

Emotion-Induced Transcranial Direct Current Stimulation for Working Memory Improvement

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Abstract

Objective: To examine the effects of anodal transcranial direct current stimulation (tDCS) on working memory under different emotion-induced states. **Method:** A total of 180 healthy right-handed adults aged 18-35 years were assigned to a 3 (emotion: happy, neutral, sad) × 4 (stimulation: sham, 1.0 mA, 1.5 mA, 2.0 mA) between-subjects design. Emotions were induced by pictures or video clips and verified using the Positive and Negative Affect Schedule (PANAS). Participants completed a letter 2-back task before and after stimulation. Accuracy and correct-trial reaction time were analyzed. **Results:** Baseline accuracy did not differ across emotion conditions, whereas baseline reaction time showed a modest emotion effect. Active anodal tDCS generally increased accuracy and reduced reaction time compared with sham stimulation. Stimulation intensity showed significant main effects on both accuracy change and reaction-time change. Emotion showed a significant main effect on reaction-time change, whereas the emotion-by-intensity interaction was not significant. **Conclusion:** Anodal tDCS may improve working memory across different emotion-induced states. Stimulation intensity appears to be the dominant factor, while emotional state may influence baseline processing speed and the magnitude of behavioral response.

Keywords

Transcranial Direct Current Stimulation; Working Memory; Emotion Induction; PANAS; 2-Back Task

1. Introduction

Working memory is a limited-capacity system that temporarily maintains, updates, and manipulates information, and it provides an important foundation for reasoning, learning, decision-making, and executive control [1,2]. During learning, language comprehension, problem solving, and complex task performance, individuals must continuously match new information to current goals while suppressing interference from irrelevant stimuli. Working memory is therefore both a basic

cognitive capacity and a functional index frequently considered in clinical psychological assessment. Declines in working memory can impair academic and occupational performance and are also observed in clinical or subclinical conditions such as attention-deficit/hyperactivity disorder, mild cognitive impairment, Alzheimer disease, and depression [3-5]. Identifying relatively safe, repeatable, and interpretable methods for modulating working memory therefore has both basic and applied value.

Transcranial direct current stimulation (tDCS) is a noninvasive neuromodulation technique that applies weak direct current through scalp electrodes to alter cortical excitability and brain-network activity [6-9]. In cognitive modulation research, the dorsolateral prefrontal cortex (DLPFC) is an important target for working-memory interventions. Previous studies suggest that anodal stimulation of the DLPFC may improve working-memory accuracy or response speed [10-12]. However, systematic reviews and meta-analyses indicate that the effects of tDCS on working memory are not fully consistent; stimulation intensity, target location, stimulation duration, task difficulty, and individual state may all influence the final outcome [13-17]. These findings suggest that tDCS is not a technique in which a single parameter can reliably produce cognitive enhancement; its behavioral effects must be interpreted in relation to participant state and task context.

State dependence is an important perspective for explaining variability in tDCS effects. The same stimulation protocol may produce different outcomes depending on an individual's current neural, cognitive, or emotional state [18-20]. Emotional state is particularly relevant because emotion can influence working-memory processing through attentional allocation, interference control, motivational salience, and the degree of prefrontal engagement [21-24]. Positive emotion may increase motivation and task engagement, whereas negative emotion may increase distraction or consume cognitive resources. A neutral state, despite lower emotional arousal, does not necessarily represent the optimal working-memory state. If prestimulation emotional state is ignored, differences in tDCS effects may be attributed solely to stimulation intensity while overlooking the participant's initial processing context at task entry.

Based on these considerations, the present study focused on behavioral outcomes and examined the effects of different intensities of anodal tDCS on working memory under happy, neutral, and sad emotion-induction conditions. Rather than using engineering-oriented online recognition or complex composite indices, PANAS was used as a manipulation check for emotion induction, and 2-back accuracy and correct-trial reaction time were used as the primary outcome measures. This design addresses questions central to clinical psychology and cognitive-intervention research: whether tDCS can improve working memory under different emotional states, whether improvement is reflected mainly in accuracy or response speed, and whether different stimulation intensities show consistent effects. We hypothesized

that active anodal tDCS would improve working-memory performance relative to sham stimulation and that emotional state might influence prestimulation performance and poststimulation changes in response speed.

2. Participants and Methods

2.1. Participants

A total of 180 healthy right-handed adults aged 18-35 years were recruited (mean age = 23 years, SD = 4 years). All participants completed a screening questionnaire before enrollment. Exclusion criteria included a history of neurological or psychiatric disorders, current use of psychoactive medication, metallic implants in the head, a history of epilepsy, severe sleep deprivation, or other conditions making transcranial electrical stimulation unsuitable. The study used a 3 (emotion: happy, neutral, sad) $\times$ 4 (stimulation intensity: sham, 1.0 mA, 1.5 mA, 2.0 mA) between-subjects design, yielding 12 experimental groups. Participants were randomly assigned to groups. The study was approved by the Human Research Ethics Committee of Qingdao University, and all participants provided written informed consent.

2.2. Experimental Design and Procedure

A single-blind, sham-controlled design was used. Participants did not know whether they were receiving active or sham stimulation. The procedure comprised enrollment screening, pre-induction PANAS assessment, emotion induction, post-induction PANAS assessment, a prestimulation 2-back task, tDCS or sham stimulation, a poststimulation 2-back task, and an adverse-event inquiry. To reduce the influence of order and learning effects on interpretation, all participants completed the same sequence and the task structure was identical before and after stimulation. The primary analysis compared poststimulation with prestimulation behavior; thus, each participant's change score reflected short-term modulation under the same emotional background and stimulation condition.

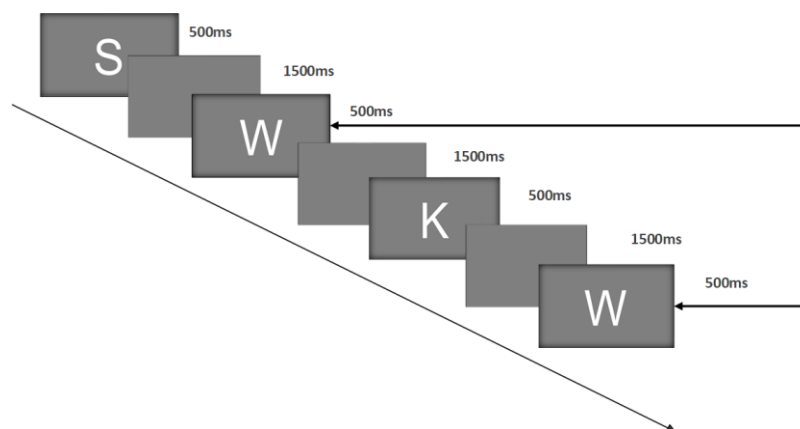


Figure 1. Flowchart of the 2-back task.

2.3. Emotion Induction and PANAS Manipulation Check

Before each experiment, the target emotional state was specified according to group assignment. Emotion induction used standardized emotional pictures or short video clips for approximately 10 min. The happy condition presented positive emotional materials, the sad condition presented negative emotional materials, and the neutral condition presented low-arousal neutral materials. During induction, participants were instructed to maintain attention and immerse themselves in the material as much as possible.

To determine whether emotion induction achieved the intended effect, the Positive and Negative Affect Schedule (PANAS) was used as a manipulation-check measure. PANAS contains positive-affect and negative-affect subscales and can be used to assess participants' current emotional experience [25,26]. Participants completed PANAS before and after emotion induction. Successful induction in the happy condition was defined by an increase in positive-affect scores without a marked increase in negative affect; the sad condition was characterized by increased negative affect or decreased positive affect; and the neutral condition was expected to show no clear shift in either positive or negative affect. The purpose of the PANAS manipulation check was to confirm that participants entered the subsequent working-memory task under the intended emotional background, rather than to construct an additional emotion-classification model.

2.4. tDCS Protocol

tDCS was delivered using the Starstim 32 tES system and controlled with the accompanying software. A bipolar montage was used, with two Ag/AgCl electrodes fixed in an elastic cap according to the international 10-20 system. F3 served as the anode and F4 as the cathode, targeting prefrontal regions associated with the DLPFC. Active-stimulation groups received 1.0, 1.5, or 2.0 mA anodal tDCS for 20 min, with 30-s ramp-up and 30-s ramp-down periods at the beginning and end. In the sham group, only brief ramp-up and ramp-down were delivered at the beginning to mimic the initial skin sensations of active stimulation; no sustained current was delivered during the remaining period. Electrode impedance was continuously monitored, and stimulation was automatically terminated if impedance exceeded 10 k Ω . After stimulation, participants were asked about headache, tingling, burning, itching, and other adverse sensations; no obvious discomfort was reported in the original experiment.

2.5. Working-Memory Task and Statistical Analysis

Working-memory performance was assessed with a letter 2-back task. Letter stimuli were presented sequentially, and participants judged whether the current letter matched the stimulus presented two positions earlier. This task requires continuous maintenance and updating of short-term information and is commonly used to

assess working memory and prefrontal executive control [27,28]. Participants completed one 2-back task before stimulation, received active or sham stimulation, and then completed the same type of task after stimulation. The primary measures were accuracy and reaction time on correct trials. Accuracy change (Δ accuracy = poststimulation accuracy - prestimulation accuracy) and reaction-time change (Δ RT = poststimulation correct-trial reaction time - prestimulation correct-trial reaction time) were used as outcome measures; a negative Δ RT indicates faster responding. Statistical analysis first tested prestimulation baseline differences in accuracy and reaction time among the three emotion conditions. Within the happy, neutral, and sad conditions, the effects of stimulation intensity on Δ accuracy and Δ RT were then compared. A two-factor analysis of variance was further used to test the main effects of emotion and stimulation intensity and their interaction. Statistical results are reported as F values, P values, and partial η^2 .

Table 1. Experimental design and main procedures.

Item	Setting	Time/Metric	Description
Emotion condition	Happy, neutral, sad	~10 min induction	PANAS before and after induction
Stimulation condition	Sham, 1.0, 1.5, 2.0 mA	20 min	Active stimulation included ramp-up/ramp-down
Stimulation target	F3 anode, F4 cathode	Impedance < 10 k Ω	DLPPFC-related region
Task measure	Letter 2-back	Pre- and poststimulation	Accuracy and correct-trial RT

3. Results

3.1. Emotion Manipulation Check and Baseline Performance

PANAS results showed that the direction of post-induction emotional change in the happy, neutral, and sad conditions was consistent with the prespecified targets, indicating that emotion induction generally met the experimental requirements. The happy condition was characterized mainly by increased positive-affect scores, the sad condition by increased negative-affect scores or decreased positive-affect scores, and the neutral condition by no obvious positive or negative shift. These results indicate that the subsequent stimulation and working-memory tasks were completed under the intended emotional backgrounds.

In the prestimulation 2-back task, baseline accuracy did not differ significantly among the three emotion conditions, $F(2,177) = 0.049$, $P = 0.952$, $\eta^2 = 0.001$. Accuracy in the happy, neutral, and sad conditions was $M = 0.699$, $SD = 0.103$; $M = 0.701$, $SD = 0.134$; and $M = 0.694$, $SD = 0.116$, respectively. Correct-trial reaction time showed a modest emotion effect, $F(2,177) = 3.279$, $P = 0.040$, $\eta^2 = 0.036$; mean reaction times were $M = 529.1$ ms, $SD = 143.7$; $M = 568.4$ ms, $SD = 190.4$; and $M = 492.4$ ms, $SD = 149.9$, respectively. Thus, emotion induction did not significantly alter initial accuracy but may have influenced prestimulation processing speed.

3.2. Effects of tDCS on Working Memory under Different Emotional States

In the happy condition, active anodal tDCS at 1.0-2.0 mA produced greater

improvement than sham stimulation. Accuracy in the active-stimulation groups increased by approximately 15.3-18.1 percentage points, and reaction time decreased by approximately 167-216 ms; the sham group showed smaller changes. One-way analysis of variance indicated significant effects of stimulation intensity on both Δ accuracy and Δ RT, suggesting that active stimulation produced relatively stable improvements in task performance under a happy emotional background, with the average improvement being especially pronounced in the 1.5 mA condition.

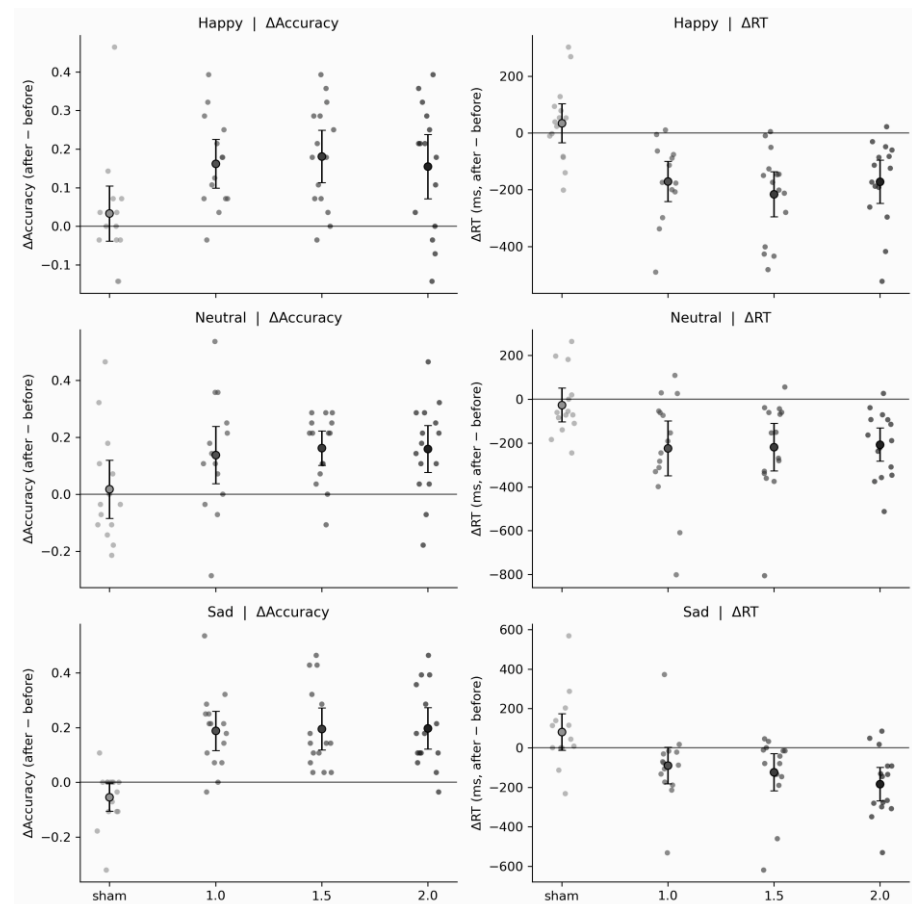


Figure 2. Effects of different tDCS stimulation intensities on changes in working memory under different emotional states.

In the neutral condition, Δ accuracy in the active-stimulation groups was approximately 13.8-16.2 percentage points and Δ RT was approximately -207 to -223 ms. Compared with the happy condition, differences among active intensities were smaller in the neutral condition, showing a relatively plateau-like pattern of improvement. Intensity had a significant effect on Δ RT and a trend-level effect on Δ accuracy, suggesting that under a neutral emotional background, the improvement associated with tDCS was more concentrated in response speed.

In the sad condition, the sham group showed a tendency toward deterioration, with accuracy decreasing by approximately 5.5 percentage points and reaction time

increasing by approximately 82 ms. All active-stimulation groups showed clear improvement, with accuracy increasing by approximately 18.8-19.8 percentage points. Reaction-time reductions were more pronounced at higher intensities, and the 2.0 mA condition showed the largest average decrease. One-way analysis of variance indicated significant effects of intensity on both Δ accuracy and Δ RT, suggesting that active tDCS may exert a more evident protective or compensatory effect on maintaining working-memory performance under a negative emotional background.

Two-factor analysis of variance showed that stimulation intensity was the main factor associated with changes in working memory. For Δ accuracy, the main effect of intensity was significant, $F(3,167) = 14.543$, $P = 1.85 \times 10^{-8}$, $\eta p^2 = 0.207$; the main effect of emotion was not significant, $F(2,167) = 0.146$, $P = 0.864$, $\eta p^2 = 0.002$; and the emotion $\times$ intensity interaction was not significant, $F(6,167) = 0.755$, $P = 0.606$, $\eta p^2 = 0.026$. For Δ RT, the main effect of intensity was significant, $F(3,167) = 15.934$, $P = 3.71 \times 10^{-9}$, $\eta p^2 = 0.223$; the main effect of emotion was also significant, $F(2,167) = 3.972$, $P = 0.0206$, $\eta p^2 = 0.045$; and the interaction was not significant, $F(6,167) = 0.416$, $P = 0.868$, $\eta p^2 = 0.015$. Thus, within the parameter range examined, stimulation intensity had a more stable influence on working-memory improvement, whereas emotion mainly affected the magnitude of response-speed improvement.

Table 2. Main analysis-of-variance results for changes in working-memory performance.

Analysis	Dependent variable	F	P	ηp^2
Intensity effect: happy	Δ accuracy	3.311	0.026	0.151
Intensity effect: happy	Δ RT	8.876	6.62×10^{-5}	0.322
Intensity effect: neutral	Δ accuracy	2.277	0.090	0.110
Intensity effect: neutral	Δ RT	3.408	0.024	0.157
Intensity effect: sad	Δ accuracy	12.311	2.71×10^{-6}	0.397
Intensity effect: sad	Δ RT	5.997	0.00128	0.243
Two-factor intensity main effect	Δ accuracy	14.543	1.85×10^{-8}	0.207
Two-factor intensity main effect	Δ RT	15.934	3.71×10^{-9}	0.223

4. Discussion

4.1. Main Findings

The results showed that under happy, neutral, and sad emotion-induction conditions, active anodal tDCS generally produced greater improvements in working memory than sham stimulation, reflected by increased accuracy and shorter correct-trial reaction times. This pattern is broadly consistent with previous evidence that anodal DLPFC stimulation may improve working memory and executive function [10,13,14,29]. Mechanistically, the prefrontal cortex contributes to the maintenance, updating, and inhibitory control of working-memory information, and anodal tDCS may improve task efficiency by modulating local cortical excitability and associated network activity.

An important finding was that accuracy and reaction time did not fully reflect the

same level of change. Baseline accuracy was similar across the three emotional states, indicating that emotion induction did not create clear initial differences in task correctness; in contrast, baseline reaction time differed, suggesting that processing speed was more sensitive to emotion. A similar pattern appeared after stimulation: stimulation intensity influenced both accuracy and reaction time, whereas emotion mainly influenced changes in reaction time. Accordingly, when interpreting tDCS-related working-memory improvement, reporting both accuracy and response speed is more informative than relying on a single composite measure.

4.2. Role of Emotional State

The two-factor analysis of variance indicated that stimulation intensity was the main factor explaining behavioral change. The main effect of emotion did not significantly influence changes in accuracy but did affect changes in reaction time, suggesting that emotion may act more strongly on processing speed than on accuracy. Baseline results support this interpretation: prestimulation accuracy was similar across the three emotional states, whereas reaction time showed a modest difference. In other words, emotion may first alter the pace of cognitive processing at entry into the stimulation phase and then influence the magnitude of post-tDCS improvement in response speed.

It should be noted that no significant emotion $\times$ stimulation-intensity interaction was observed. The present results therefore do not support the strong conclusion that a particular emotional state necessarily requires a fixed optimal stimulation intensity. A more cautious interpretation is that emotional state represents background and initial-state information in tDCS modulation of working memory. It has some influence on indices such as response speed, but within the parameters examined here, stimulation intensity remained the more prominent and stable behavioral factor.

4.3. Stimulation Intensity and Practical Application

Active stimulation was generally superior to sham stimulation, but the pattern of behavioral improvement across intensities was not identical in the three emotional conditions. In the happy condition, improvement was particularly pronounced at 1.5 mA; in the neutral condition, 1.0-2.0 mA produced a relatively plateau-like pattern; and in the sad condition, higher intensity produced a larger reduction in reaction time. These findings suggest that the cognitive effects of tDCS may be jointly influenced by stimulation parameters and individual state, and that clinical or applied use should not simply assume that higher current necessarily produces better effects.

From an applied perspective, these findings suggest that future tDCS interventions for cognitive enhancement or clinical cognitive rehabilitation should not report only a fixed stimulation protocol; prestimulation emotional state and task baseline

should also be recorded. Among individuals with more pronounced emotional distress or impaired response speed, emotional state may affect the magnitude of the response to stimulation. In future studies involving depression, anxiety, mild cognitive impairment, or related populations, PANAS or other emotion scales may provide a simple state-assessment tool for helping explain individual differences in intervention effects.

4.4. Interpretation of Outcome Measures and Safety Observations

Accuracy and correct-trial reaction time were selected as the primary outcomes because they reflect, respectively, accurate maintenance in the working-memory task and processing efficiency. Increased accuracy indicates more stable maintenance and updating of target information, whereas shorter reaction time indicates less time required to make the same judgment. If stimulation increases speed while clearly sacrificing accuracy, it cannot simply be interpreted as cognitive improvement; conversely, if accuracy increases while responses become substantially slower, a speed-accuracy trade-off may be present. The present study therefore reports both measures and interprets the direction of both when evaluating tDCS effects. Under most active-stimulation conditions, accuracy increased while reaction time decreased, suggesting that the observed improvement was not solely attributable to a speed-accuracy trade-off.

Safety is also an important aspect of tDCS research. In the original experiment, ramp-up and ramp-down procedures were used in all stimulation conditions, impedance was continuously monitored, and participants were asked after stimulation about headache, tingling, burning, itching, and other adverse sensations; no obvious discomfort was reported. This observation supports the acceptability of the 1.0-2.0 mA, 20-min stimulation parameters used here in a healthy young-adult sample. However, safety conclusions should not be generalized directly to all clinical populations. Individuals with neurological disorders, psychiatric disorders, medication use, or severe sleep deprivation still require stricter screening and monitoring in accordance with transcranial electrical-stimulation safety guidelines.

4.5. Methodological Choices and Limitations

The present study used PANAS as a manipulation check for emotion induction while retaining the tDCS protocol and 2-back behavioral outcomes. This approach is more consistent with the reporting style commonly used in Chinese clinical psychology journals. PANAS directly indicates whether emotion induction achieved its intended effect and avoids allowing complex model structures, training parameters, and public-dataset validation to occupy excessive space; accuracy and reaction time are also among the most direct and readily interpretable measures in working-memory tasks. For the current research question, clearly describing the relationship among emotional state, stimulation intensity, and changes in working memory is more

consistent with the main focus of the study than expanding the paper around algorithmic models.

Several limitations should be acknowledged. First, the sample consisted of healthy young adults, and whether the findings generalize to older adults or to clinical populations such as individuals with depression, mild cognitive impairment, or attention-deficit/hyperactivity disorder requires further investigation. Second, emotion induction relied mainly on pictures or short videos and PANAS self-report; although appropriate for a behavioral experiment, continuous physiological measures were not included. Third, the study used a between-subjects design, so uncontrolled individual differences may have remained among stimulation-intensity groups. Fourth, the analysis focused primarily on short-term behavioral changes before and after stimulation and did not examine long-term maintenance effects. Future work could use a more rigorous randomized double-blind crossover design and add follow-up assessments to test the stability of tDCS-related working-memory improvement under different emotional states.

5. Conclusion

Using emotion induction, PANAS manipulation checks, anodal tDCS, and a 2-back task, this study examined stimulation-related modulation of working memory under different emotional states. Active anodal tDCS generally improved working-memory performance relative to sham stimulation, and stimulation intensity was an important factor influencing changes in both accuracy and reaction time. Emotional state was reflected mainly in prestimulation processing speed and in the magnitude of reaction-time improvement. These results support incorporating emotional-state assessment into tDCS interventions for working memory, while the current evidence is better interpreted as an effect of state background rather than as support for fixed stimulation intensities corresponding to specific emotions.

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