# The Causal Role of the Ventromedial Prefrontal Cortex in Implicit Cognitive Reappraisal

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## Abstract

Emotion regulation is crucial for maintaining individual mental health and adapting to social life; however, previous research has primarily focused on explicit emotion regulation, and our current understanding of the cognitive neural mechanisms underlying implicit emotion regulation remains very limited. To identify the core brain regions involved in implicit emotion regulation, this study used a sentence unscrambling task to prime implicit cognitive reappraisal and employed transcranial direct current stimulation (tDCS) to activate the medial prefrontal cortex, particularly the ventromedial prefrontal cortex (vmPFC), to investigate the causal role of this brain region in implicit emotion regulation. The results showed that the vmPFC-activated participant group (experimental group, n = 40) reported less negative emotion when viewing negative images under implicit cognitive reappraisal priming conditions compared to the tDCS sham stimulation group (control group, n = 40), and simultaneously exhibited lower amplitude of the late positive potential (LPP) evoked by negative images (LPP is an objective indicator of emotional experience intensity). Additionally, the experimental group showed lower occipital P1 amplitude when viewing negative images compared to the control group (P1 is an objective indicator of early visual attention allocation). These findings demonstrate that activating the medial prefrontal cortex, represented by vmPFC, not only enhances the effectiveness of implicit emotion regulation but also reduces early attentional allocation to negative stimuli. This study represents the first attempt to use tDCS technology to investigate priming-induced implicit emotion regulation; the findings not only establish the critical role of the medial prefrontal cortex, represented by vmPFC, in implicit cognitive reappraisal but also identify a potential neural modulation target for clinical research aimed at enhancing implicit emotion regulation capacity.

## Full Text

# The Causal Role of the Ventromedial Prefrontal Cortex in Implicit Cognitive Reappraisal

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## Abstract

Emotion regulation is crucial for maintaining individual mental health and adapting to social life. However, previous research has primarily focused on explicit emotion regulation, and our current understanding of the cognitive and neural mechanisms underlying implicit emotion regulation remains very limited. To identify the core brain regions involved in implicit emotion regulation, this study used a sentence unscrambling task to prime implicit cognitive reappraisal and employed transcranial direct current stimulation (tDCS) to activate the medial prefrontal cortex, particularly the ventromedial prefrontal cortex (vmPFC), to investigate the causal role of this brain region in implicit emotion regulation. The results showed that participants in the vmPFC-activated group (experimental group, n = 40) reported less negative emotion when viewing negative pictures under implicit cognitive reappraisal priming conditions compared to the tDCS sham stimulation group (control group, n = 40), and simultaneously exhibited lower amplitudes of the late positive potential (LPP) evoked by negative pictures (LPP is an objective indicator of emotional experience intensity). Additionally, the experimental group showed lower occipital P1 amplitudes when viewing negative pictures compared to the control group (P1 is an objective indicator of early visual attention allocation). These findings demonstrate that activating the medial prefrontal cortex, represented by vmPFC, not only enhances the effectiveness of implicit emotion regulation but also reduces early attention allocation to negative stimuli. This study represents the first attempt to use tDCS technology to investigate priming-induced implicit emotion regulation. The findings not only establish the critical role of the medial prefrontal cortex, represented by vmPFC, in implicit cognitive reappraisal but also identify a potential neural modulation target for clinical research aimed at enhancing implicit emotion regulation capacity.

**Keywords:** ventromedial prefrontal cortex, implicit emotion regulation, transcranial direct current stimulation, priming, cognitive reappraisal

Emotion regulation is essential for maintaining mental health and adapting to social life (Gross & John, 2003). Broadly defined, emotion regulation refers to the process of influencing the generation, experience, and expression of emotion by altering cognition, behavior, and environment during emotional episodes (Gross, 1998). Emotion regulation can be achieved through different methods and various strategies (Braunstein et al., 2017). Previous research has primarily focused on explicit (conscious, deliberate) emotion regulation, whereas recent studies have found that emotion regulation can also operate implicitly (unconsciously), consuming minimal or no cognitive control resources represented by the lateral prefrontal cortex (Gyurak et al., 2011; Koole et al., 2015; Koole & Rothermund, 2011). Implicit emotion regulation can effectively reduce negative emotional experiences and related physiological responses (Li & Yuan, 2018; Mauss et al., 2007; Wang & Li, 2017; Williams et al., 2009; Yang et al., 2015; Yuan et al., 2015a, 2019; Zhang et al., 2020). However, unlike explicit emotion regulation, our current understanding of the cognitive and neural mechanisms underlying implicit emotion regulation remains very limited.

## 2.1 Participants

This study recruited a total of 80 undergraduate and graduate students. All participants were right-handed, had no history of neurological disorders or brain injury, were in good health at the time of participation, and had normal or corrected-to-normal vision. Participants signed informed consent forms before the experiment and received 100 RMB as compensation after completion. The study protocol was approved by the Ethics Committee of Shenzhen University. Based on the effect sizes reported in relevant studies (Abend et al., 2019; Gilam et al., 2018) (mean = 0.24), we used G*Power 3.1.7 to estimate the required sample size ($\alpha = 0.05$, $\beta = 0.95$, ANOVA: repeated measures, within-between interaction). A sample size of 7 participants per group would achieve 80% statistical power. Therefore, the sample size in this study met the requirements.

On the day of the experiment, participants completed the following questionnaires: Beck Depression Inventory Second Edition (BDI-II; Beck et al., 1996), Trait form of Spielberger' s State-Trait Anxiety Inventory (STAI-T; Spielberger et al., 1983), and the cognitive reappraisal subscale of the Emotion Regulation Questionnaire (ERQ-R; Gross & John, 2003). Participants were then randomly assigned to either the anodal stimulation group or the sham stimulation group. Independent samples t-tests revealed no significant differences between the two groups in age, gender, depression level (BDI-II), trait anxiety level (STAI-T), or tendency to use cognitive reappraisal strategies (ERQ-R), as shown in Table 1 .

**Table 1.** Demographic characteristics of the two groups of participants in this study

| Variable | Anodal Stimulation Group (n = 40) | Sham Stimulation Group (n = 40) | Test Statistic |
|---|---|---|---|
| Age | 20.15 ± 0.29 | 19.52 ± 0.30 | t = 1.49, p = 0.139 |
| Gender (female/male) | 20/20 | 20/20 | $^{2}$ = 0.00, p = 1.000 |
| Depression (BDI-II) | 5.58 ± 0.95 | 5.05 ± 0.85 | t = 0.41, p = 0.681 |
| Trait Anxiety (STAI-T) | 40.25 ± 1.50 | 38.18 ± 1.35 | t = 1.03, p = 0.306 |
| Cognitive Reappraisal Frequency (ERQ-R) | 30.38 ± 0.65 | 30.65 ± 0.77 | t = -0.27, p = 0.786 |

*Note: Independent samples t-tests (two-tailed) were used for continuous variables, and chi-square test for gender. Descriptive statistics are presented as M ± SE.*

## 2.2 Experimental Procedure

This study employed a 2 (priming type: cognitive reappraisal/baseline) × 2 (tDCS group: anodal stimulation/sham stimulation) mixed experimental design. Priming type was a within-subject variable, while tDCS group was a between-subject variable.

The main experiment consisted of two blocks, corresponding to the "baseline"and "cognitive reappraisal" priming conditions (see Figure 1 [Figure 1: see original paper]A). The order of the two blocks was counterbalanced across participants, with participants performing an unrelated task for 60 minutes between blocks. Each block comprised two tasks: sentence unscrambling (60 trials) and picture viewing (30 trials). At the beginning of each block, participants received tDCS at an intensity of 1.5 mA (the anodal stimulation group received current for 10 minutes, while the sham stimulation group received current for only 1 minute at the start). The experiment began immediately after tDCS completion. Participants first completed 10 trials of the sentence unscrambling task, followed by 5 trials of the picture viewing task, repeated for 6 cycles. The cognitive reappraisal priming was maintained close to the brief picture viewing task to ensure a strong priming effect.

The sentence unscrambling task was used to prime implicit emotion regulation. In this task (Figure 1B), participants had to select 4 out of 5 scrambled words within 30 seconds to form a grammatically correct sentence (Mauss et al., 2007). Participants used the numeric keypad to enter the serial numbers of the 4 words into gray boxes on the screen. In the cognitive reappraisal block, each constructed sentence contained a word or phrase related to cognitive reappraisal strategies, whereas the baseline block contained no words or phrases related to emotion regulation. Research has shown that unscrambling sentences containing reappraisal-related words can prime automatic goal pursuit of cognitive reappraisal of emotional situations, thereby achieving implicit emotion regulation (Williams et al., 2009; Yuan et al., 2015a).

The picture viewing task was used to evoke negative emotions in participants. In this task (Figure 1C), each negative picture was presented for 5 seconds, during which participants were instructed to carefully view the picture and experience their emotions. After the picture disappeared, participants reported their current emotional valence on a continuous scale from 0 to 1. Emotion ratings were completed by clicking on the expression axis with a mouse, with the left end (0) representing extremely negative emotion and the right end (1) representing extremely positive emotion. A red vertical line appeared on the screen after clicking to indicate the response position, and participants had to complete the rating within 5 seconds. The inter-trial interval was 1 second.

Half an hour after the main experiment, participants were required to rate the valence of the 60 pictures from the picture viewing task on a 9-point scale (1 = very negative; 9 = very positive) to examine the sustained effects of implicit emotion regulation and tDCS.

To ensure the effectiveness of the implicit emotion regulation manipulation, a questionnaire was administered after the experiment to assess whether participants had guessed the experimental purpose and whether they had actively engaged in emotion regulation during the task.

## 2.3 Experimental Materials

Sixty negative pictures were selected from the International Affective Picture System (IAPS; Lang et al., 1997) and the Chinese Affective Picture System (CAPS; Bai et al., 2005). An additional 20 homogeneous participants were recruited to rate the valence and arousal levels of these 60 pictures. The pictures were then equally distributed between the two blocks. Independent samples t-tests indicated no significant differences in picture valence or arousal between the two blocks: valence ($t(58) = 0.13$, $p = 0.893$; $2.54 \pm 0.11$ vs. $2.52 \pm 0.14$) and arousal ($t(58) = -0.50$, $p = 0.622$; $6.31 \pm 0.16$ vs. $6.44 \pm 0.19$) (rated on a 1-9 scale). During the experiment, all images were displayed at the same brightness and contrast at the center of an LCD screen with a visual angle of 3.0° × 3.5°.

The experiment used 10 cognitive reappraisal-related sentences and 10 emotion regulation-unrelated sentences. Each cognitive reappraisal-related sentence contained a priming word related to cognitive reappraisal strategies. For example, "改变" (change) in the sentence "旅行可以改变心情" (Travel can change mood). The emotion regulation-unrelated sentences contained no words related to emotion regulation strategies. For example, "树木可以制造氧气" (Trees can produce oxygen) (Figure 1B). An additional 20 homogeneous participants were recruited to rate the valence and familiarity of these 20 sentences. Independent samples t-tests revealed no significant differences between cognitive reappraisal-related and emotion regulation-unrelated sentences in valence ($t(18) = 0.26$, $p = 0.794$; $6.18 \pm 0.10$ vs. $6.13 \pm 0.17$) or familiarity ($t(18) = 0.96$, $p = 0.342$; $5.99 \pm 0.12$ vs. $5.83 \pm 0.11$) (rated on a 1-9 scale). These 20 sentences were repeated 6 times throughout the experiment, with a new word order and different filler words (or distractor words) randomly set each time, so participants had to re-engage in semantic processing and sentence unscrambling for the same sentences across different trials.

## 2.4 tDCS Parameters

This study employed an offline tDCS stimulation protocol for two main reasons: online tDCS would create electrical artifacts in the EEG data, and the stimulation process might cause discomfort around the electrode sites, affecting participants' task performance.

A wireless tDCS system (NeuStim, BrainCo Ltd., Changzhou, China) was used. The target brain region was the vmPFC. Referencing previous tDCS studies that also targeted vmPFC, we placed the anodal electrode at the position between Fz and Fpz in the international 10/20 EEG system and the cathodal electrode under the chin, with the current intensity set to 1.5 mA (Bulteau et al., 2022; Junghofer et al., 2017; Winker et al., 2018, 2019, 2020; Yin et al., 2021). Finite element-based tDCS current forward modeling conducted by Junghofer et al. indicated that this electrode placement and current parameter setting could effectively deliver current to the vmPFC while minimizing effects on other brain regions (see Figure 1 in Junghofer et al., 2017).

A constant current of 1.5 mA was delivered through a pair of saline-soaked sponge electrodes measuring 3 × 3 cm. To reduce discomfort from electrical stimulation, a 30-second fade-in and fade-out period was implemented at the beginning and end of the stimulation. Participants in the anodal stimulation group received 1.5 mA current for 10 minutes. Participants in the sham stimulation group received only a 1-minute fade-in and fade-out current during the initial minute of the 10-minute period. Previous research has shown that 1 minute of current stimulation produces scalp sensations similar to those experienced by the active stimulation group without significantly affecting brain neural activity during subsequent experimental tasks (Mungee et al., 2014; Riva et al., 2015).

After the experiment, participants reported their negative experiences during tDCS, including the degree of physical discomfort and negative emotion induced by the stimulation. Ratings were made on a 1-9 scale, with higher scores indicating stronger negative experiences.

## 2.5 EEG Signal Acquisition and Analysis

EEG signals were recorded using a 32-channel wireless amplifier (NeuSen W32, BrainCo Ltd., Changzhou, China) at a sampling rate of 250 Hz, with electrode impedance below 10 kΩ. The left mastoid was used as the online reference electrode, and offline analysis was performed using the “whole-brain average potential” for re-referencing.

EEG data were preprocessed using MATLAB (v2020a). Picture onset was set as time zero, and the following steps were performed sequentially: re-referencing, filtering (0.01-30 Hz), segmentation (-200 to 5000 ms), baseline correction (-200 to 0 ms), and rejection of trials with amplitudes exceeding $\pm$ 150  V. The parietal LPP component was calculated as the average amplitude of Pz and its surrounding electrodes (P3, P4, Pz, CP1, and CP2). The time window was selected based on previous studies from our research group (Li et al., 2022; Zhao et al., 2021): starting from the end of the classic P3 component and ending at the conclusion of implicit emotion regulation, i.e., 1-5 s after picture presentation as the LPP time window. In addition to the a priori focus on parietal LPP, we also found that occipital P1 components were significantly affected by experimental variables. For the occipital P1 component (post-hoc analysis), the average amplitude of O1, O2, P7, and P8 was used, with the time window selected as 100-150 ms based on previous literature (Clark & Hillyard, 1996; Gu et al., 2020; Zhang et al., 2022; Żochowska et al., 2022). This study focused on the effects of priming type and tDCS group on P1 amplitude and did not examine hemispheric differences in P1 amplitude.

## 2.6 Statistical Methods

Statistical analyses were conducted using SPSS Statistics 20.0 (IBM, Somers, USA). Descriptive statistics are presented as “mean $\pm$ standard error.” The significance level was set at 0.05. Effect sizes were calculated for ANOVA. Two-way repeated measures ANOVA was performed on self-reported emotion ratings, picture valence ratings, parietal LPP amplitudes, and occipital P1 amplitudes, with “priming type” as the within-subject factor and “tDCS group” as the between-subject factor. Two-tailed Pearson correlations were used for exploratory correlation analyses of dependent variables.

## 3.2 EEG Results

LPP amplitude results showed a significant main effect of priming, $F(1,78) = 70.3$, $p < 0.001$, $^2 = 0.474$: LPP amplitudes in the cognitive reappraisal priming condition (1.39 ± 0.18 μV) were significantly lower than in the baseline condition (2.50 ± 0.16 μV). The main effect of tDCS group was also significant, $F(1,78) = 7.9$, $p = 0.006$, $^2 = 0.092$: LPP amplitudes in the anodal stimulation group (1.51 ± 0.22 μV) were lower than in the sham stimulation group (2.39 ± 0.22 μV). The most important finding was the significant interaction between priming type and tDCS group: $F(1,78) = 5.7$, $p = 0.019$, $^2 = 0.068$ (Figure 3 [Figure 3: see original paper]AC). Simple effects analysis indicated that in the cognitive reappraisal priming condition, $F(1,78) = 11.0$, $p = 0.001$, $^2 = 0.124$, LPP amplitudes in the anodal stimulation group (0.80 ± 0.26 μV) were significantly lower than in the sham stimulation group (1.99 ± 0.26 μV). However, this between-group difference was not significant in the baseline priming condition, $F(1,78) = 3.1$, $p = 0.080$, $^2 = 0.039$ (anodal stimulation group: 2.22 ± 0.22 μV, sham stimulation group: 2.78 ± 0.22 μV). Exploratory analysis revealed that self-reported emotion ratings were negatively correlated with LPP amplitudes (Table 3, Figure 3B).

In addition to the LPP amplitude that was the focus of our hypothesis, we unexpectedly found that bilateral occipital P1 components were also significantly affected by experimental variables (Figure 4 [Figure 4: see original paper]). The main effect of tDCS group was significant, $F(1,78) = 6.1$, $p = 0.016$, $^2 = 0.072$: P1 amplitudes in the anodal stimulation group (4.71 ± 0.40 μV) were lower than in the sham stimulation group (6.12 ± 0.40 μV). The main effect of priming was not significant, and the interaction between the two independent variables was not significant.

## 4.1 Immediate Effects of Ventromedial Prefrontal Cortex Activation

This study used tDCS to investigate the causal role of vmPFC in implicit emotion regulation. Consistent with our predictions, we found that anodal activation of the medial prefrontal cortex, represented by vmPFC, led to a significant enhancement of implicit emotion regulation effects. Specifically, we found that implicit cognitive reappraisal could simultaneously down-regulate negative emotion and EEG LPP amplitudes, and this down-regulation effect was more pronounced in the group with activated vmPFC.

The primary contribution of this study is that we examined the causal role of this brain region in implicit emotion regulation by manipulating vmPFC activation levels. The interaction between priming type and tDCS group indicates that vmPFC plays a causal role in priming-induced implicit emotion regulation, and that activating vmPFC can significantly enhance the down-regulation effect of implicit cognitive reappraisal on negative emotion.

Although previous studies have suggested that vmPFC is an important brain region for implicit emotion regulation (Braunstein et al., 2017; Etkin et al., 2015; Phillips et al., 2008; Rive et al., 2013), this study is the first to use neuromodulation techniques to activate vmPFC while directly manipulating implicit emotion regulation by comparing primed and unprimed conditions. Notably, we found that between-group differences in emotion regulation effects only emerged under cognitive reappraisal priming conditions, with no between-group differences in baseline conditions. In contrast to our findings, Abend et al. (2019) observed reduced negative emotion when activating vmPFC with tDCS without priming implicit emotion regulation (similar to our baseline or neutral priming condition). We believe this discrepancy may be related to differences in tDCS electrode placement.

In this study, tDCS electrodes were placed at the top of the forehead (between Fz and Fpz points) and under the chin. Electric field modeling shows (Junghofer et al., 2017) that this electrode placement can concentrate current delivery primarily in the vmPFC while reducing current intensity in neighboring brain regions (such as dorsomedial prefrontal cortex and orbitofrontal cortex).

In contrast, Abend et al. (2019) placed the two electrodes on the forehead (above the nasion) and the back of the head (below the inion), which delivered current stimulation to the entire sagittal axis of the brain (including vmPFC, ACC, posterior cingulate cortex, medial occipital regions, etc.). Therefore, the emotion regulation-like effects observed by Abend et al. may not have been directly caused by vmPFC modulation.

In addition to demonstrating that vmPFC is a key brain region for implicit emotion regulation, we unexpectedly found that activating vmPFC can influence attention to stimuli during early stages of emotional stimulus processing. Specifically, we found that during the early attention stage 100-150 ms after negative picture presentation, the vmPFC-activated experimental group exhibited smaller P1 amplitudes than the sham stimulation group. The P1 component reflects early attention to visual stimuli, with larger P1 amplitudes indicating greater attention allocated to the stimulus (Clark & Hillyard, 1996). For example, due to attentional bias toward negative emotional information, many studies have found that negative pictures elicit larger P1 amplitudes than positive and neutral pictures (Carretié et al., 2004; Delplanque et al., 2004; Smith et al., 2003). Therefore, our finding that vmPFC activation reduced P1 amplitude suggests that participants in the tDCS anodal group showed reduced early visual attentional processing of negative emotional stimuli. This result indicates that vmPFC not only participates in later-stage emotion regulation processes but also reduces attention to negative stimuli during early visual processing of emotional information. Consistent with our findings, Junghofer et al. (2017) combined magnetoencephalography and tDCS techniques to find that vmPFC activation reduced early (approximately 100 ms) responses in occipital and temporo-occipital cortices related to visual attention to negative stimuli.

## 4.2 Sustained Effects of Ventromedial Prefrontal Cortex Activation

Finally, this study also found that half an hour later, when viewing pictures again, both implicit emotion regulation and anodal vmPFC activation continued to influence participants' re-experience of the pictures. Specifically, the main effect of priming type was marginally significant, with picture valence ratings in the cognitive reappraisal priming condition being more positive than in the baseline condition. The main effect of tDCS group was significant, with the vmPFC-activated experimental group showing more positive valence ratings than the sham stimulation group. Previous studies have found that explicit emotion regulation affects the re-experience of emotional stimuli (Erk et al., 2010; Hermann et al., 2017, 2021). For example, MacNamara et al. (2011) found that cognitive reappraisal of negative pictures produced lasting emotion regulation effects after 30 minutes, evidenced by more positive picture valence ratings and smaller LPP amplitudes compared to control conditions. Additionally, Walter et al. (2009) found reduced amygdala activation when previously regulated negative pictures were viewed again after a 10-minute interval. Therefore, our results suggest that implicit emotion regulation also has the potential to produce sustained emotional improvement. However, it should be noted that the sustained effect of implicit emotion regulation found in this study was relatively weak: the main effect of priming type on picture valence ratings was only marginally significant. This may be because short-term priming effects have limited duration. Future studies should consider using multiple training sessions (e.g., continuous training for one week, 30 minutes per day) instead of "priming" to enhance the sustained effects of implicit emotion regulation (Hopp et al., 2011). Furthermore, we found a significant main effect of tDCS group on picture valence ratings. Previous research has found that vmPFC activation can influence emotional responses when participants are re-exposed to negative stimuli, which may be related to fear extinction processes for negative stimuli (Dittert et al., 2018; Guhn et al., 2014). Therefore, our findings may indicate that vmPFC activation facilitated fear extinction for negative pictures.

## 4.3 The Role of Ventromedial Prefrontal Cortex in Implicit Emotion Regulation

Integrating previous research and our current findings, we propose that vmPFC may have at least three functional roles in regulating negative emotion. First, vmPFC modulates bottom-up information input by influencing attention to negative stimuli during early visual processing stages (Wolf et al., 2014). Second, vmPFC serves as a core region for information integration and value encoding, integrating information and computing the affective value of stimuli (Roy et al., 2012; Winecoff et al., 2013). Specifically, vmPFC extracts relevant prior information through functional connections with the amygdala, temporal lobe, and ventral striatum to evaluate the affective value of stimuli (D' Argembeau et al., 2008; Sharot et al., 2007; Torrisi et al., 2018), and updates the affective value of stimuli during middle and late stages of emotional information processing (Quirk et al., 2006; Roy et al., 2012; Winecoff et al., 2013). Finally, during the emotional response stage, vmPFC acts as a brain region that inhibits negative emotional responses by top-down modulation of amygdala activity through negative functional connectivity with the amygdala, thereby influencing emotional expression (Diekhof et al., 2011; Johnstone et al., 2007; Motzkin et al., 2015; Urry et al., 2006). For example, during fear extinction, vmPFC is responsible for eliminating conditioned fear signals encoded in the amygdala (Gottfried & Dolan, 2004; Sotres-Bayon & Quirk, 2010) and facilitates fear extinction upon re-exposure by influencing emotional memory (Maren & Quirk, 2004; Raij et al., 2018). Notably, these vmPFC functions require modulation and supervision by the lateral prefrontal cortex during explicit emotion regulation (He et al., 2020; Li et al., 2022; Ochsner et al., 2002; Ochsner & Gross, 2005; Smith & Lane, 2015; Zhao et al., 2021), whereas vmPFC can operate relatively independently during implicit emotion regulation (Mauss et al., 2007; Zhang et al., 2020), consuming almost no cognitive resources from the lateral prefrontal cortex (Yang et al., 2015; Yuan et al., 2019).

## 4.4 Correlation Between Subjective and Objective Emotion Measures

Another contribution of this study is that we clarified the validity of self-reported emotion ratings in measuring implicit emotion regulation effects. Self-reported emotion ratings are a direct measure of emotional experience and are commonly used to assess explicit emotion regulation effects (Mauss & Robinson, 2009), but their application in implicit emotion regulation research has been controversial. Some researchers have suggested that unipolar emotion ratings (e.g., rating only negative or positive valence) may lead participants to guess the experimental purpose, thereby reducing the reliability of rating results (Haeffel & Howard, 2010; Polivy & Doyle, 1980). Consequently, some implicit emotion regulation studies have not used self-reported emotion ratings as an indicator of regulation effects (Mocaiber et al., 2010; Payer et al., 2012; Williams et al., 2009). In this study, we used a bipolar rating scale (ranging from negative to positive) to avoid potential guessing of experimental purpose induced by the rating task. Our results showed that implicit cognitive reappraisal priming could effectively reduce self-reported emotion ratings, and that self-reported emotion ratings were significantly negatively correlated with the objective indicator of parietal LPP amplitude. This demonstrates that self-reported emotion ratings have high accuracy in measuring implicit emotion regulation effects (He et al., 2020; Li et al., 2022; Schupp et al., 2000; Shafir et al., 2015, 2016; Zhao et al., 2021).

## 4.5 Future Directions

Future research can be extended in four directions. First, this study verified the causal role of vmPFC in implicit emotion regulation, but the measured indicators were limited to self-reported emotion ratings and EEG signals. Previous research has shown that emotion regulation also induces changes in peripheral physiological indicators such as skin conductance responses (Raio et al., 2013), heart rate variability (Williams et al., 2009), and pupil diameter (Robinson et al., 2021). Future studies could consider using multiple measurement methods to validate implicit emotion regulation effects. Second, this study recruited only healthy university students; the potential clinical application value of activating vmPFC to promote implicit emotion regulation requires experimental support from clinical samples such as individuals with depression. Third, this study focused on short-term implicit emotion regulation effects after a single tDCS intervention and sentence unscrambling task priming; future research could examine the long-term enhancement effects of implicit emotion regulation capacity through multiple tDCS sessions combined with repeated priming training. Fourth, although this study used tDCS to target vmPFC, it could not prevent current from simultaneously flowing through surrounding brain regions (e.g., dorsomedial prefrontal cortex, orbitofrontal cortex), which affects the accuracy of our conclusions. We look forward to more methodological research dedicated to exploring how to more precisely target deeper brain regions such as vmPFC using tDCS. Previous studies have suggested that multi-electrode montages can better concentrate current in the target region while reducing current density in non-target brain regions (Martínez-Pérez et al., 2020; Sergiou et al., 2022). Subsequent studies could adopt this method.

## 5 Conclusion

To reveal the causal role of vmPFC in implicit emotion regulation, this study used anodal tDCS to activate the medial prefrontal cortex represented by vmPFC and employed a sentence unscrambling task to prime implicit cognitive reappraisal. The results demonstrated that activating vmPFC can significantly facilitate implicit emotion regulation. Under implicit cognitive reappraisal priming conditions, vmPFC activation led to weaker self-reported negative emotion and smaller parietal LPP amplitudes evoked by negative emotional pictures. Additionally, we found that activating vmPFC can reduce early attention allocation to negative stimuli. This study indicates that the medial prefrontal cortex, represented by vmPFC, is a key brain region for implicit emotion regulation. Clinically, activating vmPFC combined with implicit emotion regulation cognitive training could enhance negative emotion regulation capacity in patients with emotional disorders and other psychiatric conditions.

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**References**

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**Ventromedial prefrontal cortex plays a critical role on implicit emo-**

**tion regulation: A tDCS study**

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## Abstract

Emotion regulation is crucial to mental health and social life. Traditional view conceived emotion regulation as a deliberative process. However, there is growing evidence that emotion regulation can implement at an implicit level without or with limited involvement of the lateral prefrontal cortex (LPFC) that is responsible for cognitive control. Unlike explicit emotion regulation, we have few knowledge on the neural mechanisms underlying implicit emotion regulation. Here, we investigated the effect of excitatory the ventromedial prefrontal cortex (vmPFC) using transcranial direct current stimulation (tDCS) to provide causal evidence for the key role of the vmPFC in implicit emotion regulation.

This study had a mixed design, with group (anodal vs. sham) as the between-subject factor and priming type (reappraisal vs. baseline) as the within-subject factor. A total of 80 participants were recruited and randomly assigned to the anodal group and the sham tDCS group. The task was divided into two blocks, i.e., the implicit reappraisal block and the baseline block. The order of the two blocks was counterbalanced within the participants in each group. At the beginning of each block, participants were required to complete a tDCS session (1.5 mA; 10 min for the active group and 1 min for the sham group). The anodal electrode was placed in the middle of Fz and Fpz and the ground electrode was placed under the chin). Then, participants completed six sessions of sentence unscramble task (10 trials per session) to prime the emotion regulation goal. Each session of the sentence unscramble task was followed by a picture viewing task (5 trials) to evoke negative emotions. The self-reported emotion rating and EEG signals were recorded during the picture viewing task. Half an hour after the end of the picture viewing task, participants were asked to rate the valence (1 = very unpleasant; 9 = very pleasant) of all viewed images in the picture viewing task.

The results showed that the experimental group (n = 40) reported lower negative emotional experience and showed lower LPP amplitudes (measured as the average amplitude of Pz P3, P4, CP1, CP2) when the vmPFC was activated in the cognitive reappraisal block compared to the control group (n = 40), indicating that excitatory vmPFC could effectively facilitate the ability of implicit emotion regulation. Furthermore, we also found that excitatory vmPFC can reduce the P1 amplitude (measured as the average amplitude of O1, O2) under both baseline and reappraisal conditions.

The above results indicated that activating the vmPFC could not only facilitate implicit emotion regulation but also reduce early attention distribution to negative stimuli. This study is the first attempt to use the tDCS technique to investigate priming-induced implicit emotion regulation.

The results directly reveal the causal relationship between the vmPFC and implicit cognitive reappraisal, suggesting this brain region as a potential target of neural modulation to enhance the ability of implicit emotion regulation in clinical populations.

**Key words:** ventromedial prefrontal cortex, implicit emotion regulation, transcranial direct current stimulation, priming, cognitive reappraisal