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Anodal transcranial direct current stimulation (tDCS) over the left DLPFC improves emotion regulation

Abstract: *The study of emotion regulation constitutes a major area of research for having a complete picture of human emotional experience, and several lines of evidence claim that poor emotion regulation skills are particularly deleterious in different aspects of life. Previous tDCS studies have suggested the beneficial role of DLPFC stimulation to improve emotion processing and regulation. The present study was therefore conducted to confirm and extend the effects of DLPFC stimulation on emotion regulation by including both positive and negative emotional material. In this between subjects study, participants were randomly assigned to receive active or sham stimulation over the left DLPFC. Participants viewed negative, positive, and neutral pictures while attempting to decrease, increase, or not modulate their emotional reactions. Subjective reactions were assessed via on-line ratings. The main results show that anodal tDCS stimulation over the left DLPFC slightly improves the ability to increase emotion perception for positive emotions. More interestingly, the results demonstrate that tDCS enhances the regulation of both positive and negative emotions when the baseline is considered. This study provides additional data on the use of tDCS as a tool to increase emotion regulation not only for negative affective material, but also for positive ones.*

Keywords: *emotion regulation, transcranial direct current stimulation, DLPFC*

Introduction

Emotions are central and useful in everyday life. It is important to identify, express, understand, regulate, and use emotions to enhance the general wellbeing of the individual. The study of emotion regulation (i.e., the set of processes that modify emotional experiences) constitutes a major area of research for having a complete picture of human emotional experience (Gross, 2002). Indeed, a core component of emotional processing concerns how people deal, or cope with daily emotional experiences, and this ability is particularly essential for reducing the impact of a negative emotion (Lopes, Salovey, Côté, & Beers, 2005; Nelis et al., 2011, Quoidbach, Berry, Hansenne, & Mikolajczak, 2010). Poor emotional regulation skills are reported in many psychopathological disorders (Sheppes, Suri, & Gross, 2015), and more particularly in depression (Hansenne & Bianchi, 2007; Visted, Vøllestad, Nielsen, & Schanche, 2018) and in anxiety disorders (McLean & Foa, 2017; Cisler & Olatunji, 2012). It is therefore important to propose to people some emotion regulation strategies to down-regulate their negative emotions (e.g., attentional deployment, cognitive reappraisal or expressive suppression), but also to up-regulate their positive emotions (e.g., situation selection or cognitive reappraisal) because down-regulate negative emotions and up-regulate positive ones are the two forms of regulation most often encountered in daily life (Gross, Richards, & John, 2006).

Several studies have examined the neural bases of emotion regulation, and a general pattern has emerged in which the prefrontal and dorsal anterior cingulate regions involved in cognitive control show increased activity during active attempts to regulate emotion, together with the modulation of activity in regions involved in emotion processing such as the amygdala (Kim & Hamann, 2007; Ochsner & Gross, 2005). Findings from the emotion regulation domain support an emerging multilevel functional architecture involved in cognitive emotion regulation (Ochsner & Gross, 2008). In this model, cognitive strategies modulate the activity of prefrontal and cingulate systems requested for attention, response selection, working memory, language, mental-state attribution, and autonomic control. Specifically, activated regions include dorsal portions of the prefrontal cortex implicated in working memory and selective attention, ventral portions of the prefrontal cortex that have been implicated in

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language or response inhibition, dorsal portions of the anterior cingulate cortex implicated in monitoring processes, and dorsal portions of the medial prefrontal cortex implicated in reflecting upon one's own or someone else's affective states. The regulatory effects of any given strategy can be understood in terms of that strategy's reliance upon specific control processes and the regulatory effects that those control processes exert on systems involved in various aspects of emotional responding, such as the amygdala which has been implicated in the detection and encoding of affectively arousing stimuli.

Transcranial direct current stimulation (tDCS)

Transcranial direct current stimulation (tDCS) is a technique used to modify emotional experiences and cognition by modulating underlying neural activity through a weak electrical current applied to the scalp (Nitsche & Paulus, 2000). This very simple procedure enhances performance in several important cognitive domains, like memory and attention, reduces impulsivity in different domains, allows resistance to certain addictive drugs, and promotes positive feelings (Filmer, Dux, & Mattingley, 2014; Ke et al., 2019; Kuo & Nitsche, 2012; Miler, Meron, Baldwin, & Garner, 2018; Salib, Ho, Sussman, Pendharkar, & Halpern, 2018, Soyata, Aksu, Woods, İşçen, Sacar, & Karamürsel, 2019). tDCS is also applied in many psychopathological and clinical disorders including depression, anxiety disorders, and Parkinson disease with promising results (Hampstead, Briceño, Mascaro, Mourdoukoutas, & Bikson, 2016; Heeren et al., 2017; Lefaucheur et al., 2017; Palm, Hasan, Strube, & Padberg, 2016; Salehinejad, Ghanavai, Rostami, & Nejati, 2017). For instance, it has been demonstrated that 1 mA anodal tDCS over the left dorsolateral prefrontal cortex (DLPFC) improved cognitive control (i.e., better memory performance and reduced attentional bias) among patients with major depressive disorder (Wolkenstein & Plewnia, 2013). Although several studies have reported positive results in different domains with tDCS, some studies show that tDCS effects are rather small and difficult to replicate (Horvath, Forte, & Carter, 2015; Medina & Cason 2017; Tremblay, Lepage, Latulipe-Loiselle, Fregni, Pascual-Leone, & Théoret, 2014). A major reason explaining the discrepancy of the tDCS results is that the stimulation parameters (e.g., anode and cathode placements, duration of the stimulation) differ largely between studies (Dedoncker, Brunoni, Baeken, & Vanderhasselt, 2016).

Transcranial direct current stimulation (tDCS) and emotion regulation

While previous findings demonstrate the role of DLPFC during emotion regulation from brain imaging studies, these studies are mainly correlational and only few of them have investigated causal mechanisms between DLPFC activation and emotion regulation processes. Conversely, tDCS allows addressing the question of causality, and it can be used as a neuromodulatory technique for increasing emotion regulation.

Thus, tDCS as a potential tool to increase emotion regulation has been investigated in a few studies (Choi, Scott, & Lim, 2016). In a passive emotion study, 1 mA anodal tDCS over the left DLPFC reduced the perceived intensity of emotional valence for negative stimuli, but not for positive or neutral stimuli as compared to the sham condition (Pena-Gomez, Vidal-Pineiro, Clemente, Pascual-Leone, & Bartres-Faz, 2011). These results are interpreted as a consequence of an enhancement of cognitive control of emotional perception. In addition, this study revealed that the modulatory impact of the tDCS was stronger on introverts than on extraverts. Another study found that 2 mA anodal tDCS over the left DLPFC reduced the perception of unpleasantness and personal discomfort while participants are exposed passively to aversive pain stimuli (i.e., images depicted humans suffering) (Boggio, Zaghi, & Fregni, 2009). These results suggested that increased DLPFC activity induced a better emotion regulation when participants are confronted to others' pain. In a study investigating the cognitive control on negative and positive emotional materials with the Cued Emotional Control Task (CECT), a 2 mA anodal stimulation over the left DLPFC induced a shortened reaction time when participants were asked to inhibit a habitual response to positive in comparison to negative emotional material (Vanderhasselt, De Raedt, Brunoni, Campanha, Baeken, Remue, & Boggio, 2013). These findings suggested that cognitive control was specifically enhanced for positive affective information after tDCS stimulation. In contrast, another study demonstrated a significant effect of a 1 mA anodal tDCS over the left DLPFC on both positive and negative faces reaction time identification (Nitsche, Koschack, Pohlers, Hullemann, Paulus, & Happe, 2012), and Yang, Ren and Ma (2018) showed that 1.5 mA anodal tDCS over the right DLPFC specifically facilitated the perception of positive faces, but did not influence the processing of negative ones.

Whereas the above-mentioned studies investigated the emotional processing under tDCS stimulation over the DLPFC, the experimental designs didn't specifically include an active emotion regulation task. In order to explicitly assess whether tDCS could improve emotional processing while participants were trying to reappraise an emotional material, Feeser, Prehn, Kazzer, Mungee, and Bajbouj (2014) investigated the impact of tDCS on cognitive reappraisal. Participants were exposed to negative and neutral pictures from the IAPS (Lang, Bradley, & Cuthbert, 1995) and were instructed to apply one of the three emotion regulation strategies explained the day before (i.e., down-regulate, up-regulate, or maintain) for each negative picture and then, to rate the intensity of the emotion evoked by the pictures at the end of the trial. The results showed that after a 1.5 mA tDCS applied over the right DLPFC (with the cathode placed over the left supraorbital area), participants exhibited less emotional arousal during both down-regulation and maintain conditions as compared to the sham stimulation, and higher emotional arousal in the up-regulation condition. These findings suggested that tDCS improves cognitive reappraisal in both directions, meaning that tDCS increases or decreases emotional arousal depending on the regulatory aim. Interestingly, in the maintain condition, participants reported less arousal after tDCS stimulation, with is congruent with previous passive tasks.

Marques, Morello, and Boggio (2018) did not replicate that 1.5 mA tDCS over the DLPFC modulate the responses on the emotional regulation task, but they showed that tDCS applied over the ventrolateral prefrontal cortex (VLPFC) resulted in less negative valence of negative images on earlier moments of emotional processing. Unfortunately, these studies are limited to cognitive regulation on negative emotions only. Additional findings confirmed the role of the VLPFC by showing that tDCS over the rVLPFC reduced the perception of specific negative emotions such as fear and sadness, compared to other negative or positive feelings, arguing that the rVLPFC is particularly relevant for regulating negative emotions, mostly associated with the anticipation of dangerous situations (Vergallito, Riva, Pisoni, & Lauro, 2018).

In the same vein, a previous study suggested that the rVLPFC was particularly important for the regulation of emotion induced by social exclusion manipulation (Riva, Lauro, DeWall, & Bushman, 2012). The findings revealed that stimulation over the rVLPFC decreased the painful effects of social exclusion induced by the virtual ball game Cyberball, in that excluded participants who received active tDCS over the rVLPFC reported lesser feelings of disagreeableness and hurt than those who received sham stimulation. The role of the rVLPFC was also demonstrated while participants used emotion regulation strategies to reappraise pictures of social exclusion (He, Lin, Xia, Liu, Zhang, & Elliott, 2018). Participants were confronted to social exclusion pictures depicted one rejected and a group of rejecters, and were instructed to passively watch the picture or regulate their emotion via a reappraisal strategy. The results showed that anodal tDCS over the rVLPFC induced less negative emotion ratings as compared to sham stimulation, arguing for a causal role for this brain area in the regulation of negative emotions provoked by social exclusion.

The present study

The aim of the present study is therefore to replicate and extend the findings of the impact of tDCS on emotion regulation by including both positive and negative emotional material. In the present study, participants would be requested to either down-regulate or up-regulate their emotional feelings induced by negative and positive pictures, respectively. In order to focus more particularly on the cognitive control of emotion regulation and to turn mood and emotion into more positive states, tDCS was applied over the left DLPFC (Fregni, Boggio, Nitsche, Marcolin, Rigonatti, & Pascual-Leone, 2006; Nitsche et al., 2012; Vanderhasselt et al., 2013).

Method

Participants

Because emotional responses differ largely between men and women (Kring & Gordon 1998), we decided to include only women for having a more homogenous group. Thus, forty right-handed women (mean age of 22.2 years, SD = 2.93) participated in the experiment. Participants were free of any history of psychiatric or neurological diseases based on a free psychological interview assessing current and past mood, anxiety, addiction, and psychotropic's use. They were excluded if they had an implanted metal object. They all gave their written informed consent to take part in the study, which was approved by the Ethics Committee of the Psychology School of the University of Liège, Belgium.

Personality assessment

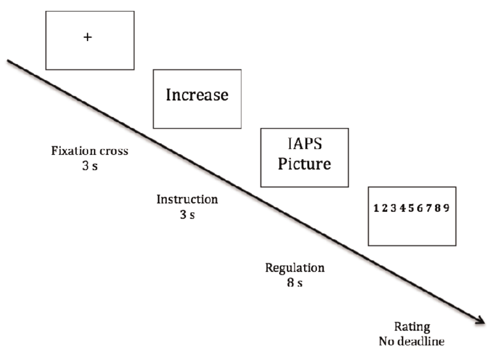
Since previous behavioral studies demonstrated an association between personality and emotion (Costa & McCrae, 1980), and that a former tDCS study showed that the modulatory impact of the tDCS was stronger on introverts than on extraverts (Pena-Gomez et al., 2011), personality traits were assessed as control variables with the French version of the Big Five Inventory (BFI; Plaisant, Courtois, Réveillère, Mendelsohn, & John, 2008). This well-validated instrument composed of forty-four 5-point items provides reliable measures of neuroticism (a = .82), extraversion (a = .82), openness to experience (a = .74), agreeableness (a = .75), and conscientiousness (a = .80) of the big five traits of personality. Only neuroticism and extraversion were included in the present study. The two groups included in the present study (active stimulation N= 20, sham stimulation N =20) did not differ as regards either to extraversion (28.20 + 2.54 vs 27.00 + 2.61, t=1.47 p=0.15) or neuroticism (24.65 + 3.49 vs 23.15 + 2.91, t=1.48, p=0.15).

Task and procedure

Participants were shown colored pictures that were designed to elicit either a negative (e.g., vermin, accidents, illness, domestic violence, pollution), positive (e.g., domestic pets, landscapes, babies, romantic couples), or neutral (e.g., domestic objective) affective response. The stimuli consisted of 42 negative pictures, 42 positive pictures, and 16 neutral pictures selected from the IAPS (Lang et al., 1995). The negative and positive pictures were assigned to the three experimental conditions (i.e., increase, decrease, or watch condition). The images were randomly assigned to active regulation or watch condition to be sure that images that triggered strong arousal were not landed in the active condition. Neutral pictures were always assigned to the watch condition. In order to familiarize participants with the experimental procedure prior to the task, an additional set of 20 pictures was selected for a practice task. The stimuli were the same than used in a former emotion regulation study (Hansenne et al., 2014), and they were validated earlier (Mardaga & Hansenne, 2019a; b).

The regulation task was the same as that used in previous emotion regulation studies (Hansenne et al., 2014; Kim & Hamann, 2007). Participants were instructed to either increase or decrease their emotional reactions to each picture. In the increase condition, participants were instructed to think about the pictures as if the event in the pictures happened to themselves (actor perspective) or a loved one in order to feel the emotions elicited by the pictures more intensely. In the decrease condition, participants were instructed to imagine the event in the pictures objectively from the third-person perspective of someone who is not involved (e.g., looking at the pictures as if the event in the pictures happened to a stranger, or if the event depicted was a fake), with the aim to feel the emotions elicited by the pictures less intensely. In the watch condition, participants were instructed to view the picture in a natural way and try not to change the emotion elicited by the picture. Examples of regulation strategies were given to participants. Particularly, we explained the main principles of attentional deployment, cognitive reappraisal and expressive suppression for allowing participants to reevaluate negative content of the pictures and to increase the impact of the positive images.

Figure 1. Design of the experimental trials. Timeline for events on each trial. An initial cue instructs participants to decrease, increase, or watch for 3 seconds. Then, the picture is presented for 8 seconds. During the presentation of the picture, participants follow the instruction. Participants then provide a rating of their current affect without a time deadline and finally have a moment to relax before the onset of the next trial for 3 seconds (cross fixation).



Procedure

In the task, a fixation cross was presented in the middle of the screen for 3 seconds. Just after, a regulation instruction (increase, decrease, or watch) was presented before the picture for 3 seconds. Then, the picture was shown for 8 seconds. Next, a Likert scale ranging from 1 (weak) to 9 (strong) was presented and participants were asked to rate the strength of the emotion they were currently feeling by pressing a button on a response box without a response deadline. Following the rating scale, a fixation cross in a black screen was presented for three seconds while participants were instructed to rest (Figure 1). A total of 100 trials were completed. There were twenty-one pictures per condition (increase positive, decrease negative, watch positive and watch negative) and sixteen for the neutral condition (watch neutral).

Transcranial direct current stimulation

tDCS was applied through a pair of saline-soaked surface sponge electrodes (anodal surface = 9 cm^2, cathodal surface = 25 cm^2) connected to a battery-driven constant current stimulator. In line with the studies of Vanderhasselt et al. (2013) and Nitsche et al. (2012), the anode electrode was placed over the left DLPFC (F3 localization according to the 10/20 EEG international system), and the cathode was placed above the right supraorbital region (Fp2). Active stimulation consisted of a constant current of 1.5 mA applied for 25 min, corresponding to the duration of the task. These tDCS parameters have been previously found to be valid and efficient, and are relevant for the current research question (Woods et al., 2016). The sham condition consisted of stimulation for 30 seconds, and then the stimulator was turned off. The participants were randomly assigned to the active or the sham condition. The stimulation was applied during the entire emotion regulation task.

Results

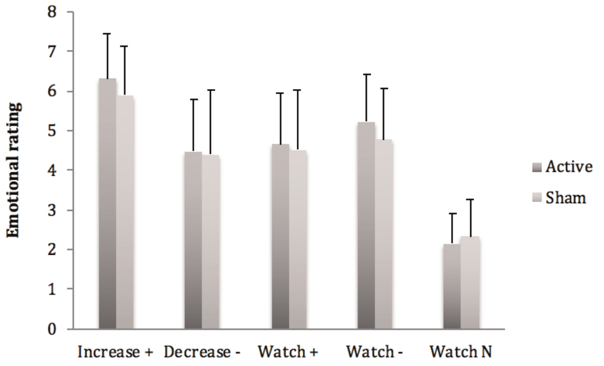
Self-ratings of emotional arousal

A 2 groups (active tDCS, and sham) x 5 conditions (increase positive, decrease negative, watch positive, watch negative, and watch neutral) repeated-measures analysis of variance with extraversion and neuroticism as covariates (ANCOVA) on on-line ratings for emotional arousal was conducted (Table 1). The results showed neither a main effect of conditions ($F(4,144) = 0.88$, $p = 0.47$), nor a main effect of groups ($F(4,144) = 0.90$, $p = 0.35$) (Figure 2). Despite the lack of a main effect of conditions, planned comparisons revealed greater arousal during the increase positive condition than the watch positive condition ($F(1,36) = 36.90$, $p < .001$), and lower arousal during the decrease negative condition than the watch negative condition ($F(1,36) = 43.33$, $p < .001$), suggesting that participants performed the regulation tasks correctly. Analyses yielded a significant group x condition interaction ($F(4,144) = 2.69$, $p = 0.03$). However, planned comparisons didn't find any significant differences between active and sham stimulation across conditions, albeit a marginal difference between the groups was found in the increase positive condition ($F(1,36) = 3.77$, $p = 0.06$). Of the covariates, extraversion and neuroticism x condition interaction showed significantly influences on emotional arousal (respectively $F(1,36) = 4.55$, $p = 0.04$; $F(1,36) = 3.76$, p = 0.006).

Self-ratings of emotional arousal difference scores

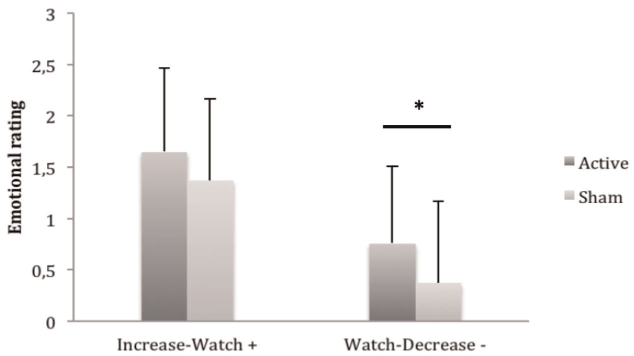
In a next step, in order to take into account the effect of regulation (up-regulate positive and down-regulate

Figure 2. Mean emotional arousal ratings for both groups (anodal and sham) for the five conditions: increase positive, decrease negative, watch positive, watch negative, and watch neutral.



negative) in reference to the individual baseline (either watch positive or negative), we analyzed the differences between active and sham stimulation for the difference arousal scores for both positive and negative pictures (i.e., increase positive minus watch positive, and watch negative minus decrease negative). Higher scores for the difference scores mean better emotion regulation. A 2 groups (active tDCS, and sham) x 2 conditions (increase positive minus watch positive, and watch negative minus decrease negative) repeated-measures analysis of variance with extraversion and neuroticism as covariates (ANCOVA) on the difference arousal scores revealed a main effect of groups ($F(1,36) = 7.06$, $p = 0.01$), but no main effect of conditions ($F(1,36) = 1.10$, $p = 0.74$) nor a group x condition interaction ($F(1,36) = 0.08$, $p = 0.77$) (Figure 3). Planned comparisons revealed a significant difference between active and sham stimulation for the negative pictures ($F(1,36) = 5.53$, $p = 0.02$), and a marginal difference for the positive pictures ($F(1,36) = 3.01$, $p = 0.09$), meaning that participants exhibited higher emotion regulation under anodal tDCS as compared to sham stimulation. Of the covariates, only neuroticism was significantly related to emotional arousal ($F(1,36) = 13.42$, $p = 0.001$).

Figure 3. Mean emotional arousal ratings for both groups (anodal and sham) for the difference scores (increase positive minus watch positive, and watch negative minus decrease negative).



* indicates significant post-hoc comparisons ($p < 0.05$).

Discussion

Previous tDCS studies have suggested the beneficial role of DLPFC stimulation to improve emotion processing and regulation. The present study was therefore conducted to confirm and extend the effects of DLPFC stimulation on emotion regulation by including both positive and negative emotional material. The main results show that anodal tDCS stimulation over the left DLPFC slightly improves the ability to increase emotion perception under emotional regulation for positive emotion. More interestingly, tDCS enhances the regulation of both positive and negative emotions when the baseline is considered.

Several lines of evidence from neuroimaging studies demonstrated a clear role of the left DLPFC in emotion regulation (Kim & Hamann, 2007; Ochsner & Gross, 2008). Besides psychological interventions designed to enhance emotion regulation (e.g., Hansenne, Nélis, Feyers, Salmon, & Majerus, 2014), it might be relevant to consider neuromodulation techniques as an interesting way to improve cognitive control on emotional material. When we consider the individual baseline to reflect more directly the emotion regulation processes, the findings suggest that anodal tDCS stimulation over the left DLPFC induces a better cognitive control on both positive and negative affective stimuli, meaning that tDCS targets the general process of emotional regulation regardless of the valence and the direction (i.e., increasing or decreasing emotional responsiveness). Indeed, since the measures are based on differences between increase and maintain positive, and between maintain and decrease negative, the findings directly reflect the regulation mechanism per se. Findings from neuroimaging studies are grounded in the same principle (Kim & Hamman, 1997; Hansenne et al., 2014), and it should be emphasized that this way could represent the theoretical assumptions behind the research question much better. Indeed, studying up-regulation of positive emotion without considering how the individual deal with positive emotion without any emotion regulation strategies is less appropriate when the research question is to enhance emotion regulation. The same findings are reported in a previous study showing that tDCS facilitates cognitive reappraisal in both directions by either increase or decrease emotional arousal induced by negative pictures (Feeser et al., 2014). Therefore, the present study confirms, and extends to positive emotions, the possible use of tDCS as a tool to modulate emotional reactivity by cognitive control (i.e., reappraisal). However, since the two studies targeted the left and the right DLPFC, future studies must be conducted with a similar methodology. Conversely, Marques et al. (2018) did not report significant impact of DLPFC stimulation on cognitive reappraisal while participants viewed negative images, but they showed the causal role of the VLPFC in emotion regulation. Since that study included only negative stimuli, it could be argued that the evaluation of negative stimuli is much more based on the VLPFC than on the DLPCF.

The picture is different when the emotion regulation conditions are considered without the baseline, considered here as the maintain condition. Indeed, while the results revealed a significant condition x group interaction, only a marginal effect of tDCS is reported for the increase positive condition, which is in line with the results of Nitsche et al. (2012), but which is not coherent with the study of Pena-Gomez et al. (2011) that described an effect for negative stimuli only. In contrast, the absence of tDCS effect in the decrease negative condition is not in agreement neither with the studies showing that tDCS decreased the perception of negative affective stimuli (Pena-Gomez et al., 2011; Boggio et al., 2009), nor with the effect during the decrease condition observed by Feeser et al. (2014) in an active regulation task for negative affective pictures. Despite similar anodal stimulation sites (left DLPFC, except right DLPFC for Feeser et al.'s study), the intensity of stimulation and the cathode placements were not comparable, and could lead to different results. In addition, the tasks were different. More particularly, it might be advanced that the emotional intensity induced by the IAPS pictures was not sufficiently high to necessitate strong emotional regulation. Future studies could include pictures displaying higher emotional arousal.

Before concluding, some limitations must be underlined. First, a major limitation of the study is that tDCS was applied only over the left DLPFC, and future studies must be conducted with stimulation over both right and left DLPFC as well as over the VLPFC. Indeed, consistent findings demonstrated that the rVLPFC plays a major role in down-regulating negative emotions induced in social exclusion (He et al., 2018), and also in emotion regulation in general (Vergallito et al., 2018). Second, even if the number of participants was based on a very similar study published by Feeser et al. (2014), it should be underlined that the small size of the sample is a limitation of the study. Thus, to ensure to have sufficient power, future studies should select the sample size by a power analysis and not on the sample included into a previous study. Finally, since only women are included in the study for having a more homogenous group, future studies must comprise a larger number of subjects including men.

In conclusion, the present study provides additional data on the use of tDCS as a tool to increase emotion regulation not only for negative affective material, but also for positive ones. In this study, participants were not only able to decrease the arousal intensity for negative stimuli as reported in a previous study, but they were also able to increase their arousal ratings for positive stimuli.

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