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FULL-LENGTH REPORT

Effects of transcranial direct current stimulation of the right dorsolateral prefrontal cortex on craving and negative emotion regulation in individuals at risk for problematic pornography use: A double-blind, placebo-controlled study

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ABSTRACT

Background and aims: Sexual craving and the alleviation of negative emotions are fundamental driving forces underlying problematic pornography use (PPU). In healthy individuals, these processes can be effectively attenuated through cognitive strategies mediated by the prefrontal cortex. However, PPU is associated with impaired cognitive control functions. This study aimed to investigate whether transcranial direct current stimulation (tDCS) targeting the right dorsolateral prefrontal cortex (dlPFC) could enhance the regulation of craving and negative emotions in individuals at risk for PPU. *Methods:* A randomized, within-subject, placebo-controlled design was used, in which 45 male individuals at risk for PPU (mean age = 20.18 years, *SD* = 1.03) received both active (2.5 mA for 20 min) and sham tDCS to the right DLPFC, with sessions separated by one week. During tDCS, participants at risk for PPU performed the regulation of craving (ROC) task, comparing cue-induced craving with instructed regulation, and the emotion regulation (ER) task, contrasting negative affect with instructed regulation. Subjective ratings of craving and negative emotions were collected for each trial. *Results:* Our results demonstrated that individuals at risk for PPU effectively regulated their craving and negative affect when guided to use cognitive strategies. Furthermore, anodal tDCS of the right dlPFC during the craving regulation condition significantly reduced craving ratings compared to sham stimulation. However, no facilitative effect of right dlPFC anodal tDCS on ER was observed. *Discussion and conclusions:* These findings highlight the potential of tDCS as a novel therapeutic intervention for individuals with PPU, offering the first experimental evidence to support its effectiveness in reducing craving.

KEYWORDS

problematic pornography use, transcranial direct current stimulation, dorsolateral prefrontal cortex, regulation of craving, emotion regulation, sexual behavior

INTRODUCTION

With advancements in technology, particularly the internet, the distribution and consumption of sexually explicit content have undergone a revolutionary transformation. Internet pornography has become a global phenomenon, with its accessibility and anonymity contributing to widespread usage (Kohut et al., 2020). Research shows that pornography consumption is now common among adults (Ballester-Arnal, Castro-Calvo, García-Barba, Ruiz-Palomino, & Gil-Llario, 2021) and adolescents (Pirrone, Zondervan-Zwijnenburg,

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Reitz, van den Eijnden, & Ter Bogt, 2022) worldwide, with viewing frequencies surpassing those of earlier forms of erotic media.

While most individuals use pornography recreationally, a smaller subset develops problematic pornography use (PPU). PPU is characterized by excessive preoccupation with pornography, diminished interest in other activities, repeated failed attempts to reduce consumption, and continued use despite negative consequences (Wéry & Billieux, 2017). Prevalence estimates suggest PPU affects 3%–10% of men and 1%–7% of women (Bőthe, Lonza, Štulhofer, & Demetrovics, 2020; Bőthe et al., 2024a; Grubbs, Kraus, & Perry, 2019). However, fewer than 10% of individuals experiencing PPU actively pursue treatment (Bőthe et al., 2024a), underscoring the urgent need for evidence-based, accessible, and affordable interventions.

Addiction theories propose that the pursuit of reward and the regulation of negative emotions are core drivers of addictive behaviors (Brand et al., 2019; Potenza, 2014). Impairments in executive functions that regulate reward processing and emotional control disrupt these mechanisms, fostering compulsive and maladaptive behaviors (Brand et al., 2019; Goldstein & Volkow, 2011). Since these dysfunctions are central to addiction pathophysiology, interventions aimed at enhancing craving regulation and emotional distress management may provide novel strategies for mitigating addictive behaviors.

Craving and its regulation in PPU

Craving for pornography is often conceptualized as both a transient, intense desire and a more enduring preoccupation with its use (Marino et al., 2023). Research suggests that individuals with PPU often display increased sexual motivation and baseline craving (Antons et al., 2019; Kraus & Rosenberg, 2014; Laier, Pawlikowski, Pekal, Schulte, & Brand, 2013; Stark et al., 2017). For example, in a study by Carnes, Hopkins, and Green (2014), 41% of men and 46% of women seeking treatment for sexual behavior issues reported experiencing "obsessive thoughts centered around sexual activities." Similarly, a study on the network structure of PPU symptoms identified salience—preoccupation with pornography—as a core symptom of PPU (Bőthe et al., 2020). Individuals experiencing stronger cravings for online pornography tend to exhibit greater symptoms of PPU (Snagowski, Wegmann, Pekal, Laier, & Brand, 2015).

Craving can be triggered by cues previously associated with addiction (Kober & Mell, 2015). When exposed to sexual cues, individuals with PPU experience increased subjective craving (Snagowski, Laier, Duka, & Brand, 2016). Mechanisms such as cue-reactivity and attentional bias may amplify this response, with PPU individuals exhibiting a heightened focus on these cues, further intensifying craving (Draps et al., 2024; Mechelmans et al., 2014; Pekal, Laier, Snagowski, Stark, & Brand, 2018; Wang, Chen, & Zhang, 2021). These attentional biases can exacerbate PPU symptoms by mediating craving, ultimately diminishing control over pornography use. Cue-reactivity and craving are closely linked to heightened activity in the brain's reward system (Brand, Snagowski, Laier, & Maderwald, 2016; Gola et al., 2017; Seok & Sohn, 2015; Voon et al., 2014). This aligns with dual-process models of addiction, which suggest that automatic reward responses and impaired self-regulation drive addictive behaviors (Brand et al., 2019; Zilverstand & Goldstein, 2020).

Considering the critical role of cue-induced craving in the maintenance and development of addiction, the regulation of craving (ROC) has emerged as a central focus in addiction treatment. Cognitive-behavioral therapy (CBT) for PPU often involves strategies to help individuals manage exposure to pornography cues and cope with craving. For example, CBT guides individuals to focus on the negative outcomes associated with pornography use (Crosby & Twohig, 2016). Recent studies highlight the significant effectiveness of cognitive strategies in reducing cue-induced craving (Hall & Larkin, 2020; Hallberg et al., 2020; Holas, Draps, Kowalewska, Lewczuk, & Gola, 2020). However, empirical research on ROC in the context of PPU remains limited.

Negative emotions and its regulation in PPU

Difficulties in emotion regulation (ER) may contribute significantly to the development of PPU. Many addiction theories suggest that reducing negative emotions is a primary motivator for pornography viewing (Brand et al., 2019; Koob et al., 2014). This alleviation of negative emotions reinforces behavior, increasing the likelihood of continued use (Bőthe et al., 2021). Numerous studies have linked negative emotions, pornography consumption, and PPU (Antons, Büsche, et al., 2023; Gola et al., 2022; Testa, Villena-Moya, & Chiclana-Actis, 2024; Wang & Li, 2023). For instance, PPU often co-occurs with mood and anxiety disorders (Grant Weinandy, Lee, Hoagland, Grubbs, & Bőthe, 2023), with ER difficulties proposed as a key factor underlying this comorbidity (Lew-Starowicz, Lewczuk, Nowakowska, Kraus, & Gola, 2020). A machine learning analysis of 74 preexisting self-report datasets from independent laboratories identified emotional avoidance pornography use motivation and stress reduction pornography use motivation as two of the five strongest predictors of PPU (Bőthe et al., 2024b). Longitudinal studies further indicate that negative affect and impulsivity predict PPU over time (Rousseau, Bőthe, & Štulhofer, 2021). Negative emotions may also increase the salience of sexual cues. Specifically, heightened negative affect enhances attention to sexual stimuli, especially among individuals with elevated solitary sexual motivation (Markert, Baranowski, Koch, Stark, & Strahler, 2021). Acute stress, which elevates cortisol levels, further amplifies the incentive value of sexual cues (Stark et al., 2022).

Given the relationship between negative emotions and PPU, ER is a critical component in treating PPU. Research shows that individuals in the general population can use cognitive strategies to regulate emotional reactions to unpleasant stimuli (Gross & Jazaieri, 2014). Acceptance and

commitment therapy (ACT) targeting PPU, which employs cognitive restructuring and diffusion techniques, has been shown to effectively reduce symptom severity (Hallberg, Kaldo, Arver, Dhejne, & Öberg, 2017). However, cognitive ER remains underexplored in the context of PPU. Thus far, only one study has demonstrated that cognitive strategies can effectively mitigate negative affective reactions to aversive images in individuals at risk for PPU (Wang et al., 2024).

Common neural mechanisms underlying ROC and ER

Neuroimaging studies suggest that ROC and ER share similar neural mechanisms, involving the cognitive control network of the prefrontal cortex. For instance, a study on smokers identified activation of the dorsolateral prefrontal cortex (dlPFC), ventrolateral prefrontal cortex (vlPFC), and dorsomedial prefrontal cortex/presupplementary motor area (dmPFC/presMA) during the regulation of emotions, cravings, and action impulses (Tabibnia et al., 2014), highlighting a shared prefrontal pathway that supports various forms of cognitive regulation (Tabibnia et al., 2011, 2023). In another study, Kober et al. (2010) instructed smokers to use cognitive reappraisal to regulate cravings triggered by smoking cues. The findings showed that regulating cravings increased dlPFC activation while reducing ventral striatum activation, suggesting that craving regulation influences limbic activity via the dlPFC. Similarly, research has demonstrated that both upregulation and downregulation of negative emotions enhance activation in prefrontal cortex (Buhle et al., 2014; Ochsner et al., 2004).

While these findings highlight general neural mechanisms, neuropsychological studies indicate specific prefrontal dysfunctions in individuals with PPU. Executive control processes, essential for regulating cravings and emotions, are notably diminished when individuals with PPU are exposed to sexual cues (Antons, Müller, Neumann, Müller, & Steins-Loeber, 2023; Brand, Young, & Laier, 2014). Survey results reveal a positive correlation between impulsivity and PPU severity (Antons & Brand, 2018; Müller & Antons, 2023). Using ERP techniques, studies have shown that individuals with PPU exhibit smaller N2 and P3 amplitudes in response to irrelevant sexual stimuli, indicating impaired inhibitory control (Wang & Dai, 2020). Additionally, during pornography-induced sexual arousal, PPU individuals demonstrate deficits in executive functions, resulting in poorer decision-making (Laier, Pawlikowski, & Brand, 2014) and reduced working memory performance (Sinke et al., 2020).

Given these findings, exploring methods to enhance prefrontal function in PPU individuals is crucial for improving their regulation of cravings and negative emotions. Such advancements could provide a foundation for more effective interventions and treatments.

The present study

With increasing neurobiological evidence on the mechanisms of ROC and ER and their significance for PPU, exploring ways to enhance these processes is crucial. Transcranial Direct Current Stimulation (tDCS) is a non-invasive technique that modulates brain activity by applying low-intensity direct current to specific cortical areas through scalp electrodes (Miranda, Lomarev, & Hallett, 2006). By adjusting neuronal membrane potential, tDCS alters excitability, influencing cognitive, emotional, and behavioral functions. Anodal stimulation enhances excitability in the targeted region, while cathodal stimulation reduces it (Nitsche & Paulus, 2000). Empirical studies have shown that anodal tDCS applied to the dlPFC enhances cognitive performance across various domains (Narmashiri & Akbari, 2023). Although widely applied in substance and behavioral addiction (Mehta et al., 2024; Sauvaget et al., 2015), its use in addressing PPU remains largely unexplored.

This study investigates whether tDCS can enhance craving and negative emotion regulation in individuals with PPU by targeting the right dlPFC with anodal stimulation. The right dlPFC was chosen for two reasons. First, tDCS targeting the right dlPFC has been specifically recommended for addiction interventions (Lefaucheur et al., 2017). Second, studies indicate that the right dlPFC is critical for selecting and inhibiting responses (Cieslik et al., 2013; Lock, Garrett, Beenhakker, & Reiss, 2011; Pulopulos et al., 2022). Thus, stimulating this region may facilitate deliberate selection of stimulus-appropriate reappraisals, overriding initial responses.

Building on neuroimaging findings (Buhle et al., 2014; Ochsner et al., 2004; Tabibnia et al., 2014), we hypothesized that activating the right dlPFC via tDCS would enhance the regulation of both craving and negative emotions. During the ROC and ER tasks, participants were instructed to maintain or down-regulate craving induced by pornography images and negative emotions triggered by aversive images, using cognitive reappraisal. Subjective ratings of craving and negative affect were recorded. We expected that active tDCS, compared to sham stimulation, would enhance down-regulation in both tasks, resulting in lower subjective ratings in the downregulation conditions.

METHODS

Participants

The required sample size was calculated using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007), assuming a medium effect size ($f = 0.25$), $\alpha = 0.05$, and power = 0.9. This calculation indicated that 46 participants were needed. Accordingly, 46 male university students were selected from a pool of 734. Due to the significantly higher prevalence of PPU in males compared to females (Bőthe et al., 2024a; Grubbs et al., 2019), only male participants were recruited. One participant did not attend the second session, resulting in a final sample size of 45. Figure 1 presents the Consolidated Standards of Reporting Trials (CONSORT) flow diagram, detailing participants' progression through enrollment, allocation, follow-up, and analysis.

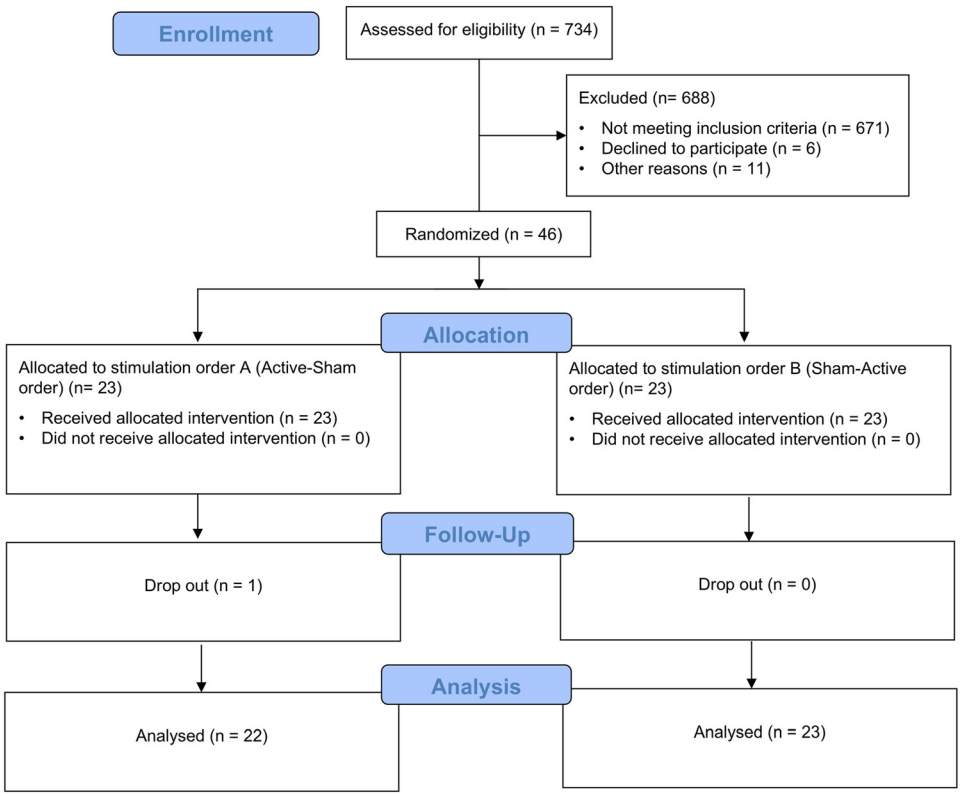

Fig. 1. The CONSORT 2010 flow diagram depicts group sample sizes at each stage of the study, from enrollment through allocation, follow-up, and analysis

Participants at risk for PPU were recruited based on the following criteria: (a) engagement in pornography use for at least six months; (b) viewing pornography at least three times per week on average in the month prior to the study (Twohig & Crosby, 2010); (c) a score of ≥76 on the Problematic Pornography Consumption Scale (PPCS; Bőthe et al., 2018); (d) age over 18 years; and (e) self-identified heterosexual orientation.

Exclusion criteria were as follows: (a) risky drinking, defined as a score of 8 or higher on the Alcohol Use Disorder Identification Test (AUDIT; Babor, Higgins-Biddle, Saunders, Monteiro, & World Health Organization, 2001); (b) nicotine dependence, defined as a score of 6 or higher on the Fagerström Test for Nicotine Dependence (FTND; Fagerström, 1978); (c) gaming disorder, defined as a score of 36 or higher on the Internet Gaming Disorder Scale (IGDS; Pontes & Griffiths, 2015); (d) gambling disorder, defined as a score of 8 or higher on the Problem Gambling Severity Index (PGSI; Ferris & Wynne, 2001); (e) moderate or severe depression, defined as a score of 20 or higher on the Beck Depression Inventory (BDI-II; Beck, Steer, Ball, & Ranieri, 1996); (f) moderate or severe anxiety, defined as a score of 22 or higher on the Beck Anxiety Inventory (BAI; Beck, Epstein, Brown, & Steer, 1988); (g) current or previous use of illegal drugs; and (h) neurological or psychiatric disorders. The demographic and clinical characteristics of participants are summarized in Table 1.

Table 1. Demographic and clinical characteristics

Variables	Min−Max	*M* (*SD*) or *n* (%)
Age (years)	18–22	20.18 (1.03)
BAI	0–14	3.93 (3.51)
BDI	0–19	6.02 (6.52)
Alcohol use (at least once per month)		18/0.40[a]
AUDIT	1–7	3.78 (1.93)[b]
Cigarette use (at least once per month)		6/0.13[a]
FTND	0–5	1.50 (1.76)[c]
PPCS	76–126	92.80 (13.36)
IGDS	9–35	19.27 (7.20)
PGSI	0–7	0.58 (1.47)
Weekly frequency of viewing pornography[d]	3–11	4.38 (1.54)
Weekly frequency of masturbation[d]	1–10	4.36 (1.77)

Abbreviations: AUDIT, Alcohol Use Disorder Identification Test; BAI, Beck Anxiety Inventory; BDI, Beck Depression Inventory; FTND, Fagerstrom Test for Nicotine Dependence; IGDS, Internet Gaming Disorder Scale; PGSI, Problem Gambling Severity Index; PPCS, Problematic Pornography Consumption Scale; PPU, Problematic Pornography Use.

[a] Number of participants (percentage).

[b] $n = 18$.

[c] $n = 6$.

[d] During the last month.

Experimental design

This study employed a within-subjects design with a placebo-controlled, double-blind protocol. Participants completed two experimental sessions separated by one week. In each session, they received either real or placebo tDCS stimulation (see Fig. 2). Participants were randomly assigned to one of two groups, following either a real-placebo or placebo-real stimulation order. During each session, participants received 20 min of stimulation while completing the ROC and ER tasks. To prevent order effects, the sequence of the ROC and ER tasks was counterbalanced across participants. The tDCS device was operated by an assistant experimenter, ensuring that both the primary experimenter and the participants remained unaware of the stimulation condition.

ROC and ER tasks

The ROC task consisted of 40 sexual images, equally divided between the passive viewing and down-regulation conditions (Kober et al., 2010; Naqvi et al., 2015). These images were matched for valence, arousal, and sexual arousal based on a pilot study. In the passive viewing condition, participants viewed sexual images and allowed themselves to experience the desires or impulses evoked without intervention. In the down-regulation condition, participants were instructed to reduce their craving by reflecting on the potential harms of excessive pornography use, such as its effects on academic performance, mental health, relationships, or quality of life.

The ER task included 40 negative emotional images from the Chinese Affective Picture System (Bai, Ma, Huang, & Luo, 2005), evenly split between passive viewing and down-regulation conditions. Images were matched for valence and arousal across conditions. In the passive viewing condition, participants viewed negative images and experienced the emotions elicited without intervention. In the down-regulation condition, participants used cognitive reappraisal to reinterpret the depicted situations as more positive or hopeful (training materials are provided in the Appendix).

Both tasks employed a block design. Each task consisted of two passive viewing blocks and two down-regulation blocks, with 10 trials per block. To avoid interference from cognitive regulation strategies, passive viewing blocks always preceded down-regulation blocks.

Each block began with a 2,000 ms cue ("Look" or "Regulate") indicating the regulation condition. Participants then viewed an image for 8 s (sexual images for the ROC task and negative images for the ER task) and either passively viewed or engaged in down-regulation as instructed. Following a 1,000 ms fixation, participants rated their level of craving (ROC task) or emotional experience (ER task) on a nine-point Likert scale (1 = "Not at all" to 9 = "Extremely strong"). Ratings were recorded for up to 4 s (Fig. 3).

tDCS procedure

The tDCS protocol was implemented using saline-soaked sponge electrodes (electrode surface area: $5 \times 7 = 35\,cm^2$). These electrodes were connected to a battery-powered constant current stimulator (tCS-E2000, YINGCHI, China). Anodal stimulation was applied to the right dlPFC by placing the anode electrode at the F4 electrode site, following the 10–20 international EEG electrode placement system. The cathode electrode was positioned over the left supraorbital area. This electrode configuration (with the anodal electrode placed over one DLPFC and the cathodal electrode positioned

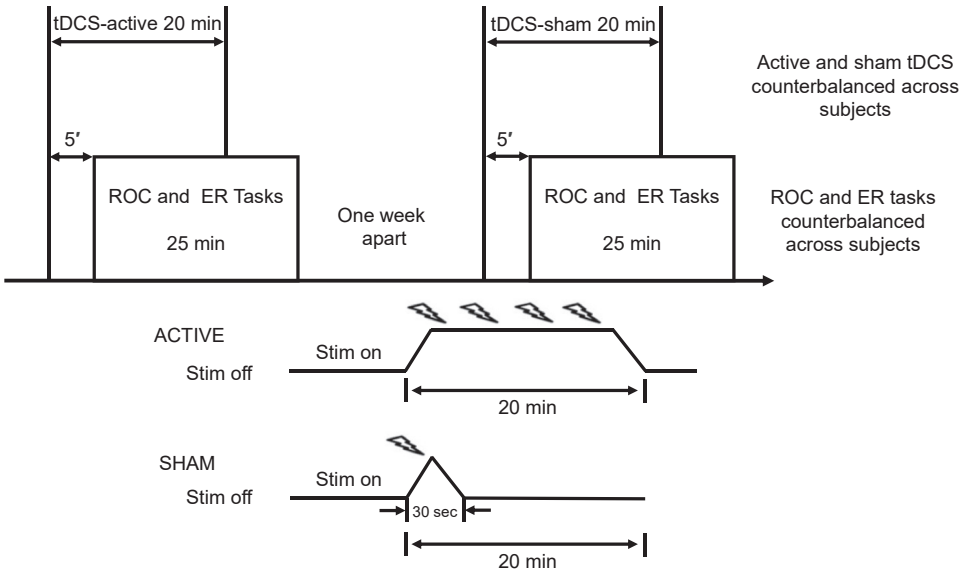

Fig. 2. Experimental design. Each participant completed both active and sham stimulation sessions, spaced one week apart, in a counterbalanced order. ROC and ER tasks were also counterbalanced across participants. During the real tDCS condition, participants received 20 min of continuous 2.5 mA stimulation. In the sham condition, the current was activated for 30 s to mimic somatic sensations without affecting cortical activity

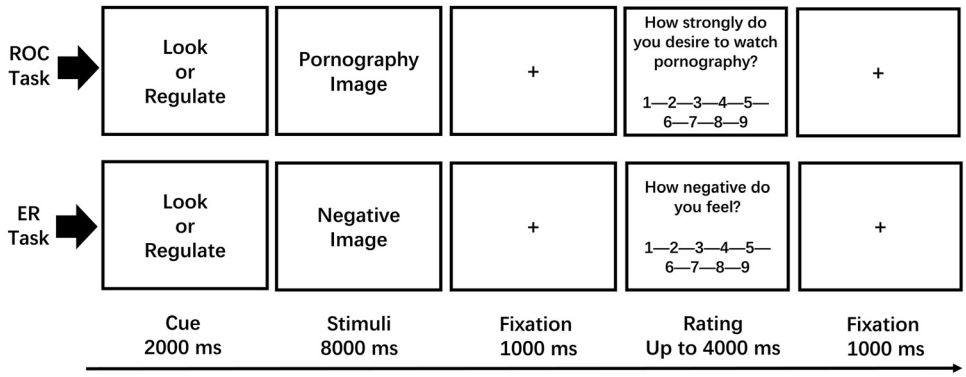

Fig. 3. Schematic of a single trial in the regulation of craving (ROC) and emotion regulation (ER) tasks. Each trial began with an instruction ("Look" or "Regulate") displayed for 2000 ms, guiding participants' focus. A picture was then shown for 8,000 ms (pornographic images for ROC; negative images for ER), followed by a 1,000 ms interstimulus interval. Participants rated their craving (ROC) or negative affect (ER) on a 9-point scale within 4,000 ms. A 1000 ms intertrial interval completed each trial

over the contralateral supraorbital area) is believed to trigger unilateral modulation of the DLPFC and has been demonstrated to be effective in numerous studies (e.g., Fecteau et al., 2007; Zmigrod, Colzato, & Hommel, 2014).

In the real stimulation condition, a constant current of 2.5 mA was applied for 20 min with 15 s ramp-up and 15 s ramp-down. 2.5 mA is the higher current intensity commonly used in clinical trials (Charvet, Shaw, Bikson, Woods, & Knotkova, 2020; Fregni et al., 2015). We chose a higher current intensity based on preliminary evidence suggesting that increased stimulation amperage enhances cortical excitability and efficacy (Shinde, Lerud, Munsch, Alsop, & Schlaug, 2021; Vöröslakos et al., 2018). In the placebo condition, stimulation was delivered for 30 s (15 s ramp-up and 15 s ramp-down) before stopping. Both conditions produced an initial tingling sensation, preventing participants from distinguishing between real and placebo stimulation (Gandiga, Hummel, & Cohen, 2006). Stimulation began 5 min before the start of the ROC and ER tasks and lasted for 20 min, ending before the completion of the tasks.[1] The device controlled resistance levels, keeping them below 5 kΩ. Figure 4 illustrates the simulated electric field using a model of the adult brain generated by SimNIBS software (Thielscher et al., 2015).

tDCS-related assessments

Participants reported potential adverse effects of tDCS—such as headache, discomfort on the scalp, and tingling sensations—using a four-point Likert scale (1 = "not at all" to 4 = "very much") after both real and placebo stimulation. Additionally, participants were asked to identify which session they believed included real stimulation, ensuring blinding effectiveness.

Data analyses

Data analysis was conducted using SPSS 22.0 (IBM, Somers, USA). Descriptive statistics were computed for demographic and clinical variables. Repeated measures ANOVA was performed on subjective craving and negative emotion ratings, with within-subject factors of regulation condition (passive viewing vs. down-regulation) and stimulation type (real vs. placebo). Significant effects were further analyzed using post-hoc pairwise *t*-tests. A significance level of 0.05 was applied to all statistical analyses. Outliers were defined as values more than 3 standard deviations from the mean, with none detected in the primary outcome measures. The data entered into the ANOVAs were assessed for normality using the Lilliefors test, and all data met the normality assumption. A "regulation success" index was calculated for both tasks, following established methods (Naqvi et al., 2015; Suzuki et al., 2020). Specifically, for both the ROC task and the ER task, the regulation success was computed by subtracting the craving score (or negative emotion score) in the down-regulation condition from that in the passive viewing condition. Positive values on the regulation success index indicated effective regulation (i.e., a reduction in craving or negative emotion), whereas negative values suggested that regulation was unsuccessful, leading to an increase in craving or negative emotion.

Ethics

The study protocol was approved by the local ethics committee. Informed written consent was obtained from all participants, who were compensated for their participation.

RESULTS

Effects of tDCS on craving ratings

A 2 × 2 repeated measures ANOVA was conducted on craving scores. The analysis revealed a significant main effect of

[1]Although stimulation ended before task completion, similar effects can be anticipated from both online and offline periods, as excitability changes following anodal stimulation often resemble those observed during stimulation (Nitsche et al., 2003; Nitsche & Paulus, 2001). Additionally, task order was counterbalanced, and no significant effects of task order on the dependent variables were observed ($ps > 0.15$), indicating that the lack of ongoing stimulation in the latter part of the task did not affect the results of ROC or ER.

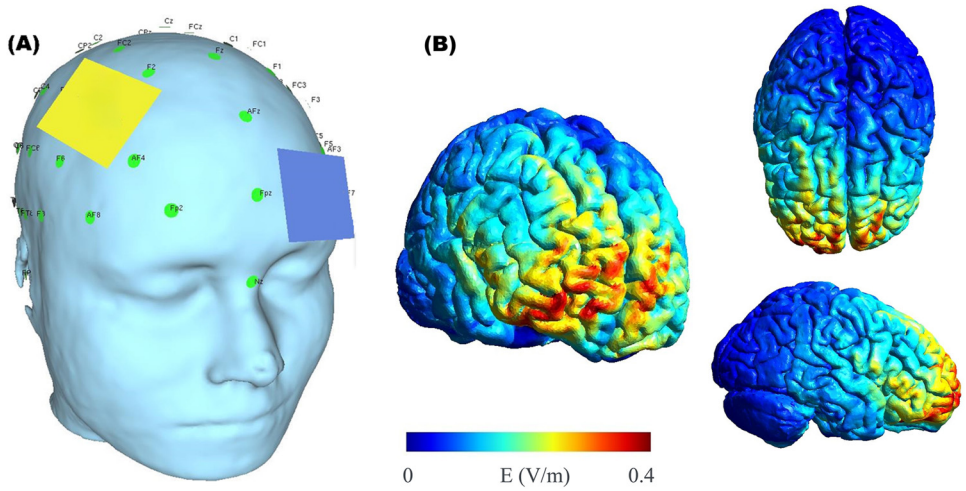

Fig. 4. tDCS settings illustrated using SimNIBS software. (A) The stimulation site is shown at the right dlPFC. (B) The simulated electric field demonstrates a gradient of field strength, with the strongest intensity located at the right dlPFC (red) and weaker areas shown in blue

regulation condition ($F_{(1, 44)} = 48.36$, $p < 0.001$, $\eta^2_p = 0.52$), with lower craving levels observed in the down-regulation condition (3.30 ± 1.76) compared to the passive viewing condition (4.56 ± 1.66). This finding indicates that participants at risk for PPU effectively down-regulated their cravings as instructed, regardless of whether real or placebo tDCS was applied.

Importantly, the interaction between regulation condition and stimulation type was significant ($F_{(1, 44)} = 6.35$, $p = 0.015$, $\eta^2_p = 0.13$) (Fig. 5A and Table 2). Paired-sample *t*-tests showed no significant difference between real (4.60 ± 1.67) and placebo (4.51 ± 1.92) stimulation under the passive viewing condition ($t_{(44)} = 0.41$, $p = 0.68$, Cohen's d = 0.06, 95% CI [−0.33, 0.50]). However, under the down-regulation condition, craving levels were significantly lower with real stimulation (3.09 ± 1.70) compared to placebo stimulation (3.50 ± 1.94) ($t_{(44)} = -2.93$, $p = 0.005$, Cohen's d = 0.44, 95% CI [−0.70, −0.13]).

To further examine the effects of tDCS on ROC, a paired-sample *t*-test was conducted on craving regulation success scores (passive viewing − down-regulation). Results showed that regulation success scores were significantly higher under real stimulation (1.51 ± 1.32) compared to placebo (1.01 ± 1.45) ($t_{(44)} = 2.52$, $p = 0.015$, Cohen's

Table 2. The mean and standard deviation of craving regulation scores and negative emotion regulation scores under the anodal tDCS and sham tDCS conditions

Test	Stimulation condition	
	Anodal tDCS	Sham tDCS
ROC task		
Passive viewing	4.60 ± 1.67	4.51 ± 1.92
Down-regulation	3.09 ± 1.70	3.50 ± 1.94
ER task		
Passive viewing	4.08 ± 1.40	4.19 ± 1.46
Down-regulation	3.05 ± 1.18	3.06 ± 1.16

Abbreviations: ER, emotion regulation; ROC, regulation of craving; tDCS, transcranial direct current stimulation.

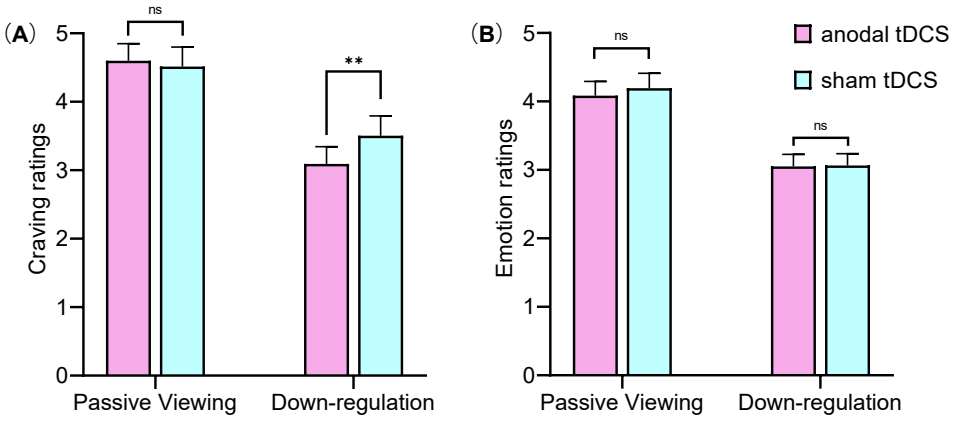

Fig. 5. Effects of tDCS on craving and negative emotion regulation. (A) Active tDCS reduced craving during down-regulation compared to sham stimulation. (B) No facilitative effect of right dlPFC anodal tDCS on negative emotion regulation was observed. Error bars indicate standard errors. Significance levels: $^{*}p < 0.05$, $^{**}p < 0.01$; ns, not significant

d = 0.38, 95% CI [0.10, 0.90]). This finding demonstrates the facilitative effect of tDCS on craving regulation (Fig. 6).

Effects of tDCS on emotional ratings

A 2 × 2 repeated measures ANOVA on negative emotion scores revealed a significant main effect of regulation condition ($F_{(1, 44)} = 35.42$, $p < 0.001$, $\eta^2_p = 0.45$). Participants reported lower negative emotion levels in the down-regulation condition (3.06 ± 1.02) compared to the passive viewing condition (4.14 ± 1.35). This indicates that participants effectively down-regulated their negative emotions regardless of stimulation type.

However, neither the main effect of stimulation type ($F_{(1, 44)} = 0.21$, $p = 0.64$) nor the interaction between regulation condition and stimulation type ($F_{(1, 44)} = 0.35$, $p = 0.55$) was significant (Fig. 5B).

tDCS-induced side effects and blinding

All participants tolerated tDCS well. Side effect ratings averaged 1.47 ($SD = 0.25$) under real stimulation and 1.39 ($SD = 0.30$) under placebo, with no significant difference between the conditions ($t_{(44)} = 1.37$, $p = 0.18$). Additionally, participants' ability to identify the real stimulation session did not exceed chance level (57.78% ± 0.50; $t_{(44)} = 1.05$, $p = 0.30$), supporting the effectiveness of the blinding procedure.

DISCUSSION

This study investigated the effects of right dlPFC stimulation on ROC and ER using a within-subject, placebo-controlled, double-blind tDCS design. The findings revealed that individuals at risk for PPU effectively regulated both craving and negative emotions through cognitive strategies, regardless of tDCS stimulation. Notably, this study provides the first experimental evidence that right dlPFC anodal tDCS enhances ROC in individuals at risk for PPU, leading to a greater reduction in sexual craving. However, no facilitative effect of right dlPFC anodal tDCS on ER was observed. These results suggest that tDCS may hold promise as a therapeutic tool for managing craving in PPU, offering preliminary experimental support for its application.

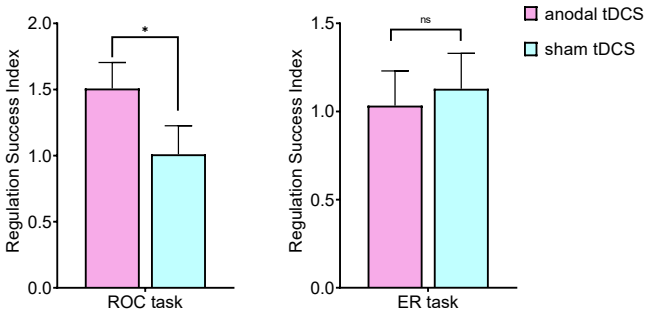

Fig. 6. The effect of tDCS on the regulation success index (passive viewing − down-regulation) in the regulation of craving (ROC) and emotion regulation (ER) tasks. The regulation success score was higher with active stimulation than with sham in the ROC task. Significance levels: $^*p < 0.05$; ns, not significant

High-risk PPU individuals can effectively regulate craving and negative emotions under guidance

The findings demonstrate that high-risk PPU individuals can successfully employ cognitive strategies to reduce craving triggered by sexual imagery, consistent with prior behavioral research in substance addiction (Kober et al., 2010; Suzuki et al., 2020). This is particularly noteworthy, given the frequent association between PPU and cognitive dysfunction (Brand et al., 2014). Similarly, the ability of PPU individuals to regulate their emotional responses to negative stimuli aligns with earlier findings (Wang et al., 2024).

However, while these individuals demonstrate effective regulation in laboratory settings, they may struggle to apply these strategies spontaneously in real-world contexts (Wang et al., 2024). Clinical observations often highlight difficulties with ER in individuals with PPU (Gola et al., 2022; Testa et al., 2024). This apparent contradiction mirrors findings in depression research, where individuals successfully use cognitive reappraisal in the lab but employ it less frequently in everyday life (Joormann & Stanton, 2016; Quigley & Dobson, 2014). For PPU individuals, the challenge may not lie in cognitive ability but in motivational factors or situational barriers that prevent strategy use in daily life. Laboratory environments provide structured guidance, which may facilitate better regulation than unstructured real-world settings. Alternatively, high emotional intensity or stress in everyday contexts might make regulation more difficult.

These findings highlight the need for targeted training to enhance craving and emotional regulation among PPU individuals. Such training could focus on improving the accessibility and spontaneous use of these strategies in real-life situations. By reinforcing regulatory skills, individuals may be better equipped to handle challenging moments, increasing the likelihood of applying these strategies outside the laboratory.

Right dlPFC tDCS enhances craving regulation but not negative emotion regulation

This study demonstrates that right dlPFC anodal stimulation significantly reduced sexual craving compared to sham stimulation. Since the dlPFC was the primary target, the enhanced ROC observed may stem from changes in activity within this region. Supporting this, previous tDCS studies have shown that modulating dlPFC activity is linked to cognitive changes in healthy individuals (Fregni et al., 2005) and both cognitive and emotional improvements in individuals with depression (Fregni, Boggio, Nitsche, Rigonatti, & Pascual-Leone, 2006). Neuroimaging studies also associate dlPFC activity with sexual craving. For instance, PPU patients show enhanced dlPFC activity when exposed to sexual cues, a response absent with neutral stimuli (Voon et al., 2014). Additionally, dlPFC activity is associated with craving for other substances, such as nicotine (George & Koob, 2013; Wilson, Sayette, Delgado, & Fiez, 2005).

Sexual craving may involve the mesolimbic dopamine pathway, which interacts with the dlPFC through the mesocorticolimbic system (Berridge & Robinson, 2003). This pathway underlies reward-related behaviors and contributes to the development of addiction. Specifically, sexual consumption sensitizes dopamine receptors, increasing dlPFC activity in response to pornography-related cues. By modulating dlPFC activity, tDCS may disrupt this neurocognitive process, reducing reward signaling and lowering sexual craving.

Although tDCS enhanced ROC, it did not facilitate ER. This discrepancy may reflect differences in prefrontal subregion activation across tasks. Although both ROC and ER engage the prefrontal cortex (Albein-Urios et al., 2014; Tabibnia et al., 2011), distinct activation patterns emerge depending on the task. A recent study recorded brain activity while participants performed both ROC and ER tasks. The results showed that, while both tasks activated the ventrolateral prefrontal cortex, they produced distinct activation patterns in other prefrontal subregions, such as the dorsolateral and ventromedial areas (Suzuki et al., 2020). These differences likely reflect the distinct regulatory strategies employed in ROC and ER tasks, respectively. For instance, ROC strategies often emphasize the negative consequences of sexual consumption, whereas ER strategies focus on generating positive reappraisals. These findings highlight the unique roles of prefrontal subregions in processes like prospective thinking, self-referential processing, and emotional regulation (Addis, Wong, & Schacter, 2007; Northoff et al., 2006; Wager, Phan, Liberzon, & Taylor, 2003).

Furthermore, the prefrontal cortex likely regulates different subcortical regions in ROC and ER tasks. For example, the prefrontal-striatal circuit plays a crucial role in ROC (Kober et al., 2010), while the prefrontal-limbic system, including the amygdala and cingulate, primarily supports ER (Morgane, Galler, & Mokler, 2005). These distinct circuits may explain the differential effects of tDCS observed in this study. As noted by Schroeder, Schwippel, Wolz, and Svaldi (2020), the effects of tDCS on inhibitory control are closely tied to the task type. Specifically, they found that tDCS had a significant effect in the stop-signal task, but a smaller or even non-significant effect in the go/no-go task. This result underscores the moderating role of task characteristics on tDCS outcomes. Therefore, the effects of tDCS may depend on the activation patterns of target brain regions and the specific demands of the task.

Additionally, given the general spatial non-specificity of tDCS, especially with large sponge electrodes, it is possible that the stimulation influenced broader areas of the prefrontal cortex rather than being restricted to the dlPFC as initially intended. Previous research has shown that tDCS results in a diffuse current flow that can spread to adjacent brain regions (Datta et al., 2009; Lang et al., 2005), making it challenging to precisely target specific subregions of the prefrontal cortex. This could lead to the activation of not only the dlPFC but also other regions such as the orbitofrontal and ventrolateral prefrontal cortex, which are involved in distinct cognitive and emotional processes (Suzuki et al., 2020).

However, it should be emphasized that several meta-analyses have pointed out that the effects of prefrontal tDCS are not always consistent, possibly due to individual differences in electrode positioning, polarity, and variability in task parameters (Schroeder et al., 2020; Tremblay et al., 2014). These inconsistencies highlight the importance of refining electrode montages and task parameters for more reliable and replicable results. Future research should consider more precise electrode placements and modulations specific to each task to enhance the effectiveness of tDCS in targeting distinct neural processes involved in cognitive control. Furthermore, integrating these technical refinements with a deeper understanding of task-related neural activation patterns may help clarify the conditions under which tDCS can reliably modulate prefrontal activity and improve inhibitory control.

Clinical significance

This study has important clinical implications. Individuals with PPU often experience diminished prefrontal cortex control, particularly when exposed to pornography-related cues (Brand et al., 2014). This reduction in control limits their ability to recognize situational triggers and manage daily distress, leading to reliance on pornography as a coping mechanism. The reinforcement gained from pornography consumption—whether positive or negative—further solidifies the expectation of future use (Brand et al., 2019).

While pharmacological treatments have shown some efficacy in reducing PPU or CSBD symptoms (Borgogna, Owen, Johnson, & Kraus, 2024; Mestre-Bach & Potenza, 2024), CBT remains the primary therapeutic approach (Antons et al., 2022). The success of CBT depends on prefrontal cognitive processes, such as planning, monitoring, self-reflection, cognitive flexibility, and working memory. When these control processes are impaired in PPU patients, it becomes more challenging for therapists to teach effective self-regulation strategies. One promising clinical strategy is combining tDCS with CBT. By enhancing both general cognitive control and addiction-specific regulatory mechanisms, tDCS could improve treatment outcomes. This combination might enable patients to better engage with CBT and strengthen their ability to apply learned strategies in real-world settings.

An additional advantage of tDCS as an adjunctive therapy is its immediate effect. Given the significant fluctuations in craving levels influenced by social contexts and biological rhythms, a treatment capable of temporarily reducing cravings within a single session would be highly beneficial. Moreover, tDCS offers several practical benefits, including safety, portability, and affordability. These features make tDCS a practical and accessible tool for addressing the challenges faced by individuals with PPU.

Limitations and future directions

This study has several limitations that warrant consideration. First, the investigation was limited to anodal stimulation of the right dlPFC. Exploring additional stimulation

sites could refine the specificity of the observed effects and determine whether stimulating other brain regions besides the dlPFC could yield comparable outcomes. Future research should examine the role of tDCS in modulating other brain regions implicated in cognitive regulation. Second, it is possible that increased dlPFC excitability influenced activity in adjacent brain regions. Given the complexity of the networks underlying ROC and ER, neuroimaging studies are needed to elucidate the specific mechanisms through which tDCS modulates cognitive regulation. Third, this study focused exclusively on pornography-related cues in the ROC task, omitting other types of reward stimuli, such as food-related cues. It remains unclear whether the observed effects are specific to pornography-induced craving or generalize to other forms of reward stimuli. Future studies should include a broader range of stimuli to address this limitation. Fourth, to assess blinding, participants were asked to identify which session involved the real stimulation, similar to methods used in previous tDCS studies (e.g., Gandiga et al., 2006). However, the 2010 CONSORT guidelines (Schulz, Altman, Moher, & Fergusson, 2010) removed the recommendation to test blinding, recognizing that such tests often reflect participants' "hunches" about treatment efficacy rather than the true validity of blinding (Sackett, 2007). Our study used a sham-controlled within-subject design to increase statistical power. However, it may be easier for participants to distinguish between real and sham stimulation in a crossover design, as compared to parallel group trials (Brunoni, Schestatsky, Lotufo, Benseñor, & Fregni, 2014). Future studies could benefit from parallel designs to improve the effectiveness of tDCS blinding. Fifth, the sample consisted of non-clinical university students. While this allows for controlled experimentation, the findings may not generalize to clinical populations, such as individuals diagnosed with CSBD. Future research should assess the efficacy of tDCS in enhancing ROC and ER in clinical populations to determine its broader therapeutic relevance. Lastly, female participants were excluded from the study due to the higher prevalence of PPU in men. Future research should explore whether these findings generalize to female populations.

CONCLUSION

In conclusion, this study provides preliminary evidence that prefrontal tDCS enhances cognitive control during ROC in individuals at risk for PPU. These findings underscore the pivotal role of the dlPFC in the ROC network and highlight the potential of tDCS as an intervention for reducing cravings. By establishing a link between prefrontal tDCS and successful ROC, this research opens new avenues for tDCS as an adjunctive treatment for PPU, particularly for individuals with deficits in craving regulation. Although these findings require further replication and validation, they represent a promising step toward integrating tDCS into therapeutic frameworks. Future studies should evaluate the clinical efficacy and explore the broader applications of this approach, including its potential synergy with existing treatments such as CBT.

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Appendix: Reappraisal Tactic Training

Cognitive reappraisal primarily involves two strategies: distancing (viewing an image from a third-person perspective) and reinterpretation (altering the perceived meaning of a situation by changing its outcomes or offering alternative explanations) (Denny & Ochsner, 2014; Zilverstand, Parvaz, & Goldstein, 2017). This study focused exclusively on the reinterpretation strategy, requiring participants to reappraise images from their own (first-person) perspective. The choice to use only one strategy was made to avoid potential confounding effects arising from differences in perspective-taking, as distancing relies on a third-person perspective, whereas reinterpretation engages a first-person viewpoint (He, Liu, Zhao, Elliott, & Zhang, 2020).

Situational reinterpretation

The following strategies involve reinterpreting the current situation depicted in a photograph. These approaches collectively help to reframe the emotional impact of distressing images by altering the interpretation of the circumstances.

Change Current Circumstances: This involves viewing the situation in a less negative light, for instance, recognizing that an injury may not be as serious as it seems or that someone appearing in pain is not suffering as much as it looks.

Reality Challenge: This strategy questions the authenticity of the scene, suggesting it might not be real or could be part of a staged event, like a movie or a Halloween costume.

Change Future Consequences: Here, the focus is on the potential for improvement over time, emphasizing that suffering is temporary and that future outcomes may differ from initial perceptions.

For example, when viewing a picture of a car accident, situational reappraisal can be expressed as:
"The damage looks serious, but the people involved might have just minor injuries and are receiving help."
"This could be a staged photo or part of a safety demonstration; it doesn't represent a real accident."
"Although it looks bad now, the situation will improve; insurance will cover the damages, and everyone will recover."