Examining the Role of Left Prefrontal Cortex in Emotion Regulation
Using Noninvasive Transcranial Direct Current Stimulation

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Abstract

Emotion regulation (ER) is the set of processes that support the flexible adjustment of emotional responses to valenced stimuli depending on context. Evidence from healthy and psychiatric populations has linked ER mechanisms to the dorsolateral prefrontal cortex (dlPFC). This region shows reliable engagement in ER tasks, especially in the left hemisphere. Few studies, however, have examined whether dlPFC causally supports up- or down-regulation of emotional responses. We used transcranial direct current stimulation (tDCS)—a noninvasive brain stimulation technique involving the application of small currents through electrodes placed over the scalp—to examine the causal contributions of left dlPFC in ER. Healthy participants (N = 95) performed a standard ER task before and during either excitatory (anodal), inhibitory (cathodal), or sham tDCS over left PFC. Performance differences at baseline among the conditions minimized the ability to detect tDCS effects. We discuss these findings in the context of the literature on ER.

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Introduction

Our everyday lives are filled with a myriad of emotions and our attempts to change the way we feel. How we achieve this type of affective regulation involves strategies that can range from thinking about a situation in a different way, to suppressing a negative emotion by focusing on an alternative task. These are both examples of *emotion regulation* (ER) which is defined as the set of purposeful but also automatic processes by which individuals influence the occurrence, duration, intensity, and expression of an emotional response to different kinds of affective stimuli or experiences (Gross & Thompson, 2007).

Successful ER has been associated with overall well-being and psychological health (Gross & John, 2003). On the other hand, deficits in emotion regulation have been implicated in an estimated 40% to 75% of different psychopathologies, including mood and anxiety disorders (see Aldao, Nolen-Hoeksema, & Schweizer, 2010; Gross & Jazairi, 2011 for reviews). One of the most common and most consistently effective emotion regulation strategies—and the focus of the present study—is *cognitive reappraisal* of emotional responses (Aldao, Nolen-Hoeksema, & Schweizer 2010; Gross, 2015; Webb, Miles, & Sheeran, 2012). Reappraisal involves reinterpreting the emotional meaning of an event or stimuli in a way that changes one's initial emotional response (Gross, 2015). Numerous studies have found that reappraisal is effective and successful at decreasing negative emotions (i.e. McRae, Ciesielski & Gross, 2011; Silvers, Weber, Wager & Ochsner, 2015; Troy et al., 2018) and this finding holds across different areas of life events (e.g., personal, academic, or professional), types of emotions (i.e., positive or negative), and the demographic characteristics of the individual (e.g., Aldao & Nolen-Hoeksema, 2012; Dixon-Gordon, Aldao, & Los Reyes, 2015). Applying reappraisal strategies has also been consistently associated with positive mental health outcomes across a variety of mental illnesses, including

anxiety, depression, eating, and substance-related disorders (Aldao, Nolen-Hoeksema, & Schweizer, 2010; Nolen-Hoeksema & Aldao, 2011; Aldao & Nolen-Hoeksema, 2012).

Previous research has identified a set of specific cortical and subcortical brain regions involved in cognitive reappraisal comprising a highly interactive brain network (Silvers, Weber, Wager, & Ochsner, 2015). A meta-analysis of instructed reappraisal studies revealed a consistent reappraisal network in frontoparietal executive regions including the dorsolateral prefrontal cortex (dlPFC), ventrolateral prefrontal cortex (vlPFC), parietal cortex, insula, supplemental motor area and pre-supplemental motor area (Buhle et al., 2014), with the dlPFC emerging as a potentially critical hub region in this network across cognitive reappraisal tasks. The dlPFC supports several cognitive control processes including selective attention, working memory, and inhibition (Inzlicht et al., 2015; Wager, Phan, Liberzon & Taylor, 2003). These processes may be important for cognitive reappraisal as an emotion regulation strategy in selecting reappraisal approaches appropriate for the situation at hand, maintaining multiple reappraisal attempts and the goals of reappraisal in working memory, as well as inhibiting competing emotional or cognitive responses. Indeed, the successful reappraisal of emotional responses at varying levels of intensity depends, in part, on the dlPFC (Silvers, Weber, Wager, & Ochsner, 2015), which has further been implicated in both the up- and down-regulation of negative emotions (Ochsner et al., 2004). In line with these findings, a study using meta-analytic connectivity modeling (MACM) found consistent dlPFC activation during a multitude of combined cognitive and affective regulation tasks (Kohn et al., 2013). Notably, dlPFC engagement was strongest during cognitive tasks that had emotional content, suggesting that the dlPFC is especially important for emotion regulation that relies on cognitive control functions like attention and memory (Kohn et al., 2013).

These and other studies using functional brain imaging measures offer substantial evidence in support of the involvement of the dlPFC in the reappraisal of positive and negative emotions. However, these results come from neuroimaging studies which are largely correlational in nature, thus, limiting our ability to address whether dlPFC mechanisms are necessary and/or sufficient for cognitive reappraisal. One way to address this shortcoming of neuroimaging studies is by using noninvasive brain stimulation, particularly transcranial direct current stimulation (tDCS). During tDCS, specific neural regions are manipulated by a continuous weak electrical current applied through two electrodes positioned over the participants' scalp surface. TDCS induces transient, polarity-dependent excitability shifts in the human cortex via neuronal de- or hyper-polarization of the neurons in the brain areas directly underneath the electrode (Miranda et al., 2006). Specifically, anodal tDCS is thought to result in increased cortical excitability and cathodal tDCS is thought to result in decreased cortical excitability (Nitsche & Paulus, 2000). Using tDCS during a cognitive or affective task has been linked to plasticity changes that can allow causal links between activity in a given brain region and behavioral task performance.

Several studies have used tDCS to examine cognitive and affective processes akin to emotion regulation. In a study examining self-regulation in smokers, for example, researchers found that anodal tDCS over the right dlPFC decreased negative affect for unpleasant pictures (Pripfl, Neumann, Kohler, & Lamm, 2013). Although not directly focusing on ER, several studies have investigated more general emotional processing using tDCS. For example, Pena-Gomez and colleagues (2011) reported that excitatory (anodal) tDCS over the left dlPFC reduced the perceived degree of emotional valence for negative emotional pictures. Another set of placebo-controlled studies using anodal tDCS over left prefrontal cortex administered over 3 or 5 consecutive days elicited consistent improvements in self-reported mood evaluation in healthy subjects, as captured

by participants reporting of reduced psychological distress from daily stressors (Austin et al., 2016). In addition to studies focusing on emotion, anodal tDCS over the left dlPFC has been associated with improved working memory, planning ability, and decreased risk-taking behavior (Andrews et al., 2011; Dockery, Hueckel-Wenig, Birbaumer, & Plewnia, 2009; Fecteau et al., 2007). Based on this work, tDCS has been used as an effective tool toward enhancing or inhibiting cognitive functioning. For this reason, here, we have chosen to use tDCS as a method to explore the potential causal role of the left dlPFC in successful emotion regulation through cognitive reappraisal.

Only one study to date has directly examined the effects of tDCS on ER. Feeser and colleagues (2014) employed a standard emotion regulation paradigm, the Cognitive Reappraisal Task (CRT), adapted from Ochsner et al. (2004). In this task participants are shown a series of images taken from the International Affective Picture System (IAPS) database and are asked to either down-regulate their emotions in response to the images by reappraisal or to simply look at the images. Participants are then asked to rate on a scale (typically ranging from 1 to 4) the intensity of their emotional response after either downregulating or looking at the pictures. Beyond these explicit behavioral responses of emotional intensity, this study additionally obtained skin conductance responses (SCRs) from each participant across trials of a particular valence and reappraisal instructions (i.e., look or regulate). SCRs provide a sensitive and reliable implicit measure of emotional arousal, with larger SCR reflective of an increased response to highly emotionally intense stimuli (Dawson, Schell, & Filion, 2000). Specifically, with regards to emotion regulation, Urry et al. (2009) found that downregulating negative emotions in response to unpleasant pictures was associated with decreased SCR when compared to maintaining negative responses to these pictures, a pattern of findings that were dissociable from participants' behavioral

ratings of effortful regulation on this task. Similarly, several studies employing variations of the Cognitive Reappraisal Task while obtaining participants' neural activity with functional magnetic resonance imaging (fMRI) have reported variability in capturing ER effectiveness between self-report (explicit) ratings and (implicit) amygdala activity (e.g., McRae et al., 2008; Domes et al., 2010). Because of such discrepancies between explicit and implicit ER measures, behavioral and neuroscience investigations of ER strategies and their effectiveness highly benefit from the inclusion of both explicit and implicit ER measures (Whittle et al., 2011). In line with this practice, Feeser and colleagues (2014) examined the impact of tDCS over PFC for ER using behavioral ratings together with SCR. Their results showed that anodal (excitatory) relative to sham (placebo) tDCS over right dlPFC during down-regulation of negative emotion resulted in a greater ability to modulate emotional responses as indicated by decreased self-reported emotional arousal ratings and decreased skin conductance responses.

Although Feeser and colleagues (2014) provided promising evidence in support of the effectiveness of tDCS over PFC as a method for modulating ER, their experiment paradoxically focused on only the right dlPFC, in contrast to most the literature on ER reporting left dlPFC engagement in cognitive reappraisal. In addition, this study involved exclusively excitatory (anodal), but not inhibitory (cathodal) tDCS, further limiting the ability to examine comprehensively whether dlPFC inhibition would causally result in ER cognitive reappraisal impairments during emotion regulation. In this context, the present study builds on the results of Feeser and colleagues (2014) by examining the necessity and sufficiency of left dlPFC involvement during down-regulation of emotional responses using both anodal and cathodal tDCS. In a mixed (between-within) subjects design, we used anodal (excitatory), cathodal (inhibitory), or sham (placebo) tDCS over the left dorsolateral prefrontal cortex (dlPFC) during a standard

emotion regulation task, the Cognitive Reappraisal Task, to investigate the effects of increased or decreased dlPFC excitability on cognitive reappraisal as measured by subjective emotional intensity ratings and skin conductance responses (SCRs). We anticipated that at baseline (i.e., prior to the onset of stimulation) participants across conditions would show decreased subjective emotional intensity ratings and SCRs for the down-regulation relative to the maintenance trials, especially for negative (relative to positive or neutral) stimuli. We further hypothesized that subjective ratings of emotional intensity, as well as autonomic arousal (SCR) would be decreased during anodal (excitatory) tDCS over left dlPFC, relative to cathodal (inhibitory) or sham stimulation—and relative to the same measures at baseline. We predicted that this pattern of results would be obtained during trials that involved down-regulation of negative (relative to positive or neutral) stimuli, but not simply trials that involved maintaining emotional responses to these stimuli. We anticipated no effects of tDCS on a negative-control, short-term memory (Forward Digit Span) task.

Method

Participants

Participants were 95 native English speakers between the ages of 18 and 33 (N = 95; mean age = 19, SD = 2.04; 64 [67.4%] female). A majority of the sample identified as Caucasian (N = 70, 73.7%), and the rest identified as: Black (n = 7), Asian (n = 6), American Indian (n = 3), more than one race (n = 4), other (n = 3), and not available (n = 2). The participants were recruited via SONA through the introductory psychology pool at a large mid-western university. Participants were excluded from the study if they reported left-handedness, current pregnancy, or a history of a mood disorder, seizure disorder, or head injury. The study was approved by the local institutional

review board; participants were required to provide consent and were debriefed and given course credit for their time at the end of the study.

Materials

Emotion Regulation Task (ERT). The reappraisal task was adapted from prior reappraisal protocols (i.e., Ochsner et al., 2004) and included five conditions: downregulate negative emotions, downregulate positive emotions, maintain negative emotions, maintain positive emotions, and maintain neutral emotions. For the 'downregulation' trials, participants were instructed to "think of something to tell yourself that helps you feel less emotional about the picture," for example, the participant could think of an outcome that changes their emotion or focus on a detail or aspect of the situation that isn't as negative/positive as it first seemed. In the 'maintain' trials participants were instructed to "simply look and respond naturally" to the pictures.

Stimuli and Trial Structure. In the task, participants were presented with 94 images from the IAPS (Lang, Bradley, & Cuthbert, 2001) randomly distributed across four runs. Each picture was paired with either a "regulate" or "look" cue. "Regulate" cues were only paired with negative or positive images, however "look" cues were paired with all three types of images. Each trial started with a cue indicating the condition ("regulate" or "look") for four seconds, followed by the image for eight seconds, the self-report rating for four seconds, and a "relax" cue for two seconds. For the rating, participants rated the intensity of arousal evoked by the picture on a nine-point scale (1 = very low, 9 = very high).

Forward-Digit-Span. The forward digit span (FDS) task was adapted from the Wechsler Adult Intelligence Scale – Fourth Edition (Pearson Education, Inc.) and it is used to measure one's ability to maintain information in phonological short-term memory. Participants are read a string of numbers and are asked to repeat these numbers back in the same order. The task begins with

two-digit number strings and progresses to nine-digit strings (two trials per sting length). Participants discontinue after responding incorrectly to both trials of a given string length.

PANAS. (PANAS; Watson et al., 1988). The PANAS is a self-report measure designed to assess both positive and negative affect. The PANAS consists of 20 adjectives pertaining to negative affect (i.e., distressed or nervous) and positive affect (i.e., excited or proud), with ten items for each subscale. Items are rated on a five-point Likert scale: 1 = "Very slightly or not at all" to 5 = "Extremely." The subscales are obtained by taking the average of each item within that subscale.

SCR. SCR was recorded continuously during the emotion regulation task with a sampling rate of 40 Hz using a biofeedback sampling device (BioPac). The SCR data were analyzed using the BioPac BSL Analysis packages. Although SCR was recorded continuously, the data analyzed were taken only from the 8 second time frame during which each image stimulus was on the screen. Two types of measurements were used, the delta score and the mean SCR score. The delta score provides the difference value between SCR at the beginning and the end of the 8 second time frame during which the image remains on the screen. The mean SCR score provides the average SCR across the entire 8 seconds the image was presented.

tDCS. tDCS was administered via two 5cm × 5cm electrodes covered with saline-soaked sponges (4 ml of saline per sponge side). The stimulation site was determined by means of a BraiNet 10/20 Placement cap (bio-medical.com) and was marked with a red marker on the participant's scalp. For anodal stimulation of the left dlPFC and the sham condition, the anode electrode was placed over area F3 according to the 10-20 international system for EEG electrode placement and the reference electrode was placed over the contralateral mastoid. For the cathodal stimulation of the left dlPFC, the cathode electrode was placed over area F3, with the reference

electrode over the contralateral mastoid. During the anodal and cathodal stimulation a constant current of 1.5 mA was applied for 20 minutes, including 10 seconds of ramp up and 10 seconds of ramp down time. The sham condition consisted of ninety seconds of stimulation and then, unbeknownst to the participants, the stimulation was automatically turned off. Electrical field modeling of the used tDCS electrode montage and stimulation strength confirmed that the electrical current was focused on the area of interest over left dlPFC and did not expand to neighboring regions or the other hemisphere (see Figure 1a, 1b).

Design and Procedure

The participants were randomly assigned to one of the tDCS conditions: anodal (n = 31); cathodal (n = 32); and sham (n = 32). Participants first completed a screening questionnaire to ensure that they were eligible to participate in the tDCS portion for the study and females were given a pregnancy test. If eligible, the participant then completed a set of demographic questionnaires and the PANAS. After completing the PANAS, the SCR electrodes were placed on both the middle and index fingers of the left hand of the participant for calibration purposes. The participant was then walked through a presentation with instructions for both the ERT and FDS that included several practice trials. After the participant confirmed that they understood the instructions, they completed two runs of the ERT while SCR was being recorded. Following the first two runs of the ERT, the participant completed the PANAS for the second time. The tDCS electrodes were then placed on the participant's scalp.

The order in which participants completed the second two runs of the ERT and the FDS task was counterbalanced with some subjects completing the FDS first and other subjects completing the ERT first. After these two tasks were completed the tDCS and SCR electrodes were taken off the participant and the participant completed the PANAS for the final time. The

participant then completed a questionnaire on tDCS side effects they may have experienced during the stimulation portion of the study. Lastly, participants were given two debriefing forms and a short summary of the experiment verbally.

Results

Baseline Comparisons

Demographic and individual variables measures were examined at baseline to determine any potential differences among the three stimulation conditions that could interact with the electrical stimulation manipulation. Analyses of variance (ANOVAs) showed no statistically significant differences among conditions on age, level of education, neurological or psychiatric disability status, depression, gender, or race/ethnicity (p values ranged from 0.08 to 0.93; see Table 1). Participants also did not differ among conditions on their mood in the beginning of the experiment as measured by the positive (F[2, 87] = 1. 45, p = .24, η^2 = .03) and negative (F[2, 86] = 0. 09, p = .91, η^2 = .002) scores on the PANAS. Affective scores on the PANAS did not differ among conditions either immediately before the stimulation procedure (F[2, 84] = 1. 36, p = .26, η^2 = .03 for positive affect and F[2, 83] = 0. 16, p = .85, η^2 = .003 for negative affect) or following stimulation (F[2, 84] = 1. 19, p = .31, η^2 = .03 for positive affect and F[2, 84] = 0. 01, p = .96, η^2 < .001 for negative affect; Table 2).

We then examined any differences among conditions prior to the onset of stimulation on the primary variables of interest: SCR (delta, mean response), ER task emotional intensity ratings, and RTs associated with providing these ratings. We examined each of these variables across groups separately for each task condition: downregulate for negative stimuli, downregulate for positive stimuli, look (i.e., maintain) at negative stimuli, look at positive stimuli, and look at neutral stimuli. Four participants (all in the anodal stimulation condition) presented as multivariate outliers

(with over 2 standard deviation performance differences across all measures) and were, thus, excluded from all further analyses.

A series of one-way ANOVAs revealed that participants differed among groups with regards to SCR delta (i.e., the difference value between SCR at the beginning and the end of the 8 second time frame during which the image is on the screen) when downregulating responses to positive stimuli ($F[2, 92] = 3.56$, $p = .03$, $\eta^2 = .07$). Tukey's Honestly Significant Difference (HSD) post hoc comparisons indicated that the anodal condition, overall, showed significantly higher delta relative to the sham condition ($p = .03$) but not the cathodal condition ($p = .18$). The cathodal and sham conditions did not differ from each other ($p = .96$). Participants further showed lower emotional intensity ratings when downregulating in response to negative stimuli among conditions ($F[2, 92] = 4.01$, $p = .02$, $\eta^2 = .08$). Tukey's HSD post hoc comparisons indicated that the anodal condition, overall, showed significantly lower emotional intensity ratings relative to the cathodal condition ($p = .03$) and marginally lower ratings relative to the sham condition ($p = .06$), with the cathodal and sham conditions not differing from each other ($p = .68$). Although the pattern of results for baseline performance on all other measures was similar to those reported above, the three stimulation conditions did not significantly differ from each other (all ps $\geq .11$ see Table 3).

Stimulation Effects

Task Order Effects. A 2 × 3 ANOVA (with task order [FDS administered first or ER administered first during the stimulation phase] and condition [anodal, cathodal, sham] as between-subject variables) did not reveal any significant effects of task order during the stimulation procedure ($F[1, 91] = 0.36$, $p = .70$, $\eta^2 = .001$) or any task order by condition interaction ($F[2, 91] = 0.7$, $p = .80$, $\eta^2 = .008$) for any of the measures. In the absence of task order differences, all further results are collapsed across task order conditions.

Forward Digit Span (FDS). With regards to performance on the FDS, a one-way ANOVA did not reveal any differences among conditions (F[2, 90] = 1. 03, p = .36, η^2 = .02); thus, this particular tDCS montage did not have an effect on performance on the negative control forward digit span task (see Figure 2).

SCR Median Delta. A 2 × 3 repeated measures ANOVA (with time [baseline, stimulation] as the within-subjects factor and stimulation condition [anodal, cathodal, sham stimulation] as the between-subject factor) on SCR delta during downregulation for negative stimuli revealed no main effects for time (F[1,88] <.01 , p = .99, η^2 < .001) or stimulation (F[2,88] = 0.95 , p = .39, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.57, p = .57, η^2 = .01; see Table 4). For downregulation of positive stimuli, 2 × 3 repeated measures ANOVA did not reveal a main effects for time (F[1,88] = 2.07 , p = .15, η^2 = .02) or stimulation (F[2,88] = 1.48 , p = .23, η^2 = .03); the time × stimulation condition interaction was significant (F[2,88] = 3.34, p = .04, η^2 = .07; see Table 4), although none of the post hoc comparisons reached statistical significance (all ps > 23). For looking at negative stimuli a similar analyses did not reveal any main effects for time (F[1,88] 0.41 , p = .52, η^2 = .005) or stimulation (F[2,88] = 0.21 , p = .81, η^2 = .005), and no time × stimulation condition interaction (F[2,88] = 0.12, p = .89, η^2 = .003; see Table 4). Similarly, for looking at positive stimuli, a similar analyses showed no main effects for time (F[1,88] = 0.16 , p = .69, η^2 = .002) or stimulation (F[2,88] = 0.81 , p = .45, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.76 , p = .47, η^2 = .02; see Table 4). Lastly, for neutral stimuli, a similar analyses did not reveal any main effects for time (F[1,88] = 1.25, p = .27, η^2 = .014) or stimulation (F[2,88] = 0.24 , p = .79, η^2 = .005), and no time × stimulation condition interaction (F[2,88] = 0.80, p = .93, η^2 = .002; see Table 4). Overall, tDCS did not significantly influence ER

performance as measured by SCR delta, an effect likely attributed to the baseline differences in delta among participants prior to stimulation (see Figure 3).

Mean SCR. A similar 2 × 3 repeated measures ANOVA for mean SCR showed a marginal main effect of time (F[1,88] = 3.64 , p = .06, η^2 = .04), no main effect of stimulation (F[2,88] = 1.56, p = .22, η^2 = .03), and no time × stimulation condition interaction (F[2,88] = 0.40, p = .06, η^2 = .009; see Table 5). With regards to downregulating positive stimuli, the same analysis showed a marginally significant effect of time (F[1,88] = 3.85 , p = .053, η^2 = .04), no effect of stimulation (F[2,88] = 1.76, p = .18, η^2 = .04), and no time × stimulation condition interaction (F[2,88] = 0.58, p = .57, η^2 = .01; see Table 5). Regarding looking at negative stimuli, a 2 × 3 repeated measures ANOVA revealed a significant main effect of time (F[1,88] = 6.23 , p = .01, η^2 = .07), no main effect of stimulation (F[2,88] = 1.66, p = .20, η^2 = .04), and no time × stimulation condition interaction (F[2,88] = 0.46, p = .63, η^2 = .01; see Table 5). Looking at positive stimuli elicited a similar pattern of results, with a marginally significant main effect of time (F[1,88] = 3.53, p = .06, η^2 = .04), no main effect of stimulation (F[2,88] = 1.07, p = .35, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 1.54, p = .22, η^2 = .03; see Table 5). Lastly, 2 × 3 repeated measures ANOVA for looking at neutral stimuli was associated with a marginal main effect of time (F[1,88] = 3.71, p = .06, η^2 = .04), no main effect of stimulation (F[2,88] = 1.70, p = .19, η^2 = .04), and no time × stimulation condition interaction (F[2,88] = 0.91, p = .41, η^2 = .02; see Table 5). Across all stimulus and instruction categories, Tukey's HSD post hoc tests did not reveal any significant pairwise differences between conditions (all ps > .15). Overall, participants across conditions showed increased mean SCR during the second portion of the experiment, regardless of tDCS stimulation condition (see Figure 4).

ER Task Ratings. A 2 × 3 repeated measures ANOVA (with time [baseline, stimulation] as the within-subjects factor and stimulation condition [anodal, cathodal, sham stimulation] as the between-subject factor) on ER task ratings during downregulation for negative stimuli revealed a marginally significant main effect for time (F[1,88] = 3.46, p = .07, η^2 = .04), no main effect of stimulation (F[2,88] = 1.78, p = .18, η^2 = .04), and no time × stimulation condition interaction (F[2,88] = 0.26, p = .77, η^2 = .006); see Table 6). None of the post hoc comparisons reached statistical significance (all ps > .22). For downregulation of positive stimuli, a 2 × 3 repeated measures ANOVA showed a marginally significant main effect for time (F[1,88] = 3.46 , p = .07, η^2 = .04), no main effect of stimulation (F[2,88] = 1.31, p = .43, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.84, p = .28, η^2 = .03; see Table 6); none of the post hoc comparisons reached statistical significance (all ps > .42). For looking at negative stimuli a similar analyses showed a marginal main effect of time (F[1,88] = 3.71 , p = .06, η^2 = .04), no main effect of stimulation (F[2,88] = 1.01, p = .37, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.05, p = .95, η^2 = .001; see Table 6). Similarly, for looking at positive stimuli, analyses showed a marginally significant main effect for time (F[1,88] = 33.04, p < .001, η^2 = .27), no main effect of stimulation (F[2,88] = 0.69 , p = .50, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.46 , p = .63, η^2 = .01; see Table 6); no post hoc Tukey HSD tests were significant (all ps > .34). Lastly, for neutral stimuli, a similar analyses showed a significant main effect of time (F[1,88] = 10.77, p = .001, η^2 = .11), no main effect of stimulation (F[2,88] = 0.67, p = .51, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.7, p = .94, η^2 = .002; see Table 6), with no significant Tukey's HSD post hoc tests (all ps > .56). Overall, across

conditions, emotional intensity ratings for the ER task decreased during the second phase of the experiment and this effect was not modulated by stimulation condition (see Figure 5).

ER Task RTs. A similar series of 2 × 3 repeated measures ANOVAs for ER task response RTs showed a significant main effect of time (F[1,88] = 55.89 , p < .001, η^2 = .39), no main effect of stimulation (F[2,88] = 0.66, p = .52, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.85, p = .43, η^2 = .02; see Table 7). With regards to downregulating positive stimuli, the same analysis showed similarly a significant effect of time (F[1,88] = 37.29 , p < .001, η^2 = .30), no effect of stimulation (F[2,88] = 0.14, p = .87, η^2 = .003), and no time × stimulation condition interaction (F[2,88] = 1.27, p = .29, η^2 = .03; see Table 7). For trials involving looking at negative stimuli, a 2 × 3 repeated measures ANOVA revealed a significant main effect of time (F[1,88] = 34.19 , p < .001, η^2 = .28), no main effect of stimulation (F[2,88] = 0.67, p = .51, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.39, p = .68, η^2 = .009; see Table 7). Looking at positive stimuli elicited a similar pattern of results, with a significant main effect of time (F[1,88] = 23.26 , p < .001, η^2 = .21), no main effect of stimulation (F[2,88] = 0.38, p = .68, η^2 = .009), and no time × stimulation condition interaction (F[2,88] = 0.51, p = .60, η^2 = .01; see Table 7). Lastly, 2 × 3 repeated measures ANOVA for looking at neutral stimuli was associated with a main effect of time (F[1,88] = 17.62, p < .001, η^2 = .17), no main effect of stimulation (F[2,88] = 0.06, p = .94, η^2 = .001), and no time × stimulation condition interaction (F[2,88] = 1.62, p = .20, η^2 = .04; see Table 7). Across all stimulus and instruction categories, Tukey's HSD post hoc tests did not reveal any significant pairwise differences between conditions (all ps > .68). Overall, ER ratings RTs decreased during tDCS (relative to baseline), regardless of stimulation type (see Figure 6).

Comparisons by Stimulus Valence

To obtain a measure of emotion downregulation by stimulus category (positive, negative, neutral), we examined for each measure differences between downregulation trials and non-regulation trials in response to each type of tDCS (anodal, cathodal, sham). For SCR Delta, the difference between downregulating negative stimuli and maintaining an emotional response to such stimuli elicited no main effect of time (F[1,88] = 0.29, p = .59, η^2 = .003), no main effect of stimulation (F[2,88] = 0.64, p = .53, η^2 = .01), and no time × stimulation condition interaction (F[2,88] = 1.15, p = .32, η^2 = .03; see Table 8). For all stimulus and instruction categories, Tukey's HSD post hoc tests did not reveal any significant pairwise differences between conditions (all ps > .33). For mean SCR, a similar analysis showed a significant main effect of time (F[1,88] = 7.58, p = .007, η^2 = .08), a marginal main effect of stimulation (F[2,88] = 2.79, p = .07, η^2 = .06), and no time × stimulation condition interaction (F[2,88] = 0.25, p = .78, η^2 = .006; see Table 9). Tukey's HSD post hoc tests suggested a marginal difference between the anodal and the sham conditions (p = .07), driven by the sham condition having significantly larger downregulation score on this measure at baseline; other pairwise comparisons were not significant (all ps > .21). The same differences for ER task ratings showed similar results, with no main effect of time (F[1,88] = 0.44, p = .83, η^2 = .001), no main effect of stimulation (F[2,88] = 0.50, p = .61, η^2 = .01), and no time × stimulation condition interaction (F[2,88] = 0.38, p = .69, η^2 = .009; see Table 10), with all non-significant multiple comparisons (all ps > .59). For ER task ratings RTs, on the other hand, there was a significant effect of time (F[1,88] = 5.46, p = .02, η^2 = .06), with participants becoming faster on the task in the section portion of the experiment regardless of condition, no effect of stimulation (F[2,88] = 0.04, p = .97, η^2 = .001), and no time × stimulation condition interaction (F[2,88] = 0.28, p = .78, η^2 = .006; post hoc tests were all not significant all ps > .97, see Table 11).

Regarding differences between downregulating in response to negative stimuli, relative to neutral stimuli, for SCR Delta there was no main effect of time (F[1,88] = 1.24, p = .27, η^2 = .01), no main effect of stimulation (F[2,88] = 1.00, p = .37, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 0.95, p = .39, η^2 = .02; see Table 8), with all non-significant multiple comparisons (all ps > .39). For mean SCR, similarly there was no main effect of time (F[1,88] = 0.08, p = .78, η^2 = .001), no main effect of stimulation (F[2,88] = 0.68, p = .51, η^2 = .02), but a marginal time × stimulation condition interaction (F[2,88] = 2.90, p = .06, η^2 = .06; see Table 9). Tukey's HSD post hoc tests were not significant (all ps > .55). For the same comparison with regards to ER task ratings there was a significant main effect of time (F[1,88] = 11.39, p = .001, η^2 = .12) with the difference between the two stimulus conditions larger at baseline, no main effect of stimulation (F[2,88] = 1.26, p = .29, η^2 = .03), and no time × stimulation condition interaction (F[2,88] = 0.14, p = .87, η^2 = .003; see Table 10), with all non-significant multiple comparisons (all ps > .26). Similarly, for ER task ratings RTs, there was a significant main effect of time (F[1,88] = 8.46, p = .005, η^2 = .09), no main effect of stimulation (F[2,88] = 1.26, p = .29, η^2 = .03), and a non-significant time × stimulation condition interaction (F[2,88] = 2.64, p = .08, η^2 = .06; see Table 11), with all conditions showing a reduction in RTs in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all ps > .15).

When comparing downregulation trials for positive stimuli relative to looking at neutral stimuli, for SCR Delta there was a significant main effect of time (F[1,88] = 4.08, p = .046, η^2 = .04), no main effect of stimulation (F[2,88] = 0.70, p = .50, η^2 = .02), and no time × stimulation condition interaction (F[2,88] = 1.76, p = .18, η^2 = .04; see Table 8). All Tukey's HSD post hoc tests were not significant (all ps > .15). For mean SCR, there was no main effect of time (F[1,88] = 0.57, p = .45, η^2 = .006), no main effect of stimulation (F[2,88] = 0.004, p = .99, η^2 < .001), and

no time × stimulation condition interaction (F[2,88] = 0.80, p = .45, η^2 = .02; see Table 9), with none of the Tukey's HSD post hoc pairwise tests reaching significance (all ps > .99). For ER ratings, there was similarly a significant main effect of time, with the difference in ratings becoming smaller in the second (under stimulation part) of the experiment (F[1,88] = 8.46, p = .005, η^2 = .09), no main effect of stimulation (F[2,88] = 0.21, p = .81, η^2 = .005), and a non-significant time × stimulation condition interaction (F[2,88] = 1.02, p = .37, η^2 = .02; see Table 10), with all conditions showing a reduction in ratings in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all ps > .80). Lastly, for ER task ratings RTs, there was a marginally significant main effect of time (F[1,88] = 3.86, p = .053, η^2 = .04), no main effect of stimulation (F[2,88] = 0.66, p = .52, η^2 = .02), and a non-significant time × stimulation condition interaction (F[2,88] = 2.65, p = .08, η^2 = .06; see Table 11), with all conditions showing a reduction in RTs in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all ps > .54).

Regarding the difference between downregulation trials for positive stimuli relative to maintenance trials for positive stimuli, for SCR Delta there was no main effect of time (F[1,88] = 0.79, p = .38, η^2 = .01), no main effect of stimulation (F[2,88] = 0.14, p = .87, η^2 = .003), and no time × stimulation condition interaction (F[2,88] = 1.56, p = .22, η^2 = .03; see Table 8). All Tukey's HSD post hoc tests were not significant (all ps > .89). For mean SCR, there was no main effect of time (F[1,88] = 0.70, p = .40, η^2 = .008), a marginal effect of stimulation (F[2,88] = 2.56, p = .08, η^2 = .06), and no time × stimulation condition interaction (F[2,88] = 1.93, p = .15, η^2 = .04; see Table 9), with none of the Tukey's HSD post hoc pairwise tests reaching significance (all ps > .08). For ER ratings, there was similarly a significant main effect of time, with the difference in ratings becoming smaller in the second (under stimulation part) of the experiment (F[1,88] = 20.40,

$p < .001$, $\eta^2 = .19$), no main effect of stimulation ($F[2,88] = 1.20$, $p = .31$, $\eta^2 = .03$), and a non-significant time × stimulation condition interaction ($F[2,88] = 1.48$, $p = .23$, $\eta^2 = .03$; see Table 10), with all conditions showing a reduction in ratings in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all *p*s > .34). Lastly, for ER task ratings RTs, there was no significant main effect of time ($F[1,88] = 1.29$, $p = .26$, $\eta^2 = .01$), no main effect of stimulation ($F[2,88] = 0.11$, $p = .89$, $\eta^2 = .003$), and a non-significant time × stimulation condition interaction ($F[2,88] = 0.51$, $p = .60$, $\eta^2 = .01$; see Table 11), with all conditions showing a reduction in RTs in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all *p*s > .89).

To explore further the marginally significant interactions in the downregulation conditions for positive and negative stimuli, we examined any differences between these two trial types directly, as a function of stimulation type. For SCR Delta there was no main effect of time ($F[1,88] = 1.61$, $p = .21$, $\eta^2 = .02$), no main effect of stimulation ($F[2,88] = 0.56$, $p = .57$, $\eta^2 = .02$), but a significant time × stimulation condition interaction ($F[2,88] = 4.02$, $p = .02$, $\eta^2 = .08$; see Table 8), although none of the Tukey's HSD post hoc pairwise tests were significant (all *p*s > .60). For mean SCR, similar analysis showed no main effect of time ($F[1,88] = 0.18$, $p = .68$, $\eta^2 = .002$), no main effect of stimulation ($F[2,88] = 0.49$, $p = .62$, $\eta^2 = .01$), and no time × stimulation condition interaction ($F[2,88] = 0.73$, $p = .49$, $\eta^2 = .02$; see Table 9); none of the Tukey's HSD post hoc pairwise tests were significant (all *p*s > .65).With regards to ER task ratings, there was no main effect of time ($F[1,88] = 0.09$, $p = .77$, $\eta^2 = .001$), no main effect of stimulation ($F[2,88] = 1.52$, $p = .22$, $\eta^2 = .03$), and a non-significant time × stimulation condition interaction ($F[2,88] = 0.18$, $p = .83$, $\eta^2 = .004$; see Table 10), with all conditions showing a reduction in RTs in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all *p*s > .22). Lastly, for

ER task ratings RTs, there was similarly no main effect of time (F[1,88] = 0.84, p = .36, η^2 = .009), no main effect of stimulation (F[2,88] = 0.42, p = .66, η^2 = .009), and a non-significant time × stimulation condition interaction (F[2,88] = 0.61, p = .54, η^2 = .01; see Table 11), with all conditions showing a reduction in RTs in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all ps > .64).

We further examined any effects of stimulation on the differences between negative and positive look trials: For SCR Delta there was no main effect of time (F[1,88] = 0.80, p = .78, η^2 = .001), no main effect of stimulation (F[2,88] = 0.22, p = .80, η^2 = .005), and no time × stimulation condition interaction (F[2,88] = 0.29, p = .75, η^2 = .007; see Table 8), with none of the Tukey's HSD post hoc pairwise tests reaching statistical significance (all ps > .80). For mean SCR similarly there was no main effect of time (F[1,88] = 0.05, p = .83, η^2 = .001), no main effect of stimulation (F[2,88] = 2.02, p = .14, η^2 = .04), and no time × stimulation condition interaction (F[2,88] = 2.08, p = .13, η^2 = .05; see Table 9), with none of the Tukey's HSD post hoc pairwise tests reaching statistical significance (all ps > .80). With regards to ER task ratings, there a was a significant main effect of time with the difference in ratings between negative and positive look conditions increasing during tDCS (F[1,88] = 12.34, p = .001, η^2 = .12), no main effect of stimulation (F[2,88] = 0.03, p = .97, η^2 = .001), and a non-significant time × stimulation condition interaction (F[2,88] = 0.43, p = .65, η^2 = .01; see Table 10), with all conditions showing a reduction in RTs in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all ps > .22). Lastly, for ER task ratings RTs, there was no main effect of time (F[1,88] = 0.08, p = .93, η^2 < .001), no main effect of stimulation (F[2,88] = 0.15, p = .86, η^2 = .003), and a non-significant time × stimulation condition interaction (F[2,88] = 0.10, p = .91, η^2 = .002; see Table 11), with all

conditions showing a reduction in RTs in the second half of the experiment. All Tukey's HSD post hoc tests were not significant (all *p*s > .86)

Overall Effects

To examine any possible interactions between all variables (time, stimulation type, and stimulus valence), we conducted a 2 × 5 × 3 ANOVA with time (baseline, stimulation) and trial type (negative downregulate, negative maintain, positive downregulate, positive maintain, neutral maintain) as the within-subjects factors and stimulation condition [anodal, cathodal, sham stimulation] as the between-subject factor. In the absence of any task order effects (between the ER task and the control forward digit span task), all analyses were collapsed across task order. For SCR Delta there was no main effect of time (F[1,88] = 0.21, p = .65, η^2 = .002), a significant main effect of trial type (F[4,88] = 2.88, p = .02, η^2 = .03), no main effect of stimulation (F[2,88] = 0.80, p = .45, η^2 = .01), and no interactions between trial type × condition (F[2,88] = 0.45, p = .89, η^2 = .003), time × trial type (F[4,88] = 1.29, p = .27, η^2 = .01), or time × condition (F[2,88] = 0.50, p = .61, η^2 = .01). The 3-way interaction among time × trial type × condition was not significant (F[8,88] = 1.43, p = .18, η^2 = .03). For Mean SCR there was a significant main effect of time (F[1,88] = 4.59, p = .035, η^2 = .05) and a significant interaction between trial type × condition (F[8,88] = 2.12, p = .03, η^2 = .003). There was no main effect of trial type (F[4,88] = 0.84, p = .50, η^2 = .009), no main effect of stimulation (F[2,88] = 1.58, p = .21, η^2 = .04), and no time × trial type (F[4,88] = 0.93, p = .45, η^2 = .01) or time × condition (F[2,88] = 0.79, p = .46, η^2 = .02) interactions. The 3-way interaction among time × trial type × condition did not reach statistical significance (F[8,88] = 1.79, p = .08, η^2 = .04). For the ER task Ratings there was a significant main effect of time (F[1,88] = 10.24, p = .002, η^2 = .10), a significant main effect of trial type (F[4,88] = 191.33, p < .001, η^2 = .69) and a significant time × trial type interaction

(F[4,88] = 14.45, p < .001, η^2 = .14). There was no main effect of stimulation (F[2,88] = 1.13, p = .33, η^2 = .03), no interaction between trial type × condition (F[8,88] = 0.86, p = .55, η^2 = .02), and no time × condition interaction (F[2,88] = 0.20, p = .82, η^2 = .005). The 3-way interaction among time × trial type × condition was not significant (F[8,88] = 0.48, p = .62, η^2 = .01). Lastly, regarding RTs for the ER ratings there was a significant main effect of time (F[1,88] = 88.22, p < .0001, η^2 = .50), a significant main effect of trial type (F[4,88] = 62.34, p < .001, η^2 = .42), and a significant interaction between time × trial type (F[4,88] = 2.87, p = .02, η^2 = .03). There was no main effect of stimulation (F[2,88] = 0.30, p = .74, η^2 = .007) and no time × condition (F[2,88] = 0.45, p = .64, η^2 = .01) or trial type × condition (F[8,88] = 0.76, p = .64, η^2 = .02) interactions. The 3-way interaction among time × trial type × condition was not significant (F[8,88] = 1.22, p = .29, η^2 = .03).

Discussion

The aim of the current study was to examine the causal involvement of left dlPFC in ER achieved through cognitive reappraisal using tDCS. Based on past research (Feeser et al., 2014), we hypothesized that anodal tDCS over the left dlPFC would lead to improvements in emotion regulation defined by greater decreases in skin conductance responses (delta, mean SCR) and lower emotional intensity ratings and RTs for these ratings when participants were asked to downregulate their emotional responses relative to maintaining these responses, especially for negative (relative to positive or neutral) stimuli. On the other hand, we hypothesized that cathodal tDCS over the left dlPFC would lead to the opposite effects, with sham tDCS producing no effect on any measure. Contrary to these predictions, neither anodal or cathodal stimulation had any effects on performance on this task on any of the measures and for all trial types, as indicated by the lack of differences among the three participant groups.

There are several explanations for these primarily non-significant findings regarding the impact of tDCS over the left dlPFC for cognitive reappraisal on this ER task. Although our three groups did not significantly differ on any demographic variables or baseline mood, there were significant baseline differences in regards to their ability for cognitive reappraisal of both negative and positive stimuli prior to the onset of stimulation. When downregulating positive stimuli at baseline, participants in the anodal condition had significantly stronger decreases in skin conductance (delta) during the cognitive reappraisal of positive stimuli compared to participants in the sham condition. In addition, when downregulating emotional responses to negative stimuli at baseline, participants in the anodal condition indicated significantly lower emotional intensity ratings across conditions compared to participants in the cathodal and sham conditions. Taken together, these two findings prior to the onset of stimulation suggest that participants randomly assigned to the anodal condition seemed to be better able to reappraise both positive and negative stimuli at baseline, as indicated by greater decreases in skin conductance and lower emotional intensity ratings. These baseline differences likely impacted our ability to manipulate cognitive reappraisal in this ER task with tDCS, because participants in the anodal condition were already more successful at downregulating their emotional responses relative to participants in the other two conditions, and this difference was in the direction of the hypothesized effect. Anodal tDCS did not, thus, seem to have a significant impact in exaggerating this difference.

In addition, our results showed several significant effects of time (i.e., performance at baseline relative to under stimulation) for mean skin conductance responses, emotional intensity ratings, and reaction times which might have further influenced our ability to induce measurable tDCS effects. Both conditions in which participants had to maintain their emotional responses to either negative or positive stimuli showed an increase in mean SCR from baseline relative to

stimulation, regardless of stimulation condition. This stronger mean autonomic response (SCR) indicates a stronger emotional response when looking at negative and positive images during the second portion of the ERT administration that occurred under tDCS, and could reflect increased arousal as a result of the tDCS procedure (i.e., the application of electrodes or other demand characteristics of the study), but not the experimental manipulation itself (i.e., the stimulation intensity). Interestingly, we found an opposite relationship with emotional intensity ratings. Average emotional intensity ratings were marginally lower during the second part of the ERT for the negative decrease, positive decrease, and positive look conditions as compared to baseline, an effect that was independent of stimulation condition. This indicates that participants were rating positive and negative images as less intense during the second part of ER task administration, either because they viewed these images as less intense from the onset of the image or because they were better able to decrease their initial emotional response to these images during the second part of the study. We also found significant differences in reaction times to complete these emotional intensity ratings across all trial types from baseline to stimulation, regardless of stimulation type. For the reappraisal, but not the maintenance, conditions (i.e., downregulation trials for either negative or positive stimuli) participants had significantly longer reaction times during the second part of the ERT (under tDCS), regardless of tDCS condition. For the maintenance trials, participants showed significantly shorter reaction times during the second part of the ERT under tDCS. This indicates that when regulating, participants were taking significantly longer to make their judgement of the emotional intensity of their experience and that when maintaining their emotional response they took a significantly shorter time to make their ratings during the second part of the study.

None of the above effects were due to tDCS stimulation, but instead they could be attributed to practice effects during the stimulation phase by having already completed two rounds of the task. Although the images used in the second portion of the experiment under stimulation were different than the images used in the first portion of the experiment at baseline, it is possible that participants became habituated both to viewing these images and the task itself. For example, the shorter reaction times could simply indicate that participants were becoming faster at completing the task and not because of any changes in emotion regulation ability.

In addition, although this study can be viewed as an extension of the experiment by Feeser et al. (2014), our study design did deviate from theirs in several ways. First, they stimulated the right dlPFC instead of the left dlPFC. We chose to stimulate the left dlPFC because most previously mentioned tDCS studies on emotional processing implicated the left dlPFC, especially for cognitive reappraisal tasks (e.g., Austin et al., 2016; Pena-Gomez et al., 2011) and because of the strong associations between activity in this region and reappraisal abilities as shown in fMRI research (see Buhle et al., 2014). Another difference was in the specific reappraisal instructions given to participants. Feeser et al. (2014) instructed participants to "view the scene objectively from a third-person perspective" when regulating, while we instructed participants to "tell yourself something about the picture that helps you feel less emotional." We chose these instructions because they allow for a more broad interpretation of reappraisal which is an emotion regulation strategy with many variations in the specific way it is used. Another difference in the CRT between the two studies pertains to the valence of the images included. Feeser et al. (2014) only showed negative images, whereas in the present study we showed both negative and positive images. Finally, Feeser et al. (2014) included an up-regulate condition, in which participants were instructed to intensify their emotional response to the images, whereas we only instructed

participants to down-regulate their emotional responses or maintain these responses. It is possible that these differences in instructions and valence types contributed to the differences in the findings between the two studies.

These discrepancies highlight the importance of future research in this area. For example, future investigations should examine the effect of stimulation on other brain regions associated with emotion regulation, as guided by an extensive body of work pointing to a network of regions across dorsal, ventral, and medial PFC and subcortical regions. Although our electrical field modeling alleviated any concerns regarding electrical stimulation from our particular tDCS montage spilling over neighboring brain regions, the use of concurrent brain imaging with tDCS could help specify exactly which brain region(s) modulate their activity in response to tDCS and which regions are not.

A limitation of the current study was its relatively small sample size. This aspect of the present experiment may perhaps account, in part, for the lack of significant findings due to the random but demonstrated differences among participants at baseline on several of the key study measures. The significant effect of time (baseline, under stimulation) on many of our variables limited our ability to examine any effects specific to the tDCS manipulation. Although the mixed design used in this study allowed us to compare each participants' performance on this task relative to their own baseline performance (i.e., prior to stimulation), it is further possible that the repeated administration of the task improved emotion regulation that overshadowed our ability to examine the impact of increased or decreased left dlPFC engagement on emotion regulation as a result of tDCS.

The present study is only the second to our knowledge to test directly the effects of tDCS over prefrontal cortex on emotion regulation. A large body of imaging research has identified

several brain regions to be consistently involved in emotion regulation, including the dlPFC (see Buhle et al., 2014), however these studies are correlational in nature and cannot tap into the potential causal relationship between these brain regions and successful emotion regulation. tDCS is one tool that can be used to begin to infer such causal relationships. Our study did not find an effect of tDCS on the ability to reappraise negative or positive images, however several potential reasons have been outlined above which could explain these null findings.

The experience of emotions makes up a large part of our day-to-day lives. Successful emotion regulation has been associated with overall well-being (Gross, 2015). Conversely, deficits in emotion regulation have been implicated in numerous psychopathologies (i.e. Aldao, Nolen-Hoeksema, & Schweizer, 2010). Thus, the importance of understanding what drives successful emotion regulation is central for cognitive and affective neuroscience research. Identifying the critical brain regions involved in emotion regulation through neuroimaging can be complemented with findings from noninvasive brain stimulation that can demarcate the causal role of each of these areas, as well as the larger network they comprise, in successful emotion regulation in health and disease.

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Table 1
Demographic Characteristics

Variable	*N (%)* Anodal (*N* = 27)	Cathodal (*N* = 32)	Sham (*N* = 32)
Age, mean (*SD*)	19.27 (1.87)	18.97 (1.47)	19.53 (2.64)
Education			
High School	26 (96.3%)	31 (96.9%)	31 (96.9%)
GED	0	0	1 (3.1%)
No HX Depression	25 (92.6%)	31 (96.9%)	29 (90.6%)
Gender			
Male	10 (37.0%)	10 (31.3%)	11 (34.4%)
Female	17 (63.0%)	22 (68.8%)	21 (65.6%)
Race			
White	25 (92.6%)	20 (62.5%)	22 (68.8%)
Black	0	3 (9.4%)	4 (12.5%)
American Indian	0	1 (3.1%)	1 (3.1%)
More than One	0	3 (9.4%)	1 (3.1%
Ethnicity			
Hispanic or Latino	1 (3.7%)	4 (12.5%)	1 (3.1%)
Not Hispanic or Latino	26 (96.3%)	27 (84.4)	31 (96.9%)

Note. N = sample, *%* = percent of condition sample.

Table 2
Means and Standard Deviations of PANAS

Phase	Valence	*M* (*SD*) Anodal	Cathodal	Sham
Baseline	Negative	16.26 (4.37)	15.63 (3.62)	15.84 (4.33)
	Positive	26.19 (6.51)	24.09 (6.00)	26.81 (7.05)
Pre-Stimulation	Negative	15.08 (3.53)	14.42 (3.63)	14.64 (2.76)
	Positive	21.65 (6.55)	21.55 (7.25)	24.33 (7.32)
Post-Stimulation	Negative	14.63 (3.41)	14.69 (3.66)	14.50 (4.05)
	Positive	21.07 (7.52)	20.94 (8.15)	23.19 (8.13)

Note. *M* = mean, *SD* = standard deviation.

Table 3

Means and Standard Deviations for Baseline SCR and Emotion Regulation Task Variables

Valence/Instruction	Metric	*M (SD)* Anodal	Cathodal	Sham
Negative Decrease	Delta	-0.13 (0.13)	-0.16 (0.13)	-0.11 (0.01)
	Mean	7.24 (5.17)	5.41 (3.08)	6.43 (4.71)
	Rating	3.83 (1.36)	4.48 (1.32)	4.39 (1.31)
	RT	1848.02 (506.56)	1667.05 (460.68)	1658.06 (407.89)
Positive Decrease	Delta	-0.15 (0.12)	-0.12 (0.10)	-0.10 (0.10)
	Mean	7.23 (5.16)	5.37 (3.04)	6.44 (4.69)
	Rating	2.98 (1.57)	3.59 (1.52)	3.14 (1.40)
	RT	1724.71 (639.12)	1612.30 (567.68)	156.70 (541.70)
Negative Look	Delta	-0.13 (0.17)	-0.12 (0.11)	-0.12 (0.11)
	Mean	7.09 (5.25)	5.27 (3.15)	6.20 (4.73)
	Rating	5.37 (1.36)	5.64 (1.23)	5.86 (1.23)
	RT	1519.37 (618.87)	1362.34 (579.44)	1320.39 (512.70)
Positive Look	Delta	-0.11 (0.10)	-0.10 (0.08)	-0.10 (0.10)
	Mean	6.91 (5.03)	5.18 (3.20)	6.27 (4.78)
	Rating	4.74 (1.56)	4.84 (1.44)	5.03 (1.53)
	RT	1375.19 (594.61)	1226.22 (521.45)	1224.97 (487.98)
Neutral Look	Delta	-0.14 (0.13)	-0.13 (0.10)	-0.13 (0.13)
	Mean	7.25 (5.18)	5.37 (3.09)	6.50 (4.69)
	Rating	1.89 (1.06)	2.13 (1.34)	1.88 (0.87)
	RT	1081.72 (567.39)	1194.42 (434.79)	1202.25 (430.07)

Note. M = mean, *SD* = standard deviation.

Table 4
Means and Standard Deviations for SCR Median Delta

Valence/Instruction	Phase	*M (SD)* Anodal	Cathodal	Sham
Negative Decrease	Baseline	-0.13 (0.13)	-0.16 (0.13)	-0.11 (0.01)
	Stimulation	-0.13 (0.18)	-0.15 (0.12)	-0.13 (0.11)
Positive Decrease	Baseline	-0.15 (0.12)	-0.12 (0.10)	-0.10 (0.10)
	Stimulation	-0.12 (0.10)	-0.18 (0.17)	-0.13 (0.10)
Negative Look	Baseline	-0.13 (0.17)	-0.12 (0.11)	-0.12 (0.11)
	Stimulation	-0.14 (0.15)	-0.14 (0.16)	-0.12 (0.09)
Positive Look	Baseline	-0.11 (0.10)	-0.10 (0.08)	-0.10 (0.10)
	Stimulation	-0.11 (0.09)	-0.13 (0.17)	-0.09 (0.13)
Neutral Look	Baseline	-0.14 (0.13)	-0.13 (0.10)	-0.13 (0.13)
	Stimulation	-0.12 (0.12)	-0.13 (0.11)	-0.11 (0.12)

Note. M = mean, *SD* = standard deviation.

Table 5
Means and Standard Deviations for Mean SCR

Valence/Instruction	Phase	*M (SD)* Anodal	Cathodal	Sham
Negative Decrease	Baseline	7.24 (5.17)	5.41 (3.08)	6.43 (4.71)
	Stimulation	7.85 (4.94)	6.13 (2.70)	6.62 (3.27)
Positive Decrease	Baseline	7.23 (5.16)	5.37 (3.04)	6.44 (4.69)
	Stimulation	7.94 (4.74)	6.12 (2.72)	6.56 (3.15)
Negative Look	Baseline	7.09 (5.25)	5.27 (3.15)	6.20 (4.73)
	Stimulation	7.96 (4.87)	6.16 (2.77)	6.52 (3.21)
Positive Look	Baseline	6.91 (5.03)	5.18 (3.20)	6.27 (4.78)
	Stimulation	7.90 (4.86)	6.15 (2.59)	6.63 (3.24)
Neutral Look	Baseline	7.25 (5.18)	5.37 (3.09)	6.50 (4.69)
	Stimulation	7.94 (4.92)	6.14 (2.66)	6.52 (3.21)

Note. *M* = mean, *SD* = standard deviation.

Table 6
Means and Standard Deviations for Emotion Regulation Task Ratings

				M (SD)
Valence/Instruction	Phase	Anodal	Cathodal	Sham
Negative Decrease	Baseline	3.83 (1.36)	4.48 (1.32)	4.39 (1.31)
	Stimulation	3.65 (1.49)	4.17 (1.34)	4.27 (1.83)
Positive Decrease	Baseline	2.98 (1.57)	3.59 (1.52)	3.14 (1.40)
	Stimulation	2.93 (1.41)	3.22 (1.46)	3.06 (1.31)
Negative Look	Baseline	5.37 (1.36)	5.64 (1.23)	5.86 (1.23)
	Stimulation	5.13 (1.52)	5.45 (1.34)	5.58 (1.65)
Positive Look	Baseline	4.74 (1.56)	4.84 (1.44)	5.03 (1.53)
	Stimulation	3.80 (1.50)	4.14 (1.51)	4.39 (1.84)
Neutral Look	Baseline	1.89 (1.06)	2.13 (1.34)	1.88 (0.87)
	Stimulation	2.15 (0.97)	2.44 (1.12)	2.22 (1.00)

Note. *M* = mean, *SD* = standard deviation.

Table 7
Means and Standard Deviations for Emotion Regulation Task Reaction Times

Valence/Instruction	Metric (Medians)	*M (SD)* Anodal	Cathodal	Sham
Negative Decrease	Baseline	1848.02 (506.56)	1667.05 (460.68)	1658.06 (407.89)
	Stimulation	1376.94 (651.79)	1356.56 (541.33)	1303.33 (509.53)
Positive Decrease	Baseline	1724.71 (639.12)	1612.30 (567.68)	1562.70 (541.70)
	Stimulation	1307.41 (623.86)	1278.80 (616.35)	1350.66 (555.25)
Negative Look	Baseline	1519.37 (618.87)	1362.34 (579.44)	1320.39 (512.70)
	Stimulation	1216.65 (625.27)	1124.30 (576.79)	1109.64 (507.11)
Positive Look	Baseline	1375.19 (594.61)	1226.22 (521.45)	1224.97 (487.98)
	Stimulation	1058.75 (596.89)	1034.66 (563.32)	998.88 (470.81)
Neutral Look	Baseline	1081.72 (567.39)	1194.42 (434.79)	1202.25 (430.07)
	Stimulation	1008.22 (570.58)	928.20 (471.31)	967.98 (467.93)

Note. *M* = mean, *SD* = standard deviation.

Table 8
Means and Standard Deviations for Delta Valence Comparisons

Valence/Instruction	Phase	*M (SD)* Anodal	Cathodal	Sham
ND – NL	Baseline	0.00 (0.03)	-0.04 (0.02)	0.00 (0.01)
	Stimulation	0.01 (0.03)	-0.01 (0.02)	-0.01 (0.01)
ND – NEU	Baseline	0.02 (0.02)	-0.03 (0.02)	0.01 (0.02)
	Stimulation	-0.03 (0.02)	-0.02 (0.01)	-0.02 (0.02)
PD – PL	Baseline	-0.04 (0.02)	-0.01 (0.01)	0.00 (0.02)
	Stimulation	-0.02 (0.02)	-0.04 (0.03)	-0.04 (0.02)
PD – NEU	Baseline	-0.01 (0.02)	0.02 (0.01)	0.03 (0.02)
	Stimulation	0.00 (0.02)	-0.05 (0.03)	-0.02 (0.02)
ND – PD	Baseline	0.03 (0.02)	-0.05 (0.02)	-0.02 (0.01)
	Stimulation	-0.01 (0.03)	0.03 (0.03)	0.00 (0.01)
NL – PL	Baseline	-0.01 (0.03)	-0.02 (0.02)	-0.02 (0.01)
	Stimulation	-0.03 (0.03)	-0.01 (0.02)	-0.03 (0.02)

Note. *M* = mean, *SD* = standard deviation.

Table 9
Means and Standard Deviations for Mean SCR Valence Comps

Valence/Instruction	Phase	*M (SD)* Anodal	Cathodal	Sham
ND – NL	Baseline	0.14 (0.30)	0.15 (0.49)	0.24 (0.54)
	Stimulation	-0.11 (0.31)	-0.03 (0.45)	-0.01 (0.36)
ND – NEU	Baseline	-0.15 (0.27)	0.05 (0.47)	-0.01 (0.38)
	Stimulation	-0.10 (0.27)	-0.01 (0.36)	0.10 (0.34)
PD – PL	Baseline	0.32 (0.46)	0.19 (0.42)	0.17 (0.54)
	Stimulation	0.55 (2.77)	-0.74 (2.51)	0.21 (1.20)
PD – NEU	Baseline	-0.02 (0.29)	0.01 (0.45)	-0.06 (0.32)
	Stimulation	-0.01 (0.38)	-0.02 (0.26)	0.05 (0.27)
ND – PD	Baseline	0.01 (0.33)	0.05 (0.64)	0.02 (0.46)
	Stimulation	-0.09 (0.36)	0.02 (0.30)	0.06 (0.27)
NL – PL	Baseline	0.18 (0.45)	0.09 (0.55)	0.06 (0.46)
	Stimulation	0.57 (2.92)	-0.70 (2.51)	0.17 (2.03)

Note. *M* = mean, *SD* = standard deviation.

Table 10

Means and Standard Deviations for Rating Valence Comparisons

Valence/Instruction	Phase	*M (SD)* Anodal	Cathodal	Sham
ND – NL	Baseline	-1.54 (0.22)	-1.16 (0.23)	-1.47 (0.22)
	Stimulation	-1.48 (0.26)	-1.28 (0.22)	-1.31 (0.26)
ND – NEU	Baseline	1.94 (0.20)	2.36 (0.33)	2.52 (0.24)
	Stimulation	1.50 (0.23)	1.73 (0.25)	2.05 (0.34)
PD – PL	Baseline	-1.76 (0.30)	-1.25 (0.29)	-1.89 (0.25)
	Stimulation	-0.87 (0.21)	-0.92 (0.32)	-1.33 (0.23)
PD – NEU	Baseline	1.09 (0.21)	1.47 (0.28)	1.27 (0.22)
	Stimulation	0.78 (0.18)	0.78 (0.22)	0.84 (0.21)
ND – PD	Baseline	0.85 (0.18)	0.89 (0.25)	1.25 (0.20)
	Stimulation	0.72 (0.16)	0.95 (0.21)	1.20 (0.24)
NL – PL	Baseline	0.63 (0.24)	0.80 (0.25)	0.83 (0.25)
	Stimulation	1.33 (0.23)	1.31 (0.30)	1.19 (0.23)

Note. *M* = mean, *SD* = standard deviation.

Table 11
Means and Standard Deviations for Rating Reaction Time Valence Comparisons

Valence/Instruction	Phase	*M (SD)* Anodal	Cathodal	Sham
ND – NL	Baseline	328.65 (97.23)	304.70 (81.91)	337.67 (76.11)
	Stimulation	160.30 (83.57)	232.27 (86.67)	193.69 (74.37)
ND – NEU	Baseline	766.30 (104.51)	472.63 (72.83)	455.81 (66.69)
	Stimulation	368.72 (97.75)	428.36 (86.61)	335.34 (85.00)
PD – PL	Baseline	349.52 (131.25)	386.08 (75.88)	337.73 (94.08)
	Stimulation	248.66 (84.85)	244.13 (69.56)	351.78 (82.63)
PD – NEU	Baseline	642.98 (121.29)	417.88 (79.05)	360.45 (81.91)
	Stimulation	299.19 (83.61)	350.59 (65.08)	382.67 (86.19)
ND – PD	Baseline	123.31 (81.59)	54.75 (73.37)	95.36 (74.02)
	Stimulation	69.54 (72.63)	77.77 (89.17)	-47.33 (72.43)
NL – PL	Baseline	144.19 (125.25)	136.13 (78.64)	95.42 (62.68)
	Stimulation	157.90 (58.95)	89.63 (103.56)	110.77 (63.52)

Note. *M* = mean, *SD* = standard deviation.

Figure 1a. Electrical Field Modeling showing electrical potential for the unilateral montage with anodal Stimulation over F3.

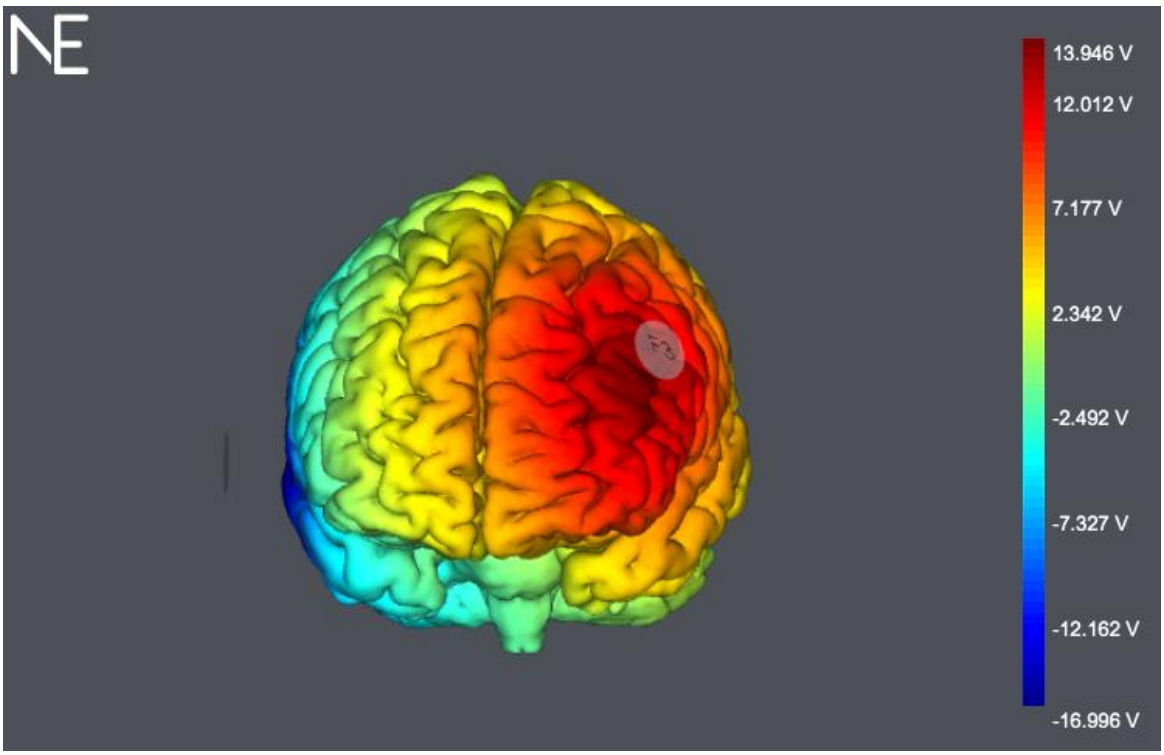

Figure 1b. Influence map showing high electrical potential for the area of interest for the unilateral montage with anodal stimulation over F3.

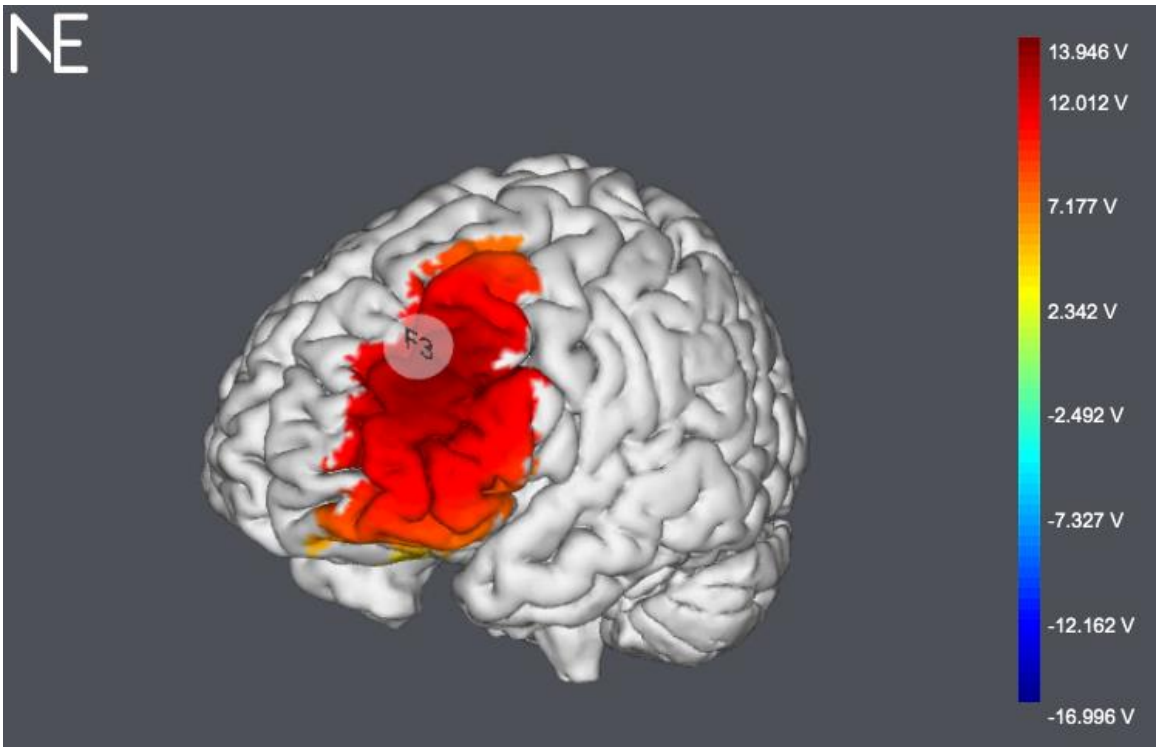

Figure 2. Effect of Stimulation Condition on Forward Digit Span Performance

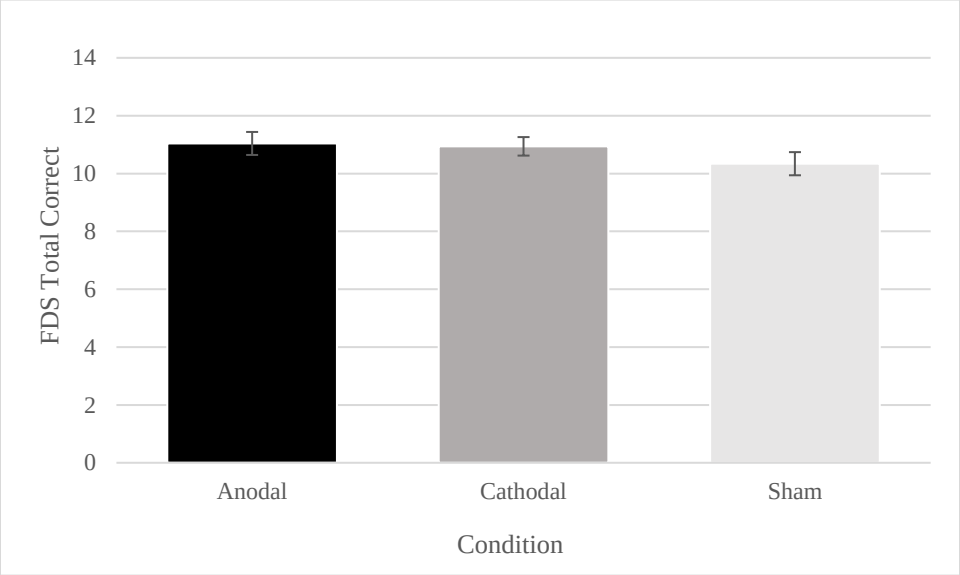

Figure 3. Effect of Stimulation Condition on SCR Median Delta Scores

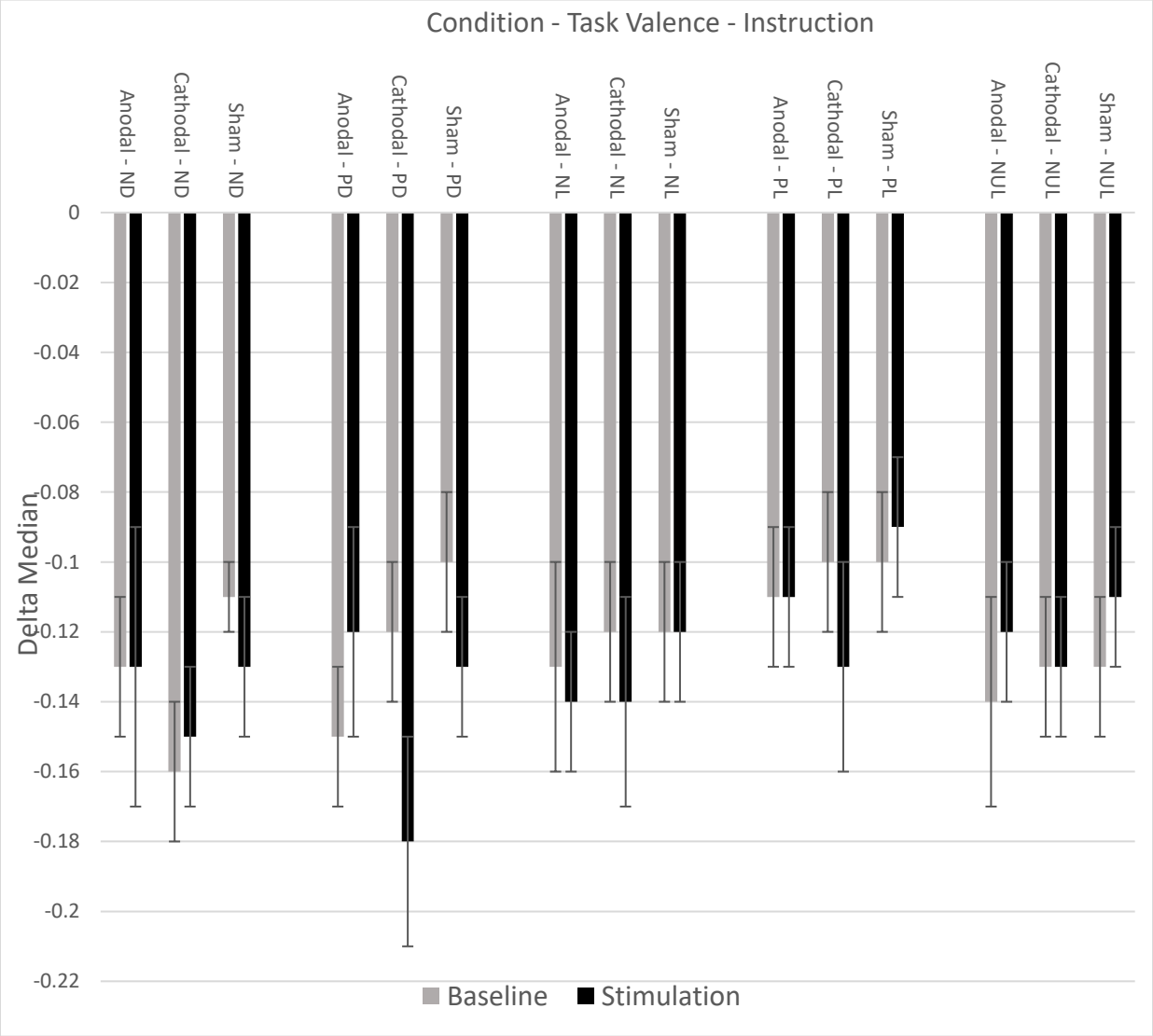

Figure 4. Effect of Stimulation Condition on SCR Mean Scores

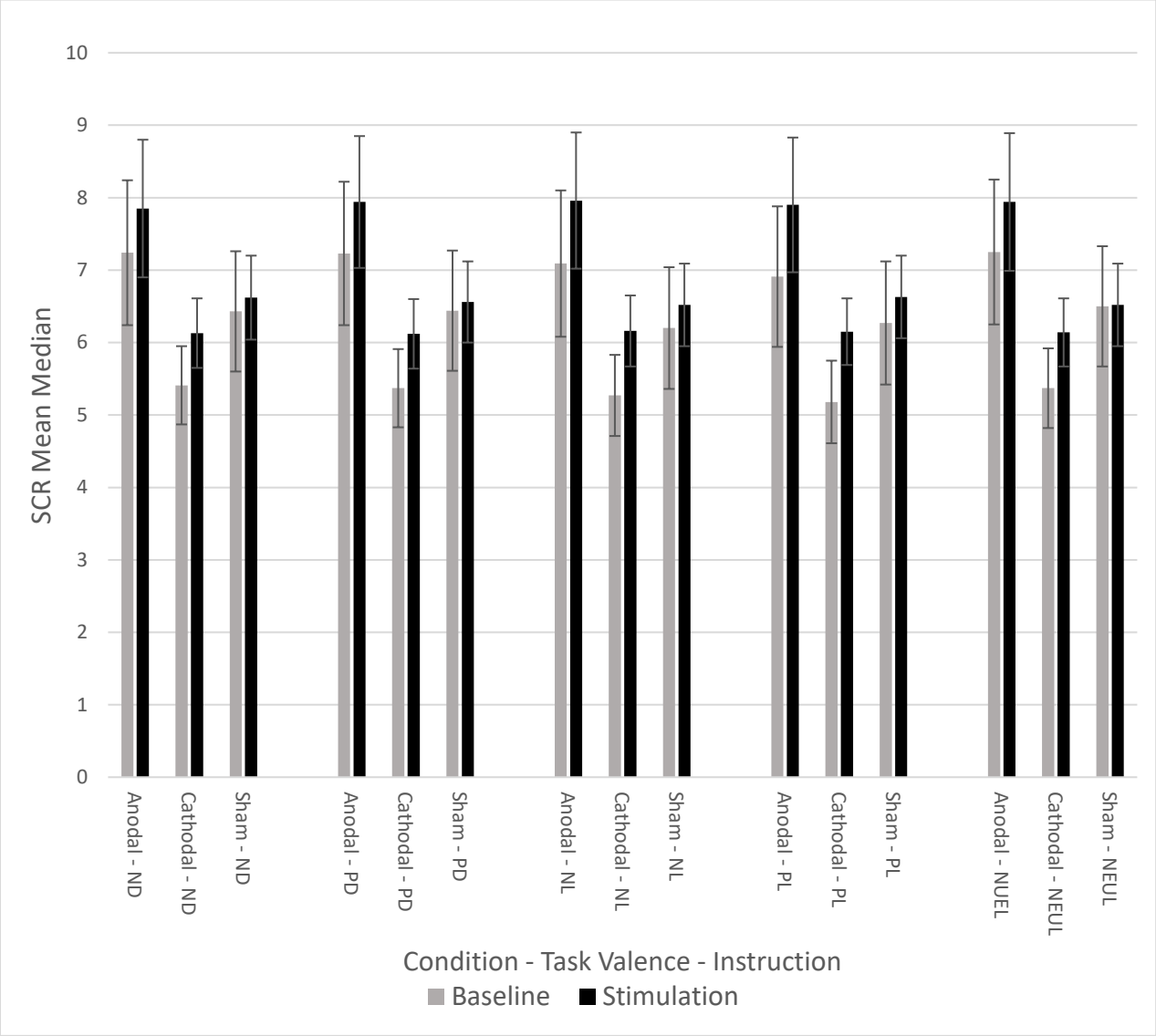

Figure 5. Effect of Stimulation Condition on SCR Median Rating Scores

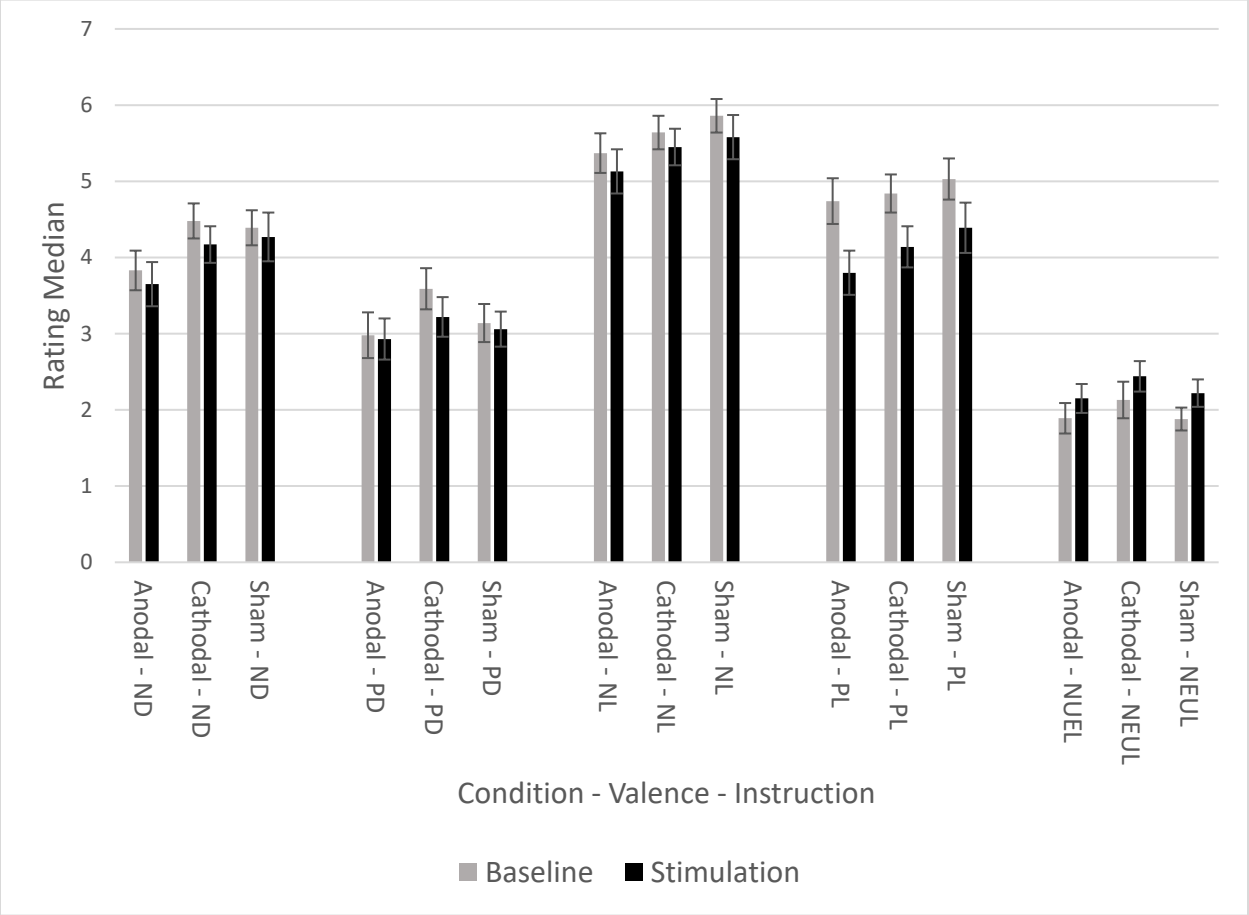

Figure 6. Effect of Stimulation Condition on SCR Median Rating Reaction Time Scores