of blinding [34] and prior expectations of tDCS efficacy [35]. Overall, these sources of variability can be split into (1) participants' characteristics, (2) variable state-based factors, and (3) experimental/contextual factors – for a comprehensive review following this categorization, see [36].

A recent umbrella review of meta-analyses examining the impact of prefrontal tDCS across various cognitive domains found that only about a quarter of comparisons demonstrated significant effects, with most evidence classified as low or very low quality [37]. These findings suggest the need to identify potential moderators – variables that could account for the significant variability in observed cognitive outcomes beyond neuroanatomical and experimental factors. Recently, increasing attention has been directed toward psychological characteristics of participants, both their transient state at the time of stimulation (e.g., psychological state) and more stable individual differences (e.g., psychological traits).

In this context, one particularly relevant individual characteristic is negative affectivity, which is characterized by a predisposition to experience negative emotions such as anxiety, stress, and sadness [38]. Negative affectivity can be considered both as a state (momentary emotional experiences) and as a trait (a stable dispositional characteristic), both of which have been linked to cognitive performance [39–42]. From a neuroscience

perspective, extensive evidence supports the notion that cognitive and emotional processes are closely interrelated through dynamic interactions of distributed brain regions [43]. Research suggests that individuals with high negative affectivity exhibit altered functional connectivity and neural responses in key brain regions implicated in cognitive control and memory, such as the prefrontal and parietal cortices [40,44]. Since the prefrontal and parietal cortices are primary targets for neuromodulation in both WM and AM studies, understanding how tDCS effects interact with affective states and traits is crucial.

Given the inconsistent findings on the effects of tDCS on cognitive functions, particularly WM and AM, exploring the interaction between tDCS-induced cognitive changes and emotional factors may help in understanding the source(s) of variability in cognitive neuromodulation. A recent meta-analysis revealed that the effects of prefrontal tDCS on executive functions are significantly moderated by mood, further supporting the hypothesis that emotional factors play a key role in neuromodulatory efficacy [45]. Additionally, the concept of affective-state dependency in tDCS has been proposed as a framework [46] for exploring how affective traits and states interact with cortical activity to influence cognitive functions. However, it remains unclear if these effects are due to within-person variations in emotional *state* or whether the negative emotionality represents a relevant, relatively stable *trait* that makes people more or less susceptible to neuromodulatory effects. Our study represents a direct testing of this framework prediction that affective profiles act as internal contextual variables capable of shaping tDCS outcomes through cortical gating mechanisms.

This paper aims to explore the role of negative affectivity in shaping the cognitive effects induced by tDCS. Specifically, we present a comprehensive secondary analysis of multiple experiments examining the effects of tDCS on WM and AM, focusing on how emotional state and negative affectivity as trait influence these effects. To this end, we pooled together data from six memory experiments [33,47,48] to analyze how trait and state-level of negative affectivity (depression, anxiety, and stress) moderate the effects of tDCS on WM and AM performance.

Method

Study Design

The data from six experiments encompassing a total of 351 tDCS sessions (207 anodal active tDCS and 144 sham tDCS – from now on just sham) were reanalyzed. All six experiments employed a sham-controlled, within-subject design with counterbalanced order

of stimulation conditions and used parallel forms of tasks for repeated assessments. In all six experiments, participants underwent each experimental session separately, with a minimum of one week between sessions. Table 1 presents an overview of the main methodological aspects of the studies.

Table 1
Description of studies

Study		Sample	Stimulation protocol	Anode placement	Current intensity	Task
Exp. 1	Bjekić et al. (2019)	20 (M_{age} = 26.40, SD_{age} = 3.71, 11 females)	offline	P3	1.5mA	Face-word (AM)
Exp. 2	Bjekić et al. (2019)	21 (M_{age} = 24.15, SD_{age} = 2.74, 12 females)	offline	P4	1.5mA	Object-location (AM)
Exp. 3	Živanović et al. (2021)	21 (M_{age} = 26.76, SD_{age} = 4.83, 12 females)	offline	F3 P3	1.8mA	Verbal 3-back (WM)
Exp. 4	Živanović et al. (2021)	21 (M_{age} = 26.43, SD_{age} = 4.78, 12 females)	offline	F4 P4	1.8mA	Spatial 3-back (WM)
Exp. 5	Živanović et al. (2021)	21 (M_{age} = 24.90, SD_{age} = 2.49, 11 females)	online	F3 P3	1.5mA	Verbal 3-back (WM) Spatial 3-back (WM)
Exp. 6	Živanović et al. (2022)	40 (M_{age} = 25.15, SD_{age} = 3.65, 25 females)	online	P3	1.5mA	Short-term associative memory (AM)

Note. The return electrode (i.e., cathode) in all experiments was placed on the contralateral cheek.

Experiments 1, 2, and 6 consisted of two sessions – one active tDCS and one sham condition, while Experiments 3–5 involved participants going through three experimental sessions – two active tDCS and one sham condition. In Experiments 1 and 6, electrical current was delivered over the left posterior parietal cortex (PPC), while in Experiment 2, the current was applied over the right PPC. In Experiments 3 and 5, the current was delivered either over the left dorsolateral prefrontal cortex (DLPFC) or left PPC, while in Experiment 4, tDCS was applied either over the right DLPFC or right PPC. So, since the beginning of the session, in Experiments 1, 2, and 6, two electrodes were placed on the participant's head, whereas in Experiments 3–5, three electrodes were positioned on the participant's head.

Participants

Six memory experiments included a total of 144 young, healthy participants (age range: 21–35 years; 57.6% females). Experiment 1 included 20 participants, Experiments 3–5 enrolled 21 participants each, while Experiment 6 included 40 participants. All participants met the inclusion criteria for involvement in tDCS studies (Antal et al., 2017; Živanović &

Bjekić, 2023), were right-handed, and had normal or corrected-to-normal vision. Each study was approved by the Institutional Ethics Board, and all procedures adhered to the Declaration of Helsinki.

tDCS parameters

In all experiments, the electrode of interest delivered anodal stimulation, either in the active or sham condition. In Experiments 1, 2, 5, and 6, a constant current intensity of 1.5 mA was used, while in Experiments 3 and 4, the current intensity was 1.8 mA. In Experiments 1 to 5, square 5 x 5 cm electrodes (25 cm^2) were used, while in Experiment 6, round electrodes also of 25 cm^2 were used. In all experiments, the rubber electrodes were inserted into saline-soaked sponge pockets before being positioned on the scalp.

In Experiments 1 and 6, the active or sham tDCS electrode was placed over the left PPC (P3), while in Experiment 2 it was placed over the right PPC (P4). In Experiments 3–5, the electrode location was randomized across sessions and targeted either the DLPFC (left i.e. F3 in Experiments 3 and 5, right, i.e., F4 in Experiment 4) or the PPC (left i.e. P3 in Experiments 3 and 5, right, i.e., P4 in Experiment 4). In all experiments, the return (i.e., cathodal) electrode was placed on the contralateral cheek.

In all six experiments, the active tDCS condition was delivered for 20 min, using a 30 s ramp-up and 30 s ramp-down period. In sham conditions, the electrode montage was kept the same to the active tDCS condition, and the current was only briefly delivered at the beginning and at the end of the 20 min in a ramp-up/down manner (i.e., over the first and last 60 s).

Memory Assessment

In Experiment 1, AM was assessed using a face-word memory task [47]. The task consisted of two learning blocks, each followed by a test block. During the learning block, participants were successively presented with 20 face-word pairs and instructed to memorize as many pairs as possible. In the test block, the pictures of the same 20 faces ("old faces") were intermixed with 30 new faces and successively presented in quasi-random order, and the participants were asked to recognize the faces from the previous block. For each face recognized as "old", participants were asked to write in the word that a given face had been previously paired with. After the first test block, the participants had another opportunity to learn the same face-word pairs in the second learning block, followed by another face-cued

word recall test block. The percentage of correctly recalled face-word associations in both test blocks served as the outcome measure for this task.

In Experiment 2, AM was assessed using the object-location associative memory task [47]. The task consisted of two learning blocks, each followed by a test block. In the learning block, 15 colored images of everyday objects (e.g., furniture) and living things (e.g., animals) were sequentially, quasi-randomly presented in a 4 x 4 grid. Participants were instructed to memorize the locations of each stimulus in the grid. In the test block, the same images were shown above the grid, and participants needed to recall the location in which each stimulus had been previously presented. As in the previous task, in the second learning block, participants had another opportunity to remember object-location associations, which was, again, followed by a test block. The percentage of correctly recalled locations in both test blocks was used as the outcome measure.

In Experiments 3–5, WM was assessed using verbal and spatial 3-back tasks [48]. Both tasks had a similar structure, consisting of one training and five test blocks. In the verbal 3-back task, ten Latin alphabet letters were sequentially presented on the screen. Participants were instructed to respond by keypress when presented with the same letter as in the three steps before. In the spatial 3-back task, participants were shown a black square that successively changes its position in the 3 x 3 white grid. They were instructed to press a key when the black square was in the same position as in the three trials before. In both tasks, 25% of all trials required participants to react. Outcome measures in verbal and spatial 3-back tasks were calculated as the percentage of hits, i.e., correctly identified targets.

In Experiment 6, AM was assessed using the short-term AM task [33]. The stimuli in this task consisted of 10 single digits (0 to 9) printed in white, sequentially presented in fixed pre-randomized order on backgrounds (color cards) of different colors (blue, green, red, yellow, pink, or grey). Digit-color associations were presented to participants in sequences of different lengths, varying between 3 and 5 associations, and the participants were instructed to remember each digit-color association. At the end of each sequence (signaled by the appearance of the fixation point), participants were presented with one of the previously seen color cards and were instructed to recall the digit that was presented on a given color. Since the target digit could appear at each position in a sequence, its frequency was balanced across sequences. The measure of AM was calculated as the percentage of correctly recalled digits.

Across all six experiments, parallel forms of the memory tasks were used in each experimental condition.

Negative affectivity questionnaire

The Depression Anxiety Stress Scales (DASS-21) is a 21-item self-report scale designed to assess depression, anxiety, and stress, with 7 items dedicated to each domain [49]. Participants rate each item using a 4-point scale indicating how much each statement applied to their mood (0 – did not apply to me at all, 3 – applied to me very much or most of the time). For each domain and full-scale DASS, scores were calculated by averaging participants' responses on corresponding items (ranging from 0 to 3).

Procedure

In Experiments 1–4, behavioral effects were assessed in the so-called *offline* protocol, i.e., immediately after the stimulation. In Experiments 5 and 6, the *online* protocol was employed, i.e., the effects were assessed during tDCS. In each experiment, DASS-21 was administered at the beginning of each tDCS session, i.e., before active tDCS or sham conditions.

Each session lasted approximately 45 minutes in Experiments 1–4, and about 30 minutes in Experiments 5 and 6. Accounting for electrode setup and the completion of all questionnaires, the total duration of each session was around 1 hour.

Data analysis

Data from six memory experiments were aggregated into two datasets – one for WM (N = 63 participants; 378 observations) and one for AM (N = 81 participants; 163 observations); providing a stronger basis for reliable statistical analyses. All analyses were conducted using IBM SPSS Statistics 21, JASP 0.18.3, and R Studio 4.4.2.

To assess the *differences* between active tDCS and sham conditions in negative affectivity (depression, anxiety, stress, DASS-21 total scores) across experiments, a series of repeated-measures ANOVAs were conducted. To examine the *consistency* in negative affectivity between conditions (active tDCS and sham), we calculated intraclass correlation coefficients (*ICC*, two-way random effect method, absolute agreement type). *Variance decomposition* of negative affectivity was performed to differentiate trait-like stability from state-like fluctuations. To decompose the reliable variance, we used *ICC* and internal consistency measures of negative affectivity scales (Cronbach's α). Specifically, we computed the percentages of reliable variance in negative affectivity attributable to relatively stable trait-like individual differences using the formula $ICC^2/\alpha_{min}*100$, as a proxy for trait-

level (between-person) variability. The reminder variance attributable to state-level (within-person) variability was calculated as $100 - ICC^2/\alpha_{min} * 100$.

Measures of state-level fluctuations in negative affectivity were computed as difference scores between active tDCS and sham conditions for corresponding negative affectivity domains (e.g., depression before active tDCS – depression before sham), while the measures of relatively stable, trait-like individual differences for each domain of negative affectivity were calculated as the average scores of all conditions.

To examine the relationship between state fluctuations in negative emotions and tDCS-induced changes in WM and AM performance, we calculated Pearson's correlation coefficients between difference scores of each domain of negative affectivity (e.g., depression before active tDCS – depression before sham) and tDCS-induced gains in memory performance (active tDCS memory performance – sham memory performance). To examine the relationship between stable individual differences in negative emotions and memory performance, we calculated Pearson's correlation coefficients between each average negative affectivity domain (across all conditions) and tDCS-induced gains in memory performance (active memory performance tDCS – sham memory performance). Additionally, to determine if measures of negative affectivity and memory performance are related regardless of stimulation condition, we correlated average negative affectivity scores with average memory performance across conditions.

The core inferential analyses involved a series of linear mixed models (LMM) testing if state-level fluctuations or trait-level negative affectivity influence and moderate initially observed tDCS effects on WM and AM. In all models, STIMULATION condition (active tDCS *vs* sham) was used as a fixed factor while participants' ID was used as a random grouping factor (e.g., *AM_score ~ stimulation_condition + (1 | ID)*). Separate models were specified for each domain of negative affectivity at both the state and trait levels – that is in the state-level moderation analyses, difference score was introduced (e.g., *AM_score ~ stimulation_condition * anxiety_difference + (1 | ID)*), while in the trait-level moderation analyses, the average score was introduced to the model (e.g., *AM_score ~ stimulation_condition * anxiety_average + (1 | ID)*). In moderation analyses, the continuous moderators were split into three levels: low (1 *SD* below the mean of the moderator), mid (the moderator's mean value), and high (1 *SD* above the mean of the moderator). All post hoc comparisons were conducted using Satterthwaite's method for degrees of freedom estimation and were corrected for multiple comparisons using the Holm procedure.

Given the methodological constraints (an incomplete factorial design, preventing the estimation of certain interaction terms), the main analyses were performed independently of the locus and laterality of stimulation, task, and protocol type. These factors (TASK, LATERALITY, TYPE OF PROTOCOL) were all considered in the additional analyses provided in the Supplementary S2-S6.

Results

Descriptive statistics for three DASS-21 subscales and overall scores showed that, across all six experiments, participants, on average, showed relatively low negative affectivity, consistent with expectations for healthy young adult samples (see Supplementary S1).

Stability of negative affectivity

Across WM experiments, no significant differences in DASS-21 subscales between active tDCS condition(s) and sham were found (Table 2). However, in AM experiments, somewhat higher depressive symptoms were found before active tDCS compared to the sham condition.

Table 2
Differences and consistency in negative affectivity domains before active tDCS and sham stimulation, with reliability indices (Cronbach α), and % of variance attributable to stable individual differences, across cognitive domains and areas stimulated

			Active vs. Sham comparison			*Consistency & reliability*			
Cognitive domain	Area stimulated	Affective domain	*F*	*p*	η_p^2	*ICC*	α active tDCS	α sham	% stable individual differences
WM	PPC	depression	0.398	.530	.006	.834***	.879	.847	82.1
		anxiety	0.000	1.00	.000	.634***	.759	.748	53.7
		stress	3.007	.088	.046	.735***	.831	.845	65.0
		DASS total	1.674	.200	.026	.829***	.895	.873	78.7
	DLPFC	depression	0.633	.429	.010	.770***	.778	.847	76.2
		anxiety	0.566	.455	.009	.590***	.861	.748	46.5
		stress	0.814	.371	.013	.731***	.859	.845	63.2
		DASS total	0.169	.682	.003	.749***	.906	.873	64.3
AM	PPC	depression	4.246	.043	.050	.780***	.902	.845	72.0

anxiety	0.000	1.00	.000	.768***	.836	.802	73.5
stress	0.003	.953	.000	.794***	.863	.888	73.1
DASS total	0.577	.450	.007	.800***	.929	.912	70.2

Note. *ICC* – average measure of intraclass correlation coefficient (two-way random effect method, absolute agreement), $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

To estimate the variance attributable to trait-like stability in each domain of negative affectivity from its state-like fluctuations, we computed *ICC*s between corresponding scale scores in active tDCS and sham conditions. Results showed that some variations in negative affectivity emerged between the active tDCS and sham conditions, as most *ICCs* were below .80 (Table 2). The highest consistency in negative affectivity between active tDCS and sham conditions was observed for depression, followed by stress, while the lowest consistency was found for anxiety. Overall, 59.3% – 69.6% of the variance in depression (ICC^2), 53.4% – 63.0% of the variance in stress, and 34.8% – 59.0% of the variance in anxiety could be attributed to stable trait-like interindividual variability. These discrepancies in consistency of depression, stress, and anxiety could only partly be attributed to scales' measurement error, as median reliability was highest for stress (*Mdn* α = .859), and depression (*Mdn* α = .847), followed by anxiety (*Mdn* α = .802) (see Table 2). Taking reliability of these scales into account ($ICC^2/\alpha_{min}*100$), we found that on average, 76.8% of the variance in depression, 67.1% of the variance in stress, and 57.9% of the variance in anxiety could be attributed to stable trait-level variability across participants. In other words, on average, only 23.2%, 32.9%, and 42.1% of the reliable variance of depression, stress, and anxiety, respectively, could be attributed to variable, state-like changes in negative affectivity.

Relations between negative affectivity and cognitive performance

At the level of all observations (regardless of stimulation condition), domains of negative affectivity showed significant negative correlations with WM performance across all tDCS conditions (Table 3). However, when sham - tDCS between-sessions differences were considered, regardless of the area stimulated, no significant correlations were observed between tDCS-induced WM-gains and state-level changes in affectivity, as measured by differences in DASS scores between sessions. In contrast, following stimulation of PPC, trait anxiety, stress, and DASS total score were all significantly and positively related to tDCS-induced WM-gains. A similar pattern was observed following DLPFC stimulation, with higher tDCS induced WM gain observed in higher trait stress levels and a higher DASS total score, while the same trend was observed for trait anxiety. The findings indicate that almost

all shared variance between WM performance and negative affectivity can be attributed to stable factors. In addition, the average WM performance (across both stimulation conditions) was positively related to trait anxiety and DASS total score, and on a trend level, with depression as well.

On the other hand, AM performance proved to be unrelated to negative affectivity on both the state and trait levels.

Table 3

Pearson correlations between negative affectivity and WM and AM cognitive performance on state- and trait-levels

Cognitive domain	*Affective domain*	*Overall (all observations) memory performance × affectivity scores*	*State-level affectivity × active tDCS vs sham change*		*Trait-level affectivity × active tDCS vs sham change*		*Average memory performance × trait-level affectivity*
			PPC	DLPFC	PPC	DLPFC	
WM	depression	-.193**	212†	-.035	.204	.196	-.239†
	anxiety	-.244***	-.067	-.216†	.391**	.215†	-.288*
	stress	-.269***	.099	-.051	.381**	.304*	-.330**
	DASS overall	-.288***	.111	-.125	.382**	.286*	-.336**
AM	depression	-.027	.151	/	-.038	/	-.070
	anxiety	-.076	-.011	/	.026	/	-.089
	stress	-.128	-.032	/	-.077	/	-.144
	DASS overall	-.096	-.098	/	-.043	/	-.123

Note. *Overall* – correlations between WM or AM performance and negative affectivity domains for all observations (WM N = 189, AM N = 163). *Overall* column is provided here for illustrative purposes only, as a rough estimate of the amount of shared variance between cognitive performance and negative affectivity domains across the entire sample, regardless of whether the association stems from differences between individuals or from within-person differences across conditions; *State-level* – correlations between tDCS-induced gain in WM/AM performance and differences between corresponding negative affectivity domains in active tDCS and sham conditions (WM N = 63, AM N = 81); *Trait-level* – correlations between tDCS-induced gain in WM/AM performance and average negative affectivity for corresponding domains across conditions (WM N = 63, AM N = 81). *Average memory performance vs trait-level affectivity* – correlations between average WM or AM performance across active tDCS and sham conditions and average negative affectivity for corresponding domains across conditions (WM N = 63, AM N = 81). † p <.10, * p <.05, ** p <.01, *** p <.001

Negative affectivity as a moderator of tDCS effects

Working memory

Based on the combined dataset from the three WM experiments, results of the LMMs revealed an overall significant main effect of STIMULATION on WM performance [$F_{(1,314)}$ = 5.216, p = .023, η_p^2 = .02]. Initial tDCS effects on WM performance remained significant after including state-level negative affectivity in the model, i.e., tDCS-to-sham differences in

depression [$F_{(1,312.32)}$ = 5.702, p = .018, η_p^2 = .02], anxiety [$F_{(1,312.29)}$ = 5.495, p = .020, η_p^2 = .02], stress [$F_{(1,312.56)}$ = 5.391, p = .021, η_p^2 = .02], as well as in the DASS total score [$F_{(1,312.56)}$ = 5.271, p = .022, η_p^2 = .02]. Significant effect of state-level negative affectivity on WM performance was observed only for DASS total score [$F_{(1,304.77)}$ = 4.133, p = .043, η_p^2 = .01]. For depression it was observed on a trend level [$F_{(1,294.39)}$ = 3.194, p = .075, η_p^2 = .01], while the effects of anxiety [$F_{(1,370.14)}$ = 1.494, p = .222] and stress were not observed [$F_{(1,282.81)}$ = 2.126, p = .146]. In neither case, significant STIMULATION X NEGATIVE EMOTION interaction were observed [depression $F_{(1,314.14)}$ = 0.648, p = .421, anxiety $F_{(1,315.35)}$ = 1.027, p = .312, stress $F_{(1,313.40)}$ = 0.237, p = .627, DASS total score $F_{(1,313.89)}$ = 0.006, p = .937].

In the trait level analysis, introducing individual differences, i.e., average scores in depression [$F_{(1,313)}$ = 0.724, p = .396], anxiety [$F_{(1,313)}$ = 0.000, p = .0.988], stress [$F_{(1,313)}$ = 1.396, p = .238], as well as in the DASS total score [$F_{(1,313)}$ = 0.732, p = .393] to the model led to the complete abolishment of the tDCS effects on WM performance. Significant effects of trait-level negative affectivity on WM performance were observed for depression [$F_{(1,62.54)}$ = 4.517, p = .038, η_p^2 = .07], anxiety [$F_{(1,62.56)}$ = 7.061, p = .010, η_p^2 = .10], stress [$F_{(1,62.60)}$ = 9.516, p = .003, η_p^2 = .13], as well as DASS total score [$F_{(1,62.61)}$ = 9.819, p = .003, η_p^2 = .14]. Significant STIMULATION X NEGATIVE EMOTION interactions were observed for anxiety [$F_{(1,313)}$ = 8.111, p = .005, η_p^2 = .03], stress [$F_{(1,313)}$ = 10.672, p = .001, η_p^2 = .03], and DASS total score [$F_{(1,313)}$ = 10.085, p = .002, η_p^2 = .03], while a strong trend level was found for STIMULATION X depression interaction [$F_{(1,313)}$ = 3.588, p = .059, η_p^2 = .01]. In other words, trait-level negative affectivity moderated the effects of active tDCS on WM performance. For each negative emotion, significant Holm corrected tDCS effects were observed for mid and higher, but not lower levels of trait [depression: mid t(313) = 2.293, p = .045, higher t(313) = 2.961, p = .010; anxiety: mid t(313) = 2.310, p = .043, higher t(313) = 3.647, p < .001; stress: mid t(313) = 2.319, p = .042, higher t(313) = 3.950, p < .001; DASS total score: mid t(313) = 2.317, p = .042, higher t(313) = 3.884, p < .001].

To account for methodological heterogeneity of the analyzed experiments, a series of LMMs was performed, which, in addition to STIMULATION and NEGATIVE EMOTION, included factors TASK, LATERALITY, and TYPE OF PROTOCOL (Tables S2 and S3 in the Supplement). The overall pattern of results remained consistent – tDCS effects on WM were not moderated by state-level negative affectivity, but the moderation effects were observed on the trait level. TASK, LATERALITY, and TYPE OF PROTOCOL did not emerge as additional moderators of tDCS x negative affectivity interaction.

Associative memory

After pooling together data from three AM experiments, a significant overall STIMULATION effect on AM was observed [$F_{(1,80)}$ = 15.817, p < .001, η_p^2 = .17]. Initial tDCS effects on AM performance remained significant after introducing state-level negative affectivity to the model, i.e., active-to-sham tDCS differences in depression [$F_{(1,79)}$ = 12.857, p = .001, η_p^2 = .14], anxiety [$F_{(1,79)}$ = 15.619, p < .001, η_p^2 = .17], stress [$F_{(1,79)}$ = 15.620, p < .001, η_p^2 = .17], as well as DASS total score [$F_{(1,79)}$ = 15.306, p < .001, η_p^2 = .16]. In neither case, significant main effect of state-level negative affectivity domains was observed [depression $F_{(1,79)}$ = 0.021, p = .885; anxiety $F_{(1,79)}$ = 0.338, p = .562; stress $F_{(1,79)}$ = 0.814, p = .370; DASS total score $F_{(1,79)}$ = 0.364, p = .548]. In addition, no STIMULATION X NEGATIVE EMOTION interactions were observed [depression $F_{(1,79)}$ = 1.883, p = .174; anxiety $F_{(1,79)}$ = 0.005, p = .947; stress $F_{(1,79)}$ = 0.078, p = .781; DASS total score $F_{(1,79)}$ = 0.116, p = .735].

In a trait-level analysis, initial tDCS effects on AM performance remained significant after including individual differences in depression [$F_{(1,79)}$ = 10.977, p = .001, η_p^2 = .12], anxiety [$F_{(1,79)}$ = 9.129, p = .003, η_p^2 = .10], stress [$F_{(1,79)}$ = 8.878, p = .004, η_p^2 = .10], as well as DASS total score [$F_{(1,79)}$ = 8.297, p = .005, η_p^2 = .10] to the model. In neither case, significant main effect of trait-level negative affect was observed [depression $F_{(1,79)}$ = 0.380, p = .539; anxiety $F_{(1,79)}$ = 0.621, p = .433; stress $F_{(1,79)}$ = 1.663, p = .201; DASS total score $F_{(1,79)}$ = 1.186, p = .279]. No significant STIMULATION X NEGATIVE EMOTION interactions were observed [depression $F_{(1,79)}$ = 0.132, p = .718; anxiety $F_{(1,79)}$ = 0.052, p = .819; stress $F_{(1,79)}$ = 0.512, p = .476; DASS total score $F_{(1,79)}$ = 0.159, p = .692].

To account for methodological variability across the included experiments, we applied a series of LMMs that incorporated not only STIMULATION and NEGATIVE EMOTION, but also TASK, LATERALITY, and TYPE OF PROTOCOL (Tables S4, S5, and S6 in the Supplement). Although some multifactor interactions emerged, the overall findings remained consistent – the initial effects of tDCS on AM were robust and unaffected by either state- or trait-level negative affectivity.

Discussion

Building on growing evidence of high inter- and intra-individual variability in neuromodulatory tDCS effects, in this study we explored the interaction between cognitive and affective processes as a potential source of variability in memory-related tDCS outcomes. By pooling data from multiple tDCS experiments, we demonstrated that in healthy participants, stable emotional traits, but not transient fluctuations in emotional states,

moderate the effects of tDCS on WM. Conversely, the effects of tDCS on AM proved to be robust, remaining unaffected by negative emotional states at both state and trait level.

The study addresses an underexplored area in tDCS research, with findings that both align with and extend previous work suggesting that **e**motional factors may shape the neuromodulatory effects of tDCS (for review see [46]), particularly in tasks that rely heavily on attentional and executive control processes. Recent meta-analytic findings have shown that the effects of prefrontal tDCS are significantly moderated by mood, with individuals with higher depressive symptoms experiencing greater benefits in executive functioning from tDCS application [45]. Moreover, the affective-state dependency framework [46] has been proposed as a promising approach to disentangle the dynamic relationships between emotional state, cortical excitability, and cognitive functions. Still, this framework remains largely unexplored and mostly based on indirect evidence, e.g., studies showing differential tDCS effects on emotionally charged stimuli [50], differential tDCS effects in different experimentally-induced emotional states such as high/low stress [51] or anger [52], and the relationship between emotion-regulation strategies and cognitive tDCS effects [53]. Only a few studies assessed the relationship between individual differences in emotions and cognitive tDCS effects. Namely, Esposito et al [54,55] found that responsiveness to tDCS varies depending on the trait and state anxiety levels, while another study found the effects of trait anxiety [56]. Still, the role of other negative emotions beyond anxiety remains unexplored. It is plausible that trait-level affectivity shapes the baseline configuration and variability of cortical network activations that underlie an individual cognitive response within a homeostatic neural space, while momentary emotional states may act as narrow modulators of activity within this dynamic framework. Furthermore, it remains unclear whether affective modulation of cognitive tDCS effects is driven primarily by within-person fluctuations in emotional state or by more stable, trait-like emotional characteristics.

Our data provide evidence in favor of the latter as tDCS effects on WM are shown to be sensitive to trait-level negative affectivity rather than state-level variations. This supports the hypothesis that stable emotional traits, rather than temporary emotional states, might shape cortical susceptibility to tDCS in neurotypical adults. To the best of our knowledge, only one study explored the role of relatively stable traits (e.g., proneness to experiencing negative emotions) in the context of responsiveness to tDCS [57], however, that study's findings are less robust due to a very small sample size. Consistent with a large body of literature [58,59], our data show that negative emotions exhibit considerable stability in young, healthy participants, with the majority of variance in negative affectivity, on average,

being attributable to stable individual differences rather than transient emotional states. The finding aligns with trait-based models of negative affectivity [38]. This study, using psychometrics to disaggregate variance sources, adds empirical weight to the idea of trait-based susceptibility to tDCS.

Furthermore, we found that stable individual differences in experiencing negative emotions have a differential effect on WM and AM performance. While the cognitive performance that is heavily reliant on executive control processes, such as WM, was consistently and negatively associated with trait-level negative affectivity, this was not the case for associative binding. In contrast, state-level fluctuations in negative emotions were not consistently related to tDCS-induced changes in cognitive performance, for either WM or AM. Thus, only trait-like dispositions toward experiencing negative emotions emerged as significant moderators of tDCS effects, and only on WM. Specifically, individuals with moderate and higher trait levels of depression, anxiety, and stress showed greater improvements in WM performance following tDCS. On the other hand, tDCS appeared to be ineffective in modulating WM in individuals with low levels of negative affectivity, at least with the stimulation settings used in these experiments. These findings could reflect that trait-level negative affectivity is associated with different baseline cortical excitability states in prefrontal regions involved in the WM task. Individuals with higher trait anxiety or stress may present a modified inhibitory tone, potentially enhancing the responsiveness of prefrontal circuits to neuromodulatory input [60]. Anticipatory anxiety has been shown to alter cortico-spinal excitability evaluated with transcranial magnetic stimulation [61], further supporting the link between affective states and cortical excitability levels. Moreover, a recent work [62] explored the impact of trait anxiety on motor cortical activities using EEG measures. They found that individuals with high trait anxiety had an altered cortical excitability, suggesting that trait anxiety negatively modulates motor cortical activity.

Taken together, our results suggest that the effects of tDCS on WM processes are influenced by the degree of interference arising from emotional dysregulation. Specifically, tDCS appears to have greater modulatory potential in individuals with less efficient emotional regulation. This may suggest that higher levels of negative affectivity contribute to suboptimal cognitive performance, leaving thus a room for improvement by tDCS. Conversely, people with lower levels of trait negative affectivity demonstrated reduced responsiveness to stimulation, suggesting that already optimal cognitive functioning in emotionally stable individuals limits tDCS enhancing potential. Besides influencing psychological processes at the behavioral level, emotional traits also shape underlying

neurophysiological variability [63]. Cortical activity in individuals with high negative affectivity is associated with altered functional connectivity and neural responses in prefrontal and parietal cortices [40,44]. This suggests a potential pathway by which emotional traits may influence baseline cortical excitability, which tDCS interacts with to produce varied outcomes.

Moreover, although not directly investigated in this study, our results draw attention to the possibility that some of the cognitive effects reported in the tDCS literature may be either hindered or enhanced through the concurrent neuromodulation of emotional control/processing systems. In one respect, modulation of key nodes within the central executive network is likely to influence not only cognitive functions per se, but also emotional regulation, and vice versa. However, more importantly, a strong modulatory effect on negative affectivity, especially depression, has already been established for DLPFC stimulation and has been harnessed in treatment applications for depression and other conditions associated with negative affectivity [64,65]. The latter issue may not be obvious in neurotypical individuals but can still exert a subtle impact on the results of brain stimulation studies on memory and other cognitive functions.

Interestingly, AM performance was not significantly related to state nor trait negative affectivity and demonstrated robust and consistent enhancement following tDCS. This dissociation possibly stems from differences between AM and WM at both the neural and cognitive levels. Namely, both WM and emotional regulation rely heavily on the top-down control mechanisms of the central executive network. Cognitive performance in attention/resources-demanding WM tasks is particularly influenced by a person's ability to suppress affective interference. In contrast, AM depends more on the hippocampal-cortical pathways, with critical contribution of the PPC, making it less vulnerable to emotional interference and less affected by the competition between emotional and cognitive processes for limited neural resources.

Together, these findings underscore the significance of task- and person-specific factors in determining the efficacy of tDCS interventions. While WM performance is susceptible to modulation by trait negative affectivity, improvement in AM performance was robust to state and trait level variability in negative emotions. Moreover, it seems that tDCS, in the present work, have limited potential in modulating attention-dependent cognitive processes in emotionally stable individuals who perform at their optimal level.

While our findings offer valuable insights into the interplay of emotions and cognitive tDCS effects, several limitations should be noted. First, we included only studies with healthy

young adult participants who are expected to show relatively restricted variability in emotional state. It remains an open question whether these findings would be replicated in populations where both cognitive performance and emotional states vary more substantially, such as an aging population or clinical groups. Next, to achieve the equivalence of assessment tools, we used data from the same instrument (i.e., DASS-21) to extract measures of both trait- and state-like negative affectivity. However, this approach also holds its limitations, since there is a certain amount of shared method variance between the measures. Additionally, measures of negative affectivity were collected at two or three time points within a relatively short interval of several weeks. A greater number of assessment points over a longer period would allow for a more reliable estimation of stable individual differences, reducing the influence of transient state-related fluctuations in this measure. In addition, we did not have data to test potential interactions between DLPFC stimulation, negative affectivity, and AM performance. Finally, all experiments were designed as a single-session protocol, yet, to fully capture the interplay between emotional state and tDCS-related cognitive effects, a longitudinal study would offer better insight into the potential interaction of emotional fluctuations within each person and tDCS-related cognitive outcomes. Nonetheless, the use of six distinct experiments, unified by affective measures, provides a robust foundation for the present moderation analyses.

Conclusion

The present results show that negative trait-level affectivity significantly moderates the effects of tDCS on WM performance, whereas variations in negative state-level affectivity do not appear to yield a similar moderating role. These results emphasize the importance of considering individual differences in psychological traits when evaluating the results of tDCS experiments. Negative affective traits, such as depression, anxiety and stress, may affect baseline cortical excitability, which in turn might promote tDCS effectiveness. This work aligns with recent evidence suggesting that psychological traits can shape the variability of tDCS effects. Moreover, these findings offer a promising direction for incorporating assessments of affective traits for future precision-based neuromodulation applications aimed at optimizing cognitive enhancement.

Data Availability Statement: The dataset generated and analyzed for this study is openly available in the Open Science Framework (OSF) repository at:
https://osf.io/g3my7/?view_only=ad99f16b160f4ba9a9480ad0f3e8dddd

Acknowledgement The authors would like to thank the researchers who contributed to the collection of the dataset analyzed in this study: Dunja Paunović, Uroš Konstantinović, Katarina Vulić, Marija Čolić, & Marija Stanković.

Funding: This work was supported by EU-funded HORIZON Collaboration and Support Action TWINNIBS (101059369). MŽ and JB receive institutional support from the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (451-03-137/2025-03/200163; 451-03-136/2025-03/200015). The funding body had no role in the study design, analysis and interpretation of data, writing of the report and decision to submit the article for publication.

Conflict of interest disclosure: Authors have no conflict of interest to disclose.

References

[1] Fertonani A, Miniussi C. Transcranial Electrical Stimulation: What We Know and Do Not Know About Mechanisms. The Neuroscientist 2017;23:109–23. https://doi.org/10.1177/1073858416631966.

[2] Woods AJ, Antal A, Bikson M, Boggio PS, Brunoni AR, Celnik P, et al. A technical guide to tDCS, and related non-invasive brain stimulation tools. Clin Neurophysiol 2016;127:1031–48. https://doi.org/10.1016/j.clinph.2015.11.012.

[3] Antal A, Alekseichuk I, Bikson M, Brockmöller J, Brunoni AR, Chen R, et al. Low intensity transcranial electric stimulation: Safety, ethical, legal regulatory and application guidelines. Clin Neurophysiol 2017;128:1774–809. https://doi.org/10.1016/j.clinph.2017.06.001.

[4] Coffman BA, Trumbo MC, Clark VP. Enhancement of object detection with transcranial direct current stimulation is associated with increased attention. BMC Neurosci 2012;13:108. https://doi.org/10.1186/1471-2202-13-108.

[5] Lo O, Van Donkelaar P, Chou L. Effects of transcranial direct current stimulation over right posterior parietal cortex on attention function in healthy young adults. Eur J Neurosci 2019;49:1623–31. https://doi.org/10.1111/ejn.14349.

[6] Narmashiri A, Akbari F. The Effects of Transcranial Direct Current Stimulation (tDCS) on the Cognitive Functions: A Systematic Review and Meta-analysis. Neuropsychol Rev 2025;35:126–52. https://doi.org/10.1007/s11065-023-09627-x.

[7] Bjekić J, Živanović M, Filipović SR. Transcranial Direct Current Stimulation (tDCS) for Memory Enhancement. J Vis Exp 2021:62681. https://doi.org/10.3791/62681.

[8] Javadi AH, Cheng P. Transcranial Direct Current Stimulation (tDCS) Enhances Reconsolidation of Long-Term Memory. Brain Stimulat 2013;6:668–74. https://doi.org/10.1016/j.brs.2012.10.007.

[9] Horvath JC, Forte JD, Carter O. Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: A systematic review. Neuropsychologia 2015;66:213–36. https://doi.org/10.1016/j.neuropsychologia.2014.11.021.

[10] De Boer NS, Schluter RS, Daams JG, Van Der Werf YD, Goudriaan AE, Van Holst RJ. The effect of non-invasive brain stimulation on executive functioning in healthy controls: A systematic review and meta-analysis. Neurosci Biobehav Rev 2021;125:122–47. https://doi.org/10.1016/j.neubiorev.2021.01.013.

[11] Dedoncker J, Brunoni AR, Baeken C, Vanderhasselt M-A. The effect of the interval-between-sessions on prefrontal transcranial direct current stimulation (tDCS) on cognitive outcomes: a systematic review and meta-analysis. J Neural Transm 2016;123:1159–72. https://doi.org/10.1007/s00702-016-1558-x.

[12] Imburgio MJ, Orr JM. Effects of prefrontal tDCS on executive function: Methodological considerations revealed by meta-analysis. Neuropsychologia 2018;117:156–66. https://doi.org/10.1016/j.neuropsychologia.2018.04.022.

[13] Conway ARA, Kane MJ, Engle RW. Working memory capacity and its relation to general intelligence. Trends Cogn Sci 2003;7:547–52. https://doi.org/10.1016/j.tics.2003.10.005.

[14] Old SR, Naveh-Benjamin M. Differential effects of age on item and associative measures of memory: A meta-analysis. Psychol Aging 2008;23:104–18. https://doi.org/10.1037/0882-7974.23.1.104.
[15] Baddeley A. Working Memory. Science 1992;255:556–9. https://doi.org/10.1126/science.1736359.
[16] Konkel A. Relational memory and the hippocampus: Representations and methods. Front Neurosci 2009;3:166–74. https://doi.org/10.3389/neuro.01.023.2009.
[17] Fregni F, Boggio PS, Nitsche M, Bermpohl F, Antal A, Feredoes E, et al. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. Exp Brain Res 2005;166:23–30. https://doi.org/10.1007/s00221-005-2334-6.
[18] Mancuso LE, Ilieva IP, Hamilton RH, Farah MJ. Does Transcranial Direct Current Stimulation Improve Healthy Working Memory?: A Meta-analytic Review. J Cogn Neurosci 2016;28:1063–89. https://doi.org/10.1162/jocn_a_00956.
[19] Wischnewski M, Mantell KE, Opitz A. Identifying regions in prefrontal cortex related to working memory improvement: A novel meta-analytic method using electric field modeling. Neurosci Biobehav Rev 2021;130:147–61. https://doi.org/10.1016/j.neubiorev.2021.08.017.
[20] Leshikar ED, Leach RC, McCurdy MP, Trumbo MC, Sklenar AM, Frankenstein AN, et al. Transcranial direct current stimulation of dorsolateral prefrontal cortex during encoding improves recall but not recognition memory. Neuropsychologia 2017;106:390–7. https://doi.org/10.1016/j.neuropsychologia.2017.10.022.
[21] Matzen LE, Trumbo MC, Leach RC, Leshikar ED. Effects of non-invasive brain stimulation on associative memory. Brain Res 2015;1624:286–96. https://doi.org/10.1016/j.brainres.2015.07.036.
[22] Lara GAD, Knechtges PN, Paulus W, Antal A. Anodal tDCS Over the Left DLPFC Did Not Affect the Encoding and Retrieval of Verbal Declarative Information. Front Neurosci 2017;11:452. https://doi.org/10.3389/fnins.2017.00452.
[23] Moseley P, Mitrenga KJ, Ellison A, Fernyhough C. Investigating the roles of medial prefrontal and superior temporal cortex in source monitoring. Neuropsychologia 2018;120:113–23. https://doi.org/10.1016/j.neuropsychologia.2018.10.001.
[24] Galli G, Vadillo MA, Sirota M, Feurra M, Medvedeva A. A systematic review and meta-analysis of the effects of transcranial direct current stimulation (tDCS) on episodic memory. Brain Stimulat 2019;12:231–41. https://doi.org/10.1016/j.brs.2018.11.008.
[25] Bjekić J, Manojlović M, Filipović SR. Transcranial Electrical Stimulation for Associative Memory Enhancement: State-of-the-Art from Basic to Clinical Research. Life 2023;13:1125. https://doi.org/10.3390/life13051125.
[26] Chew T, Ho K-A, Loo CK. Inter- and Intra-individual Variability in Response to Transcranial Direct Current Stimulation (tDCS) at Varying Current Intensities. Brain Stimulat 2015;8:1130–7. https://doi.org/10.1016/j.brs.2015.07.031.
[27] Datta A, Bikson M, Fregni F. Transcranial direct current stimulation in patients with skull defects and skull plates: High-resolution computational FEM study of factors altering cortical current flow. NeuroImage 2010;52:1268–78. https://doi.org/10.1016/j.neuroimage.2010.04.252.
[28] Jamil A, Nitsche MA. What Effect Does tDCS Have on the Brain? Basic Physiology of tDCS. Curr Behav Neurosci Rep 2017;4:331–40. https://doi.org/10.1007/s40473-017-0134-5.
[29] Teo JTH, Bentley G, Lawrence P, Soltesz F, Miller S, Willé D, et al. Late cortical plasticity in motor and auditory cortex: role of met-allele in BDNF Val66Met polymorphism. Int J Neuropsychopharmacol 2014;17:705–13. https://doi.org/10.1017/S1461145713001636.
[30] Kuo M-F, Paulus W, Nitsche MA. Sex differences in cortical neuroplasticity in humans. NeuroReport 2006;17:1703–7. https://doi.org/10.1097/01.wnr.0000239955.68319.c2.
[31] Bortoletto M, Pellicciari MC, Rodella C, Miniussi C. The Interaction With Task-induced Activity is More Important Than Polarization: A tDCS Study. Brain Stimulat 2015;8:269–76. https://doi.org/10.1016/j.brs.2014.11.006.
[32] Benwell CSY, Learmonth G, Miniussi C, Harvey M, Thut G. Non-linear effects of transcranial direct current stimulation as a function of individual baseline performance: Evidence from biparietal tDCS influence on lateralized attention bias. Cortex 2015;69:152–65. https://doi.org/10.1016/j.cortex.2015.05.007.

[33] Živanović M, Bjekić J, Konstantinović U, Filipović SR. Effects of online parietal transcranial electric stimulation on associative memory: a direct comparison between tDCS, theta tACS, and theta-oscillatory tDCS. Sci Rep 2022;12:14091. https://doi.org/10.1038/s41598-022-18376-5.
[34] Turi Z, Bjørkedal E, Gunkel L, Antal A, Paulus W, Mittner M. Evidence for Cognitive Placebo and Nocebo Effects in Healthy Individuals. Sci Rep 2018;8:17443. https://doi.org/10.1038/s41598-018-35124-w.
[35] Rabipour S, Wu AD, Davidson PSR, Iacoboni M. Expectations may influence the effects of transcranial direct current stimulation. Neuropsychologia 2018;119:524–34. https://doi.org/10.1016/j.neuropsychologia.2018.09.005.
[36] Vergallito A, Feroldi S, Pisoni A, Romero Lauro LJ. Inter-Individual Variability in tDCS Effects: A Narrative Review on the Contribution of Stable, Variable, and Contextual Factors. Brain Sci 2022;12:522. https://doi.org/10.3390/brainsci12050522.
[37] Farhat LC, Carvalho AF, Solmi M, Brunoni AR. Evidence-based umbrella review of cognitive effects of prefrontal tDCS. Soc Cogn Affect Neurosci 2022;17:43–60. https://doi.org/10.1093/scan/nsaa084.
[38] Watson D, Clark LA. Negative affectivity: The disposition to experience aversive emotional states. Psychol Bull 1984;96:465–90. https://doi.org/10.1037/0033-2909.96.3.465.
[39] Carvalho JO, Ready RE. Emotion and executive functioning: The effect of normal mood states on fluency tasks. J Clin Exp Neuropsychol 2010;32:225–30. https://doi.org/10.1080/13803390902902458.
[40] Crocker LD, Heller W, Spielberg JM, Warren SL, Bredemeier K, Sutton BP, et al. Neural Mechanisms of Attentional Control Differentiate Trait and State Negative Affect. Front Psychol 2012;3. https://doi.org/10.3389/fpsyg.2012.00298.
[41] Moran TP. Anxiety and working memory capacity: A meta-analysis and narrative review. Psychol Bull 2016;142:831–64. https://doi.org/10.1037/bul0000051.
[42] Park J, Banaji MR. Mood and heuristics: The influence of happy and sad states on sensitivity and bias in stereotyping. J Pers Soc Psychol 2000;78:1005–23. https://doi.org/10.1037/0022-3514.78.6.1005.
[43] Pessoa L. On the relationship between emotion and cognition. Nat Rev Neurosci 2008;9:148–58. https://doi.org/10.1038/nrn2317.
[44] Dark HE, Harnett NG, Goodman AM, Wheelock MD, Mrug S, Schuster MA, et al. Violence exposure, affective style, and stress-induced changes in resting state functional connectivity. Cogn Affect Behav Neurosci 2020;20:1261–77. https://doi.org/10.3758/s13415-020-00833-1.
[45] Di Rosa E, Masina F, Pastorino A, Galletti E, Gambarota F, Altoè G, et al. Mood moderates the effects of prefrontal tDCS on executive functions: A meta-analysis testing the affective state-dependency hypothesis. J Affect Disord 2024;351:920–30. https://doi.org/10.1016/j.jad.2024.02.009.
[46] Schutter DJLG, Smits F, Klaus J. Mind matters: A narrative review on affective state-dependency in non-invasive brain stimulation. Int J Clin Health Psychol 2023;23:100378. https://doi.org/10.1016/j.ijchp.2023.100378.
[47] Bjekić J, Čolić MV, Živanović M, Milanović SD, Filipović SR. Transcranial direct current stimulation (tDCS) over parietal cortex improves associative memory. Neurobiol Learn Mem 2019;157:114–20. https://doi.org/10.1016/j.nlm.2018.12.007.
[48] Živanović M, Paunović D, Konstantinović U, Vulić K, Bjekić J, Filipović SR. The effects of offline and online prefrontal vs parietal transcranial direct current stimulation (tDCS) on verbal and spatial working memory. Neurobiol Learn Mem 2021;179:107398. https://doi.org/10.1016/j.nlm.2021.107398.
[49] Lovibond SH, Lovibond PF. Manual for the Depression Anxiety Stress Scales. 2nd Edition. Sydney: Psychology Foundation; 1995.
[50] Abend R, Sar-el R, Gonen T, Jalon I, Vaisvaser S, Bar-Haim Y, et al. Modulating Emotional Experience Using Electrical Stimulation of the Medial-Prefrontal Cortex: A Preliminary tDCS-fMRI Study. Neuromodulation Technol Neural Interface 2019;22:884–93. https://doi.org/10.1111/ner.12787.

[51] Ankri YLE, Braw Y, Luboshits G, Meiron O. The effects of stress and transcranial direct current stimulation (tDCS) on working memory: A randomized controlled trial. Cogn Affect Behav Neurosci 2020;20:103–14. https://doi.org/10.3758/s13415-019-00755-7.
[52] Hortensius R, Schutter DJLG, Harmon-Jones E. When anger leads to aggression: induction of relative left frontal cortical activity with transcranial direct current stimulation increases the anger–aggression relationship. Soc Cogn Affect Neurosci 2012;7:342–7. https://doi.org/10.1093/scan/nsr012.
[53] Gilam G, Abend R, Gurevitch G, Erdman A, Baker H, Ben-Zion Z, et al. Attenuating anger and aggression with neuromodulation of the vmPFC: A simultaneous tDCS-fMRI study. Cortex 2018;109:156–70. https://doi.org/10.1016/j.cortex.2018.09.010.
[54] Esposito M, Mauri P, Panizza L, Mazza V, Miniussi C, Brignani D. Baseline levels of alertness influence tES effects along different age-related directions. Neuropsychologia 2021;160:107966. https://doi.org/10.1016/j.neuropsychologia.2021.107966.
[55] Esposito M, Ferrari C, Fracassi C, Miniussi C, Brignani D. Responsiveness to left□prefrontal tDCS varies according to arousal levels. Eur J Neurosci 2022;55:762–77. https://doi.org/10.1111/ejn.15584.
[56] Sagliano L, D'Olimpio F, Izzo L, Trojano L. The effect of bicephalic stimulation of the dorsolateral prefrontal cortex on the attentional bias for threat: A transcranial direct current stimulation study. Cogn Affect Behav Neurosci 2017;17:1048–57. https://doi.org/10.3758/s13415-017-0532-x.
[57] Peña-Gómez C, Vidal-Piñeiro D, Clemente IC, Pascual-Leone Á, Bartrés-Faz D. Down-Regulation of Negative Emotional Processing by Transcranial Direct Current Stimulation: Effects of Personality Characteristics. PLoS ONE 2011;6:e22812. https://doi.org/10.1371/journal.pone.0022812.
[58] Diener E, Larsen RJ. Temporal stability and cross-situational consistency of affective, behavioral, and cognitive responses. J Pers Soc Psychol 1984;47:871–83. https://doi.org/10.1037/0022-3514.47.4.871.
[59] Diener E, Larsen RJ. Temporal Stability and Cross-Situational Consistency of Affective, Behavioral, and Cognitive Responses. In: Diener E, editor. Assess. Well-Being, vol. 39, Dordrecht: Springer Netherlands; 2009, p. 7–24. https://doi.org/10.1007/978-90-481-2354-4_2.
[60] Sarkar A, Dowker A, Cohen Kadosh R. Cognitive Enhancement or Cognitive Cost: Trait-Specific Outcomes of Brain Stimulation in the Case of Mathematics Anxiety. J Neurosci 2014;34:16605–10. https://doi.org/10.1523/JNEUROSCI.3129-14.2014.
[61] Oathes DJ, Bruce JM, Nitschke JB. Worry facilitates corticospinal motor response to transcranial magnetic stimulation. Depress Anxiety 2008;25:969–76. https://doi.org/10.1002/da.20445.
[62] Cheng C-H, Chan P-YS, Chen S-Y, Chen Y-H, Lu H, Liu C-Y. Trait anxiety negatively modulates the coupling of motor event-related desynchronization and event-related synchronization. BMC Psychiatry 2025;25:447. https://doi.org/10.1186/s12888-025-06901-5.
[63] Miniussi C, Pellicciari MC. Learning from missteps: Potential of transcranial electrical stimulation in neuropsychological rehabilitation. J Neuropsychol 2025:jnp.12425. https://doi.org/10.1111/jnp.12425.
[64] Kan RLD, Padberg F, Giron CG, Lin TTZ, Zhang BBB, Brunoni AR, et al. Effects of repetitive transcranial magnetic stimulation of the left dorsolateral prefrontal cortex on symptom domains in neuropsychiatric disorders: a systematic review and cross-diagnostic meta-analysis. Lancet Psychiatry 2023;10:252–9. https://doi.org/10.1016/S2215-0366(23)00026-3.
[65] Zheng EZ, Wong NML, Yang ASY, Lee TMC. Evaluating the effects of tDCS on depressive and anxiety symptoms from a transdiagnostic perspective: a systematic review and meta-analysis of randomized controlled trials. Transl Psychiatry 2024;14:295. https://doi.org/10.1038/s41398-024-03003-w.