Asymmetric Contributions of the Fronto-Parietal Network to Emotional Conflict in the Word–Face Interference Task

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Abstract: The fronto-parietal network is involved in top-down and bottom-up processes necessary to achieve cognitive control. We investigated the role of asymmetric enhancement of the left dorsolateral prefrontal cortex (*l*DLPFC) and right posterior parietal cortex (*r*PPC) in cognitive control under conditions of emotional conflict arising from emotional distractors. The effects of anodal tDCS over the *l*DLPFC/cathodal over the *r*PPC and the effects of anodal tDCS over the *r*PPC/cathodal over the *l*DLPFC were compared to sham tDCS in a double-blind design. The findings showed that anodal stimulation over the *l*DLPFC reduced interference from emotional distractors, but only when participants had already gained experience with the task. In contrast, having already performed the task only eliminated facilitation effects for positive stimuli. Importantly, anodal stimulation of the *r*PPC did not affect distractors' interference. Therefore, the present findings indicate that the *l*DLPFC plays a crucial role in implementing top-down control to resolve emotional conflict, but that experience with the task is necessary to reveal this role.

Keywords: fronto-parietal network; left dorsolateral prefrontal cortex; right posterior parietal cortex; word–face interference; tDCS; emotional conflict; stimulus valence

1. Introduction

Attending to some information while ignoring other information relies on an interplay of goal-driven and stimulus-driven mechanisms, which calls upon the activity of the fronto-parietal network. Traditionally, the posterior parietal cortex (PPC) has been linked to spatial attention and to stimulus-driven attention based on perceptual salience [1,2]. In contrast, the dorsolateral prefrontal cortex (DLPFC) has been linked to top-down selective attention, as it allows goal-directed behaviour by selectively attending to relevant information while inhibiting irrelevant information [3,4]. However, both the PPC and the DLPFC are rich connection hubs: the DLPFC is the convergence area of afferences from the dorsal attention stream involved in top-down modulation of attention, as well as of afferences from the ventral attention stream involved in bottom-up attention [3]. Similarly, the PPC is the major source of top-down inputs that bias the competition in favour of attended targets compared with unattended distractors [5,6], and it has been linked to the integration of top-down and bottom-up attention in a salience map [7–11].

In addition to bottom-up and top-down mechanisms, attention is also prioritized by information with emotional and motivational significance (i.e., "motivated or emotional attention", [12–14]). Emotional attention is supported by neural circuitry centred on the amygdala, which, via feedback

to sensory processing areas, biases the neural representation of emotional stimuli over competing neutral ones [13,15]. The *r*PPC plays an important role in emotional attention with connections to the colliculus-pulvinar-amygdala [16–18]. The DLPFC is part of a distributed neural network for emotional processing [19,20] and it is also part of a cortico–subcortical circuit with the anterior cingulate cortex, involved in conflict monitoring [21,22]. The double involvement of the *r*PPC in biasing the competition in favour of attended stimuli *and* in emotional attention and of the DLPFC in cognitive control *and* emotional processing suggests a possible role of these brain structures in emotional conflict, which arises when goal-irrelevant emotional stimuli interfere with goal-relevant emotional stimuli. Under these conditions, it is necessary to enhance the goal-relevant emotional target and/or inhibit the goal-irrelevant emotional distractor to resolve the "emotional conflict" [23,24].

When considering the emotional conflict elicited by positive and negative distractors, the question of valence lateralization is important. The activity of the *r*DLPFC has been linked to the evaluation and suppression of negative stimuli [25–27] and the activity of the *l*DLPFC to suppression of positive stimuli [26,28,29]. Although these findings may suggest DLPFC lateralization depending on valence, the issue of whether cognitive control for emotional conflict is lateralized is inconclusive. In fact, bilateral responses of the DLPFC, irrespective of valence, have also been reported [30]. Indeed, Lindquist, Satpute, Wager, Weber, and Barrett [31], in a meta-analysis of available studies, concluded that there is bilateral DLPFC involvement in both positive and negative (vs. neutral) emotion processing. The lack of clear lateralization effects for valence has been attributed to a posterior right-hemispheric superiority for all emotions, followed by a frontal valence-specific activation [32,33] or to motivation-specific frontal asymmetries relying on approach and avoidance motivation linked to specific emotions rather than to valence. In this latter case, approach-related emotions (i.e., anger and happiness) would show left frontal lateralization whereas avoidance-related emotion (e.g., fear and sadness) would show right frontal lateralization [34].

Direct evidence on the role of the PPC and DLPFC in emotional attention and cognitive control comes from studies using non-invasive brain stimulation (NIBS) that directly modulate neuronal excitability, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS). Anodal tDCS over the *r*PPC shifts spatial attention [35] and improves covert spatial orienting [36]. In addition, emotion-specific activity of the parietal cortex has been reported for bodies and faces [37–39]. TMS over the *r*PPC disrupts configural face processing [40] and impairs processing of emotional faces [41–43] and TMS over the *l*DLPFC affects cognitive control for positive events [44]. In contrast, Bermpohl et al. [45] reported that TMS over the *l*DLPFC affected processing for both positive and negative stimuli and De Raedt, Vanderhasselt, and Baeken, [46] found efficient regulation of emotional attention when potentiating the *l*DLPFC compared to *r*DLPFC. tDCS studies also show that anodal stimulation of the *l*DLPFC improves conflict resolution and attention regulation during emotional processing. Namely, when individuals are trained to regulate their emotional attention, anodal tDCS over the *l*DLPFC improves looking towards or away from negative stimuli [47,48]. Similarly, when the task requires looking away from emotional faces, anodal tDCS over the *l*DLPFC reduces the time to disengage gaze from emotional faces [49]. In addition, for individuals with major depression, anodal stimulation over the *l*DLPFC reduces the interference from emotional stimuli in a working memory task [50]. Importantly, the *l*DLPFC has also been involved in controlling the prepotent response elicited by emotional stimuli. More specifically, Vanderhasselt, De Raedt, Brunoni, Campanhã, Baeken, Remue, and Boggio [51] used a Cued Emotional Control Task (CECT), in which a cue instructed participants to respond with the actual or opposite emotion (happy or sad) shown by a face. In this task, cognitive control is required to overcome the habitual response and respond with the opposite emotion category. After receiving sham or anodal tDCS to the *l*DLPFC, participants were faster in inhibiting a habitual response to happy (opposite/happy trials) relative to sad (opposite/sad trials) faces, suggesting that a single anodal tDCS session enhances cognitive control for positive relative to negative information. Hence, anodal stimulation of the *l*DLPFC improves top-down attentional control for emotional information and response inhibition. Surprisingly, to date, the causal roles of the

DLPFC and of the *r*PPC in cognitive control for emotional conflict, in which one emotional information needs to be prioritized over another, have not been investigated.

Typically, research on emotional conflict has used the emotion word–face interference task [52–54] a variant of the Stroop task [55], in which two emotional stimuli, a target and a distractor, are presented at the same spatial location superimposed. Targets and distractors can be either affectively congruent or incongruent and participants respond to targets while ignoring distractors. When target and distractor are incongruent, emotional conflict is high. Although the task entails responding to emotional words and ignoring emotional faces or vice versa, interference effects are larger when participants respond to words, which has been attributed to faces being processed more automatically and engendering greater emotional conflict than words [56].

Using this task, Pecchinenda et al. [54] assessed the effects of active compared to sham tDCS over the *l*DLPFC while participants were presented positive and negative words with happy, angry, or neutral distractor-faces under low or high cognitive load. Participants responded to target-words and ignored distractor-faces. Findings showed that anodal tDCS of the *l*DLPFC was not sufficient to establish top-down control and reduce interference from emotional distractors. More recently, Kuehne, Schmidt, Heinze, and Zaehle [57] used a word–face interference task with happy, sad, and neutral faces and the words happiness, sadness, or neutral. Participants responded to the face based on the emotion identity and ignored the word while receiving sham or anodal tDCS of the *l*DLPFC. ERPs were also recorded. Findings showed interference on incongruent trials during anodal tDCS but only for neutral faces (rather than for emotional ones). Of special importance is the finding that the amplitude of the N170 ERP component was reduced during anodal tDCS over the *l*DLPFC, suggesting that the *l*DLPFC modulates brain responses linked to perceptual processing of target-faces. This finding is in keep with evidence suggesting that emotional conflict occurs very early at perceptual processing stage and points to the involvement of the fronto-parietal network in implementing cognitive control under emotional conflict. Similar findings were reported, in an earlier study by Zhu, Zhang, Wu, Luo, and Luo [58] who found that when participants respond to words and ignore faces, the incongruent condition evokes a less negative N170 component (i.e., a marker of face encoding) than the congruent condition. Moreover, when participants respond to emotional faces while ignoring emotional words (and vice versa, they respond to words and ignore faces), EEG evidence shows that trials with affectively incongruent target and distractor are associated with a disengagement of fronto-parietal attentional network [59]. Finally, recent evidence from an fMRI study using the word–face interference task with adolescents provides additional insight on the involvement of the fronto-parietal network in emotional conflict elicited by emotional stimuli. Moreover, Banich, Smolker, Snyder, Lewis-Peacock, Godinez, Wager, and Hankin [60] presented target-words related to happiness and sadness on happy and sad distractor-face. Participants responded to words based on whether they were synonymous of happiness or sadness while ignoring the distractor-faces that could be congruent or incongruent. Findings showed that increased DLPFC activity was associated with reduced perceptual processing of distractor-faces, suggesting that top-down cognitive control by the DLPFC attenuates processing of task-irrelevant information by the PPC. Importantly, this finding was observed for both congruent and incongruent trials, indicating that the DLPFC exerted its influence by suppressing processing of the task-irrelevant facial information rather than by enhancing task-relevant word processing.

In summary, evidence on the role of the *l*DLPFC in maintaining cognitive control when the task requires prioritizing targets emotional information over that of distractors is rare. Although it is still debated whether cognitive control is achieved by enhancing the perceptual signal of task-relevant stimuli and/or attenuating that of task-irrelevant once [61–63], the handful of available studies suggest that the *l*DLPFC exerts this control by modulating the activity of posterior brain regions. Therefore, it may well be the case that boosting the neural activity of the *l*DLPFC is not sufficient to provide a strong biasing signal against the interference of emotional distractors and bottom-up degradation of their neural signals is necessary. This could be achieved via anodal tDCS over the *l*DLPFC and cathodal tDCS over the *r*PPC. To our knowledge, no study has yet used tDCS to modulate the activity

of the fronto-parietal network to assess the relative contribution of the *l*DLPFC and of the *r*PPC in cognitive control under emotional conflict.

Understanding the role of the fronto-parietal network in emotional conflict entails using a control condition to assess both facilitation and interference effects under active compared sham stimulation. This is because, strictly speaking, distractor-faces are always irrelevant for the task at hand (i.e., respond to words and ignore faces) and should not be processed even when they are affectively congruent with targets. However, the only tDCS study that has also used neutral distractors is that by Kuehne et al. [57], who used neutral faces in the control condition and their task yielded greater interference with neutral distractor-faces, which could be due to emotional stimuli facilitating emotional conflict resolution [64] or to neutral distractor-faces being emotionally ambiguous when presented in the context of emotional stimuli. In addition, whereas a within-subject design for sham vs. active tDCS provides statistically powerful contrasts of tDCS effects, comparing active versus sham stimulation in only one region may be limited, given that active tDCS has diffuse effects that go beyond the proposed region/neural network and affect also adjacent cortical areas. In fact, recent research shows that the higher distribution of field strengths at the brain surface resulting from tDCS tends to emerge into central areas in between the two electrodes [65]. Based on these considerations, we used the reversed polarity effects of tDCS to shift the activation between top-down (anodal tDCS over the *l*DLPFC) and bottom-up (anodal over the *r*PPC) modulation of attention while participants performed a word–face interference task with emotional targets and distractors. A control condition with scrambled neutral faces was used to assess both facilitation and interference effects when targets and distractors are affectively congruent or incongruent. To note, in the present study affective congruence was based on valence category (e.g., words with positive valence presented with happy faces). If the *l*DLPFC reduces emotional conflict by enhancing targets and reducing distractors processing, then anodal stimulation over the *l*DLPFC with the cathode over the *r*PPC should attenuate interference from emotional faces and reduce both interference and facilitation effects compared to sham stimulation. In contrast, anodal tDCS over the *r*PPC involved in bottom-up attentional control should enhance both interference and facilitation effects from emotional distractors compared to sham stimulation. These predictions would also rely on a beneficial effect of anodal tDCS/detrimental effect of cathodal tDCS over the rPPC on processing emotional faces.

2. Materials and Methods

2.1. Participants

Seventy-five participants (39 females, 36 males; *M* age = 21.2, *SE* = 0.30) took part in the study and received 5–10€ upon completion of two experimental sessions. All participants were right-handed and had normal or corrected to normal vision. Half of the participants (38: 18 males and 20 females, *M* = 20.02, *SE* = 0.29) were randomly assigned to receiving anodal stimulation over the *l*DLPFC, the other half (37: 18 males and 19 females, *M* = 22.04, *SE* = 0.46) were randomly assigned to the group receiving anodal tDCS over the *r*PPC. Four participants (two for each group) did not complete the two sessions due to adverse effects reported during stimulation.

The sample size was a priori calculated using More Power software [66] based on the effect size for the 2-way interaction taken from a behavioural study with two groups [67] for the word-task condition: $\eta_p^2 = 0.129$; $\alpha = 0.05$; $\beta - 1 = 0.95$. This established that with a $\eta_p^2 = 0.129$, $\alpha = 0.05$, power = 0.98, 34 participants are necessary to detect a moderate-large effect.

All participants gave their written informed consent, which was obtained according to the Declaration of Helsinki (1991). The study followed institutional guidelines and had received approval by the institutional Ethics Committee (#PSI-21-05-2012). Participants completed a health safety questionnaire for tDCS studies to assess whether they qualified to receive stimulation. Exclusion criteria were having suffered an—or having a first-degree relative suffering from—epileptic seizure, having suffered or being diagnosed with neurological or psychiatric disorders, having suffered head

injuries or trauma, having metallic head implants or metal fragments, using psychoactive medications, being pregnant, having a sensitive skin. All participants reported no history of neurological or psychiatric disorders and no ongoing use of medication. All participants were native Italian speakers and naïve to the aims of the study.

2.2. Word–Face Interference Task

Distractor-Faces: Full-colour photographs (13.23 × 16.53 cm) of 48 middle-age faces (24 males and 24 females), were selected from the FACES database [68]. Sixteen angry faces (eight males, eight females), 16 happy faces (8 males, 8 females) and 16 neutral faces (8 males, 8 females) served as distractors. Happy and angry expressions were used as positive and negative emotions associated with approach motivation [34]. Neutral faces were edited in scrambled images of 50 pixels using MATLAB and were used as the control condition. Twelve different faces were selected for the practice trials (see Appendix A for the complete list of stimuli). All pictures were edited, adjusted to the centre and balanced for brightness (average value: 106.5) using Adobe Photoshop 6.0 so that each picture measured 14.8 × 12.4 cm when displayed on screen.

Target-Words: Targets were 48 words (24 positive, 24 negative) selected from the Italian translation and validation [69] of the Affective Norms for English Words [70] (ANEW). Twelve different words (six positive, six negative) were used as targets in the practice session (see Appendix A for the complete list of stimuli). For the experimental set, positive and negative words differed for valence (positive: $M = 7.53$; $SE = 0.58$; negative: $M = 2.78$; $SE = 0.74$, $t (46) = 24.80$, $p < 0.001$), but did not for arousal (positive: $M = 5.44$; $SE = 0.81$; negative: $M = 5.60$; $SE = 1.02$, $t (46) = 0.6$, $p = 0.55$), and word length (positive: $M = 7.08$; $SE = 1.06$; negative: $M = 7.00$; $SE = 0.88$, $t (46) = 0.3$ $p = 0.77$).

The selected words were controlled for semantic associations using association norms for Italian words [71]. When a word was missing from the Italian association norms, the English translation was used, and associations controlled through the University of South Florida Free Association Norms [72]. Target-words were presented in uppercase, lime green, bold, 45-point Arial font (pre-tested to guarantee high visibility when presented on full colour face-pictures). The words were placed at the height of the nose of the distractor's face. Task instructions were presented on screen and after 12 practice trials, participants completed a total of 288 trials, divided into 6 blocks of 48 trials each, resulting in 8 trials per block for each factorial combination of distractor type ad target-word.

2.3. Online Transcranial Direct Current Stimulation

A double-blind, randomized crossover within-subjects design was used; each participant received both active and sham stimulation either of the *l*DLPFC or of the *r*PPC on two separated days with an interval of at least 1 week between sessions. The time-interval between the two tDCS sessions (sham and active) did not differ between the two groups (anodal *l*DLPFC: $M = 8.00$, $SE = 0.35$, range 10; anodal *r*PPC: $M = 8.14$, $SE = 0.32$, range 6), $t (73) = 0.339$, $p = 0.74$. The order of stimulation (active and sham) was counterbalanced over all participants in each group.

Following scalp measurements, participants were randomly assigned to one of the two groups differing on the stimulation electrodes placement (see Figure 1a).

For the *l*DLPFC group, the anode was placed over F3 and the cathode over the P4 according to 10–20 EEG International System. For the *r*PPC (P4) the reverse montage was used (i.e., anodal tDCS over the *r*PPC/cathodal over the *l*DLPFC). For the active stimulation, a 1.0 mA direct current (impedance was kept below 5 kΩ) was delivered by a battery-driven constant current stimulator (BrainStim E.M.S., srl Bologna, Italy) for 20 min during the word–face interference task, with a 30-s fade in/fade out ramp. For the sham stimulation, the same stimulation parameters were applied but the stimulation duration was only 2 s. The anode-electrode had a diameter of 3.5 cm (density 0.10 mA/cm^2), and the cathode-electrode measured 4.7 × 4.7 cm^2 (density 0.045 mA/cm^2). The cathode (receiver) electrode was bigger in order to maximize anodal effects over the potential cathodal effects [73]. In line with the recommendations provided by Nitsche et al. [74], using a small electrode placed over the

*l*DLPFC (F3 position) and a comparatively larger electrode positioned over the reference electrode allows to maximize stimulation focality. As a result, the current flow is most pronounced in the *l*DLPFC, the region of interest according to the literature review and study predictions.
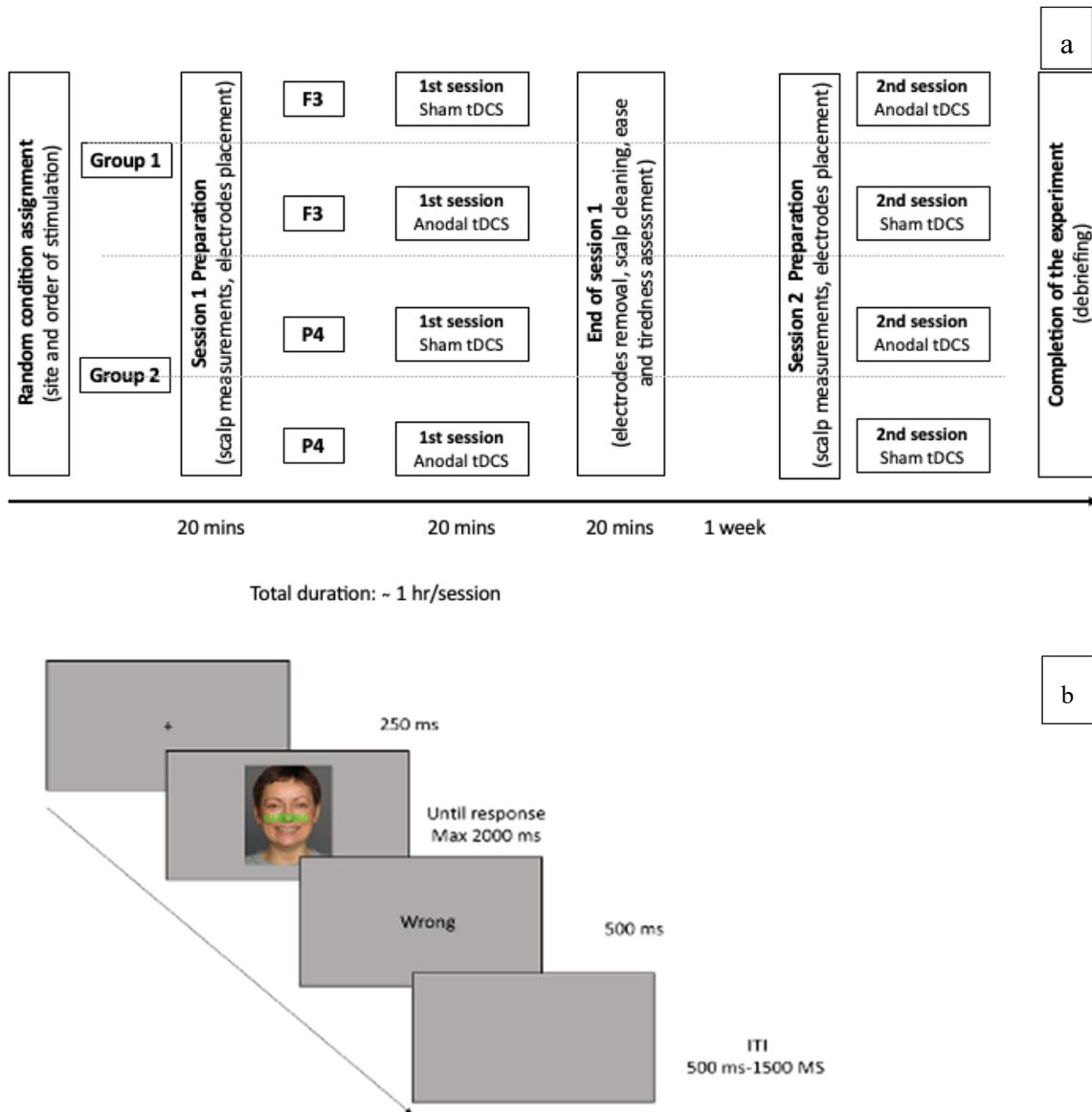

Figure 1. (**a**) Schematic diagram of group assignment and stimulation protocol. (**b**) Sequence of events in a typical trial. The example shows an incongruent trial with a negative target-word (*guerra*, Italian for war) superimposed onto a happy distractor-face (face ID: 061_m_f_h_a). Original stimuli are from FACES database. Reprinted with permission.

The 1.0 mA current intensity was chosen as recent evidence suggests that at least for stimulation of the motor cortex (M1), 1 mA of unilateral anodal tDCS increases cortical excitation, which does not hold for bilateral stimulation and for the 2 mA intensity conditions used in cognitive enhancement experiments [75].

The selected stimulation protocol was online, covering the whole duration of the task, including practice trials as it takes about 2–3 min for the tDCS to affect the stimulated area [76], so overall active stimulation lasted 20 min. Although there is a debate in the literature regarding online vs. offline stimulation application, studies that compared directly the two options show that online protocols are more effective [77,78], particularly for attention tasks [79].

2.4. Procedure

After obtaining informed written consent, participants completed a health questionnaire. An experimenter, blind to stimulation condition, started the electrodes montage and interacted with the participants. Once the electrodes were in place, participants sat in front of a computer in a dimly lit room. A second experimenter, not blind to stimulation condition, connected the electrodes and checked the impedance. All participants were told they were receiving active stimulation.

Task instructions were presented on screen and after 12 practice trials, participants completed a total of 288 trials divided in 6 blocks of 48 trials each, resulting in 8 trials per block for each factorial combination of distractor type ad target-word. The stimulation started just before participants read the task instructions presented on screen and continued throughout the task. To maintain the duration of the task and that of the stimulation within the same range, between blocks there was a fixed 15 s break. All participants completed the word–face interference task within the duration of the stimulation.

Each trial had the following sequence: After a central fixation point (250 ms), a word, presented on top of a face, appeared and remained on screen until response or a maximum of 2000 ms. A response feedback ("Correct", "Wrong" or "No response") followed for 500 ms. The inter-trial interval (ITI) ranged from 500 to 1500 ms (see Figure 1b).

Participants were instructed to respond based on whether the word denoted something positive or negative while ignoring the distractor-faces. The instructions emphasized both speed and accuracy. Participants responded by pressing the keys "1" or "2", which were appropriately labelled as "Positive" and "Negative", using their index and middle finger of the right hand. Responses were made on a USB keyboard with timing error less than 1 ms and keys assignment to "Positive" and "Negative" was counterbalanced between participants.

Each block consisted of equally probable, factorial combination of Valence (positive, negative target-words) and Condition (congruent, control, incongruent) so that target and distractor could be congruent (i.e., positive word/happy face or negative word/angry face), incongruent (i.e., positive word/angry face or negative word/happy face) or control (i.e., positive or negative word/scrambled face). In each block, targets and distractors were presented only once, and the distractor-faces were always of different identities. Stimuli were presented on a 19-inch LCD monitor (resolution 1920 × 1080, refresh rate 60 Hz), subtending 13° of visual angle when presented at 60 cm of distance. Stimulus presentation and data collection were controlled using E-Prime Version 2.0 Professional software (Psychology Software Tools, Pittsburgh, PA, USA, 2012) for Windows 7 Professional, which also records participants' responses. Responses were entered using a standard USB-keyboard with timing error less than 1 ms.

At the end of each session participants responded to two brief printed questions assessing being at ease and being tired (scale from 1 to 9, with 1 indicating not at all and 9 indicating very much) during the session. Upon completion of the second session, participants were told that in one of the two sessions they did only receive sham stimulation and were asked whether they could tell which stimulation they had received in which session. In all cases, participants were not able to report with certainty the session with active from that with sham stimulation. All participants were fully debriefed.

2.5. Experimental Design

The experimental design is a 2 (Group: *l*DLPFC vs. *r*PPC) by 2 Session (sham, active) by 2 (Valence: negative and positive target-words) by 3 (Condition: congruent, control, incongruent) mixed factorial design with the first factor between-subjects.

2.6. Data Analyses

Trials on which an error was made (3.4%) and with RTs faster than 120 ms or 2.5 SD above the overall mean were excluded from analyses (5.6%). For each condition, mean RTs and accuracy, as the proportion of correct responses, were computed. For RTs, interference was computed as

{[(RTs Incongruent − RTs Control)/[(RTs Incongruent + RTs Control)]/2} * 100 whereas Facilitation was computed as {[(RTs Congruent − RTs Control)/[(RTs Congruent + RTs Control)]/2} * 100 (see [80]). Interference is indicated by positive scores whereas facilitation by negative scores.

As response accuracy was very high, data were not analysed further. Interference and Facilitation scores were analysed with a 2 (Group: *l*DLPFC vs. *r*PPC) by 2 Session Order (sham first, active first) by 2 Stimulation (tDCS: sham vs. active) by 2 (Valence: negative vs. positive) mixed factorial ANOVA with the first two factors between-subjects.

3. Results

Overall Results

Interference: The effect of Valence, $F(1, 71) = 15.85$, $p = 0.001$, $\eta_p^2 = 0.182$ was significant; Stimulation, $F(1, 71) = 0.54$, $p = 0.46$; Group, $F(1, 71) = 0.19$, $p = 0.67$; and Session Order, $F(1, 71) = 0.57$, $p = 0.45$, were not. The 2-way interactions Valence by Session Order, $F(1, 71) = 0.81$, $p = 0.37$; Valence by Group, $F(1, 71) = 0.17$, $p = 0.68$; Session Order by Stimulation, $F(1, 71) = 3.54$, $p = 0.06$; Group by Stimulation, $F(1, 71) = 1.03$, $p = 0.31$; Group by Session Order, $F(1, 71) = 0.53$ $p = 0.47$; and Valence by Stimulation, $F(1, 71) = 0.38$, $p = 0.85$ were not statistically significant. The 3-way interactions Group by Valence by Session Order, $F(1, 71) = 1.32$, $p = 0.25$; Valence by Stimulation by Session Order, $F(1, 71) = 0.50$, $p = 0.48$; Group by Valence by Stimulation, $F(1, 71) = 0.55$, $p = 0.82$; and the 4-way interaction $F(1, 71) = 0.76$, $p = 0.39$ were not significant. However, the 3-way interaction Group by Session Order by Stimulation was significant, $F(1, 71) = 4.55$, $p = 0.036$, $\eta_p^2 = 0.060$ (see Figure 2).
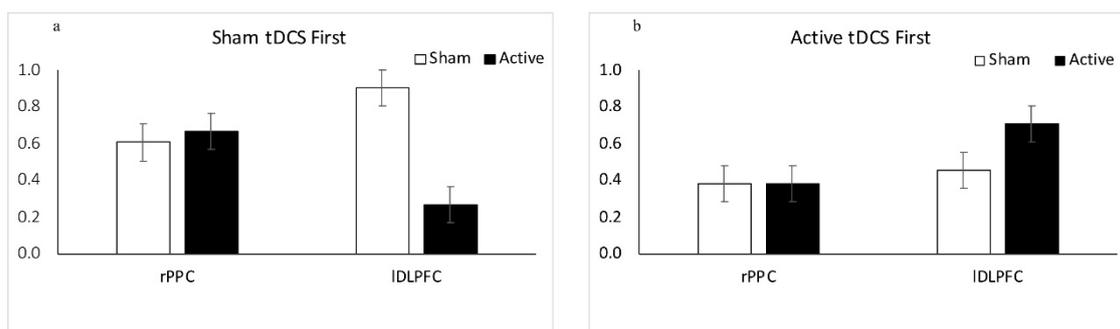

Figure 2. Interference effects for participants who received sham tDCS first (**a**) and for participants who received active tDCS first (**b**) for the two groups (*r*PPC, *l*DLPFC) as a function of stimulation (sham, active) for the 3-way interaction Group by Session Order by Stimulation. Error bars represent standard errors of the means.

Facilitation: The effect of Valence, $F(1, 71) = 50.09$, $p = 0.001$, $\eta_p^2 = 0.414$ was significant; Stimulation, $F(1, 71) = 0.01$, $p = 0.99$; Group, $F(1, 71) = 1.42$, $p = 0.24$; and Session Order, $F(1, 71) = 0.01$, $p = 0.92$ were not. The 2-way interactions Valence by Session Order, $F(1, 71) = 3.19$, $p = 0.08$; Valence by Group, $F(1, 71) = 0.83$, $p = 0.37$; Group by Stimulation, $F(1, 71) = 0.16$, $p = 0.69$; Group by Session Order, $F(1, 71) = 0.84$ $p = 0.77$; and Valence by Stimulation, $F(1, 71) = 0.16$, $p = 0.69$ were not statistically significant but Session Order by Stimulation interaction, $F(1, 71) = 13.18$, $p = 0.001$, $\eta_p^2 = 0.157$ was significant. The 3-way interactions Group by Valence by Session Order, $F(1, 71) = 0.99$, $p = 0.32$; Group by Valence by Stimulation, $F(1, 71) = 1.00$, $p = 0.32$; and Group by Session Order by Stimulation, $F(1, 71) = 1.00$, $p = 0.32$ were not significant. However, the 3-way interaction Valence by Session Order by Stimulation, $F(1, 71) = 19.21$, $p < 0.001$, $\eta_p^2 = 0.213$ was significant (see Figure 3). The 4-way interaction $F(1, 71) = 0.05$, $p = 0.82$ was not statistically significant.
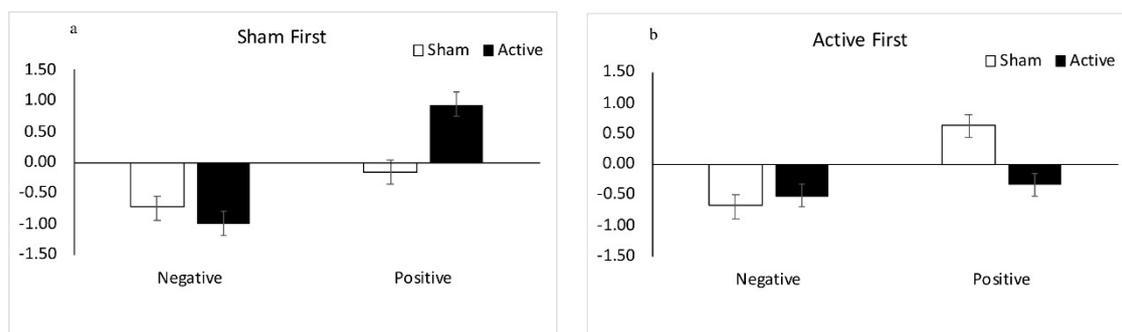
Figure 3. Facilitation effects (negative score indicates facilitation) for participants who received sham tDCS first (**a**) and for participants who received active tDCS first (**b**) for negative and positive target-words as a function of stimulation (sham, active) for the 3-way interaction Valence by Session Order by Stimulation. Error bars represent standard errors of the means.

To better understand the 3-way interactions with Session Order for interference and facilitation scores, data were analysed separately for participants who received sham stimulation first and for those who received active stimulation first. Hence, interference and facilitation scores were analysed with a 2 (Group: *l*DLPFC vs. *r*PPC) by 2 (tDCS: sham vs. active) by 2 (Valence: negative vs. positive) mixed factorial ANOVA with the first factor between-subjects. We retained the factors Group and Valence in these analyses because for interference scores the 3-way interaction involved Group and for facilitation scores it involved Valence.

Finally, data from the two post-session questionnaires were analysed with a 2 (Group: *l*DLPFC vs. *r*PPC) by 2 (tDCS: sham vs. active) mixed-factorial ANOVA with the first factor between-subject.

3.0.1. Results: Sham tDCS First

Interference on RTs: ANOVA results showed that Group was not statistically significant $F_{(1, 35)} = 0.08$, $p = 0.79$, but Stimulation, $F_{(1, 35)} = 4.40$, $p = 0.043$, $\eta_p^2 = 0.112$ and Valence, $F_{(1, 35)} = 10.90$, $p = 0.002$, $\eta_p^2 = 0.237$ were significant: Interference was greater during sham, $M = 0.76$ $SE = 0.13$ than during active stimulation, $M = 0.47$, $SE = 0.13$ and there was greater interference on positive, $M = 0.95$ $SE = 0.13$ compared to negative target-words, $M = 0.27$ $SE = 0.15$. The 2-way interaction Group by Stimulation was significant, $F_{(1, 35)} = 6.36$, $p = 0.016$, $\eta_p^2 = 0.154$ (see Figure 2a), which was due to reduced interference during active, $M = 0.27$, $SE = 0.15$ compared to sham stimulation $M = 0.91$, $SE = 0.18$ for the anodal *l*DLPFC group, $t_{(18)} = 3.64$, $p = 0.002$. This was not the case for the anodal *r*PPC group who showed similar interference during sham, $M = 0.61$, $SE = 0.18$ and active stimulation, $M = 0.67$, $SE = 0.15$, $t_{(17)} = 0.27$, $p = 0.789$. The comparison between the two groups during active tDCS, $t_{(35)} = 1.93$, $p = 0.06$ failed just short of reaching full statistical significance. Group by Valence, $F_{(1, 35)} = 0.25$, $p = 0.622$, Stimulation by Valence, $F_{(1, 35)} = 0.18$, $p = 0.671$, and the 3-way interaction, $F_{(1, 35)} = 0.85$, $p = 0.362$ were not statistically significant.

Facilitation on RTs: ANOVA results showed that Group, $F_{(1, 35)} = 0.84$, $p = 0.37$ was not statistically significant. Stimulation, $F_{(1, 35)} = 7.85$, $p = 0.008$, $\eta_p^2 = 0.183$ and Valence, $F_{(1, 35)} = 35.74$, $p < 0.001$, $\eta_p^2 = 0.505$: were significant: Facilitation was greater during sham, $M = -0.44$ $SE = 0.14$ than during active stimulation, $M = -0.04$, $SE = 0.14$ and facilitation was greater for negative, $M = -0.86$ $SE = 0.18$ than for positive target-words, $M = 0.39$ $SE = 0.14$. The interactions Group by Stimulation, $F_{(1, 35)} = 1.17$, $p = 0.287$, and Group by Valence, $F_{(1, 35)} = 0.03$, $p = 0.954$ were not statistically significant but Stimulation by Valence interaction, $F_{(1, 35)} = 17.01$, $p < 0.001$, $\eta_p^2 = 0.327$, was significant (see Figure 3a).

Post hoc analyses showed that for negative target-words facilitation under sham, $M = -0.73$ $SE = 0.20$ and under active stimulation, $M = -1.0$ $SE = 0.22$, did not differ, $t_{(36)} = 1.27$, $p = 0.214$, whereas for positive target-words there was greater facilitation under sham stimulation, $M = -0.15$ $SE = 0.17$ compared to active stimulation, $M = 0.93$ $SE = 0.18$, $t_{(36)} = 5.12$, $p < 0.001$. This was due to

lack of facilitation (i.e., positive score) under active stimulation. The 3-way interaction, F (1, 35) = 0.02, p = 0.88 was not statistically significant.

Post-Session Questionnaire: For question 1 (being at ease) Session, F (1, 35) = 1.22, p = 0.276, and Group F (1, 35) = 0.14, p = 0.91 as well as the interaction, F (1, 35) = 0.17, p = 0.90 were not statistically significant. Similarly, for question 2 (tiredness) Session, F (1, 35) = 1.42, p = 0.242, and Group, F (1, 35) = 1.56, p = 0.22 as well as the interaction were not significant, F (1, 35) = 0.23, p = 0.63.

3.0.2. Results: Active tDCS First

Interference on RTs: ANOVA results showed that Group, F (1, 36) = 0.49, p = 0.49, and Stimulation, F (1, 36) = 0.54, p = 0.466 were not statistically significant but Valence, F (1, 36) = 5.21, p = 0.028, η_p^2 = 0.126 was: interference was greater for positive, M = 0.70 SE = 0.18 than for negative target-words, M = 0.27, SE = 0.17. Stimulation by Group, F (1, 36) = 0.518 p = 0.476 (see Figure 2b), Valence by Group, F (1, 36) = 1.34, p = 0.255, Stimulation by Valence, F (1, 36) = 0.323, p = 0.573, and the 3-way interaction, F (1, 36) = 0.162, p = 0.690 were not statistically significant.

Facilitation on RTs: ANOVA results showed that Group, F (1, 36) = 0.58, p = 0.45 was not statistically significant. Stimulation, F (1, 36) = 5.74, p = 0.022, η_p^2 = 0.137 and Valence F (1, 36) = 15.46, p < 0.001, η_p^2 = 0.300 were statistically significant: facilitation was greater during active, M = −0.42 SE = 0.11 than during sham stimulation, M = −0.02, SE = 0.13; facilitation was greater for negative, M = −0.60 SE = 0.12 than for positive target-words, M = 0.15, SE = 0.14. These two main effects were qualified by a significant Stimulation by Valence interaction, F (1, 36) = 6.07, p = 0.019, η_p^2 = 0.144 (see Figure 3b). Post-hoc comparisons showed that for negative target-words there was no difference in facilitation between sham, M = −0.68 SE = 0.17 and active stimulation, M = −0.52 SE = 0.21, t (37) = 0.57, p = 0.57, whereas for positive words there was facilitation under active, M = −0.33 SE = 0.18 compared to sham stimulation, M = 0.64 SE = 0.21, t (37) = 3.44, p = 0.001. The 2-way interactions Stimulation by Group, F (1, 36) = 0.16, p = 0.70, Valence by Group, F (1, 36) = 2.01, p = 0.17, and the 3-way interaction, F (1, 36) = 0.15, p = 0.70 were not statistically significant.

Therefore, a significant interactive effect Group by Stimulation was present only when sham stimulation was received first: in this case, anodal tDCS over the *l*DLPFC/cathodal *r*PPC reduced interference from emotional distractors. In addition, the interactive effect Valence by Stimulation was present for all participants: there was facilitation for negative words under sham and active stimulation regardless of which stimulation was received first. In contrast, there was facilitation for positive words under sham stimulation only when participants received sham first and there was facilitation under active stimulation when participants received active tDCS first.

Post-Session Questionnaire: For question 1 (being at ease) Session, F (1, 36) = 3.39, p = 0.074, and Group, F (1, 36) = 2.94, p = 0.095 as well as the interaction were not statistically significant, F (1, 36) = 0.03, p = 0.87. For question 2 (tiredness), Session, F (1, 36) = 3.32, p = 0.077, and Group, F (1, 36) = 0.06, p = 0.80 were not statistically significant but Session by Group interaction was significant, F (1, 36) = 6.66, p = 0.014, η_p^2 = 0.156. For the anodal *r*PPC group there was no difference in reported tiredness between sham, M = 3.79, SE = 0.58 and active stimulation, M = 4.05, SE = 0.47, t (18) = 0.51, p = 0.614. In contrast, for the anodal *l*DLPFC group, the reported tiredness was greater during sham, M = 4.53, SE = 0.55 than during active stimulation, M = 3.00, SE = 0.43, t (18) = 3.27, p = 0.004.

We next discuss these findings in detail.

4. Discussion

We investigated to what extent the activity of the fronto-parietal network modulates cognitive control necessary to resolve the emotional conflict elicited by emotional distractors in the word–face interference task. In this task, two emotional stimuli—a target and a distractor—are simultaneously presented and participants are required to respond to targets and ignore distractors. Under these conditions, the question is whether the emotional conflict engendered by distractors is reduced by top-down enhancement of task-relevant stimuli and/or bottom-up degradation of distractor-faces.

If this were the case, then anodal tDCS over the *l*DLPFC involved in top-down attentional control with cathodal tDCS over the *r*PPC should reduce the interference from emotional distractors. In contrast, enhancing the activity of the *r*PPC involved in bottom-up attentional control and processing faces via anodal stimulation over the *r*PPC with cathodal tDCS over the *l*DLPFC should result in greater interference from emotional distractors.

The word–face interference task used in the present study yielded both interference and facilitation effects with negative distractors (i.e., angry faces) interfering more when they were affectively incongruent with target-words than positive distractors (i.e., happy faces). Probably this is because threat signals, such as angry faces, are more difficult to ignore or because they are more arousing than reward-signals such as happy faces. In addition, when participants received sham tDCS first and active stimulation a week later, anodal tDCS over the *l*DLPFC/cathodal *r*PPC reduced the interference from both angry and happy distractor-faces. This finding clearly indicates that the *l*DLPFC exerts cognitive control irrespective of stimulus valence. However, although this conclusion is in line with Lindquist et al. [31], it is also possible that cognitive control for happy and angry distractors is achieved by the *l*DLPFC because both emotional distractors are left lateralized, being approach-related [81]. Importantly, the reverse montage with anodal stimulation over *r*PPC/cathodal over *l*DLPFC, which enhances stimuli perceptual processing and face perception did not reduce the interference from emotional distractors.

This is the first evidence that inducing an asymmetric activation of the fronto-parietal network by enhancing the activity of the *l*DLPFC *and* inhibiting that of the *r*PPC reduces the interference elicited by emotional distractor-faces. In contrast, when active stimulation was administered first, followed by sham stimulation a week later, anodal tDCS over the *l*DLPFC/cathodal *r*PPC did not reduce the interference from emotional distractors. In this case, active stimulation for both groups–i.e., regardless of montage–only reduced the facilitation effects for negative and positive target-words. However, whereas reduced facilitation for negative words was present under active stimulation, regardless of at which session it was administered, facilitation for positive words was always reduced during the second session, regardless of whether active or sham stimulation was administered. That is, what reduced facilitation effects for positive words was completing the task for a second time.

That anodal tDCS over the *l*DLPFC/cathodal *r*PPC reduces interference from emotional distractors when it follows sham tDCS cannot be solely explained by learning effects as if this were the case, then the same effect should have been observed always the second time participants completed the task, regardless of the type of stimulation they received. That is, reduced interference due to learning should have occurred also under sham stimulation when delivered during the second session. Rather, the present findings indicate that anodal stimulation over the *l*DLPFC/cathodal over *r*PPC reduces distractors interference provided participants had already experienced the task. We also acknowledge that what may have reduced distractors processing is the detrimental effect of cathodal tDCS over the *r*PPC on processing faces. However, if this were the case, then it should have done so also when active stimulation was administered at the first session. Namely, reduced interference due to perceptual degradation of distractor-faces or to impairment in processing faces should be less sensitive to experience. Instead, that reduced distractors' interference was observed only when experience with the task had been gathered under sham stimulation runs against such an account and suggests that the observed effect is due to the combined contribution of experience and potentiating the activity of the *l*DLPFC. In fact, the reverse montage with anodal tDCS over the *r*PPC/cathodal *l*DLPFC does not reduce emotional conflict. Therefore, to the extent that anodal tDCS potentiates and cathodal stimulation reduces neural activity, the present study provides first evidence that cognitive control to resolve emotional conflict is improved by the asymmetric activation of the fronto-parietal network in favour of the *l*DLPFC and attenuating that of the *r*PPC.

It is surprising that the effect of anodal tDCS over *l*DLPFC/cathodal *r*PPC depended on whether participants received it after having already gathered some experience with the task under sham stimulation. This is surprising, because the order of stimulation effects in tDCS studies are typically not analysed, as the main interest is to rule them out by counterbalancing the order of sham and active

stimulation. However, they are less unusual than one may think. In fact, they were observed by Jacoby and Lavidor [82] during a sustained attention task, by Hammer, Mohammadi, Schmicker, Saliger, and Münte [83], who observed decreased memory performance in a cathodal condition compared to sham tDCS but only after learning and by Zaehle et al. [84], who suggested that performance enhancement due to task repetition might be hampered by cathodal stimulation over the *l*DLPFC. Our findings of reduced interference from angry distractor-faces indicate the other side of the coin: namely, that performance enhancement due to task repetition is potentiated by anodal stimulation of the *l*DLPFC/cathodal *r*PPC. Furthermore, Nord, Forster, Halahakoon, Penton-Voak, Munafo, and Roiser [79] also reported order of stimulation effects on a task requiring emotion recognition from faces. Their findings showed that anodal stimulation over the *l*DLPFC affected emotional deliberation.

The reduction of facilitation effects for positive target-words when active stimulation was administered during the second session could be attributed to facilitation being based more on the configural processing of distractor-faces presented in the background, which relies on the activity of posterior parietal regions. For instance, fMRI and TMS findings provide compelling evidence for the contribution of posterior parietal regions to configural face processing [40]. However, this is unlikely, as facilitation effects for positive words were also reduced by sham stimulation when delivered during the second session. This finding indeed suggests that what reduces the facilitation effects for positive target-words is not active tDCS but performing the task a second time. In fact, processing of task-relevant stimuli associated with longer RT on congruent trials has been interpreted as reflecting a need for greater processing to overcome any influence of the prepotent task-irrelevant distractor [60]. That is, even when they are affectively congruent, distractors are still to be ignored and their effects on responses needs to be controlled for. For instance, in the traditional Stroop task, poor cognitive control leads to both interference and facilitation effects because the automatic processing of the task-irrelevant dimension coincides with the response of the task-relevant dimension. If an individual pays attention to the task-relevant dimension alone, RT are longer because the task-relevant dimension to which participants are correctly directing attention takes longer to process [85]. Accordingly, that reduced facilitation effect occur with experience only for happy distractor-faces suggests that whereas happy distractor-faces can be ignored, angry distractor-faces may be more difficult to ignore or control [86].

Although the word–face interference task used in the present study shares this characteristic with the classic Stroop task, there are important differences. The most important being that modulating *l*DLPFC activity has an impact on overall reaction times but does not affect the interference effect (i.e., the slowing of responses in incongruent compared with congruent trials) in the classic Stroop task [44,87]. In a recent study Frings, Brinkmann, Friehs, and van Lipzig [88] compared the effect of anodal tDCS over the *l*DLPFC (cathode over parietal cortex–POz) with the effects of cathodal tDCS over the *l*DLPFC (anode over POz) during a Stroop task and did not observe reduced interference following anodal tDCS but only improved response accuracy after cathodal tDCS over the *l*DLPFC. These findings have been taken to suggest that in the classic Stroop, the effects of tDCS on the *l*DLPFC might be compensated through other brain regions (i.e., the anterior cingulate cortex, ACC) involved in response conflict monitoring, [24]. By contrast, the present findings show that the interference engendered by emotional distractors in a word–face interference task can be modulated by inducing an asymmetric activation of the fronto-parietal network, enhancing the *l*DLPFC activity and reducing that of the *r*PPC.

We had not anticipated order of stimulation effects, and it is interesting that the post-questionnaire data indicated that participants who received active tDCS at the first session, reported being more tired at the end of the sham stimulation. It is possible that when using a within-subject design, reported tiredness may reflect the assessment of the task after having experienced the facilitatory effects of active tDCS, even if participants are unable to reliably distinguish when they received sham or active stimulation. The present findings highlight the importance for future research to look into potential effects of order of stimulation to better understand its contribution also in view of training protocols often used to improve and/or rehabilitate cognitive control. Regarding more fundamental aspects of

the current study, future studies may also benefit from using more precise and sophisticated models of experimental design [89,90] as well as valence evaluation [91].

To sum up, the contribution of the present study is twofold. Firstly, it provides evidence that interference from emotional distractor-faces is reduced by potentiating (via anodal tDCS) the activity of the *l*DLPFC and attenuating (via cathodal tDCS) that of the *r*PPC, provided participants have acquired experience with the word–face interference task. Secondly, it shows that what eliminates the facilitation for positive target-words is not tDCS, but performing the task a second time. The present findings integrate those reported in a previous study using a similar word–face interference task [54]. Albeit acknowledging important methodological differences between the two studies, when considered together they indicate that the *l*DLPFC alone is not sufficient to overcome the emotional conflict engendered by emotional distractors.

Finally, a note of caution is necessary, as we cannot claim that we only modulated the activity of the *l*DLPFC and *r*PPC because tDCS has low spatial resolution and usually affects large brain areas under the electrodes. Indeed, anodal tDCS over the *l*DLPFC may have also affected brain areas in spatial proximity, including the ACC involved in conflict monitoring. To date, it is still unclear to what extent cognitive and emotional conflict rely on control-specific neuroanatomical networks as they may share a common conflict-detection mechanism centred on the activity of the ACC ([64,92] for different views). Although the present study cannot speak to the issue of specificity versus generality of the neural network involved in cognitive control for emotional conflict, our findings clearly indicate that enhancing the activity of the fronto-parietal network in favour of the *l*DLPFC helps enhancing cognitive control required to reduce the interference from emotional task-irrelevant stimuli and resolve the emotional conflict.

Appendix A

List of Target-Words

Practice: 6 positive: fascino (charm), gloria (glory), salute (health), canzone (song), trionfo (triumph), viaggio (journey) and 6 negative: dolore (pain), disastro (disaster), debito (debt), castigo (punishment), ulcera (ulcer), ciclone (cyclon).

Experimental blocks: 24 positive words: passione (passion), musica (music), fiducia (trust), natura (nature), speranza (hope), rispetto (respect), famiglia (family), bacio (kiss), denaro (money), angelo (angel), profumo (perfume), invito (invitation), regalo (gift), talent (talent), applauso (applause), cucciolo (puppy), giustizia (justice), bellezza (beauty), aurora (dawn), tramonto (sunset), vittoria (victory), conforto (comfort), vacanza (holiday), saluto (greeting) and 24 negative words: ricatto (blackmail), insulto (insult), trauma (trauma), vittima (victim), incubo (nightmare), caduta (fall), malaria (malaria), danno (damage), divorzio (divorce), scandalo (scandal), litigio (fight), peccato (sin), problema (difficulty), sbaglio (error), malizia (malice), palude (swam), guerra (war), inganno (deceit), schiavo (slave), miseria (misery), tortura (torture), tragedia (tragedy), pressione (pressure), processo (lawsuit).

List of Distractor-Faces

Practice: 4 angry faces: 038_m_m_a_b, 070_m_m_a_b, 080_m_f_a_b, 139_m_f_a_a; 4 happy faces: 038_m_m_h_b, 070_m_m_h_b, 080_m_f_h_b, 139_m_f_h_b; 4 neutral faces: 103_m_f_n_a, 103_m_f_n_b, 142_m_m_n_a, 142_m_m_n_b.

Experimental blocks: 16 angry faces: 011_m_f_a_a, 026_m_m_a_a, 051_m_m_a_b, 052_m_f_a_b, 056_m_m_a_b, 092_m_m_a_b, 093_m_f_a_a, 094_m_m_a_b, 104_m_m_a_b, 108_m_m_a_a, 111_m_f_a_b, 113_m_f_a_a, 117_m_f_a_b, 116_m_m_a_a, 157_m_f_a_b, 168_m_f_a_b; 16 happy faces: 007_m_m_h_b, 014_m_m_h_a, 032_m_m_h_a, 035_m_f_h_a, 043_m_f_h_a, 045_m_m_h_b, 061_m_f_h_b, 064_m_f_h_a, 073_m_f_h_b, 077_m_m_h_b, 097_m_f_h_a, 122_m_f_h_b, 126_m_m_h_b, 138_m_f_h_b, 165_m_m_h_a, 179_m_m_h_b; 16 neutral faces for scrambles: 006_m_f_n_a, 019_m_f_n_b, 029_m_f_n_a, 050_m_f_n_a, 058_m_m_n_a, 068_m_m_n_a, 082_m_m_n_a, 084_m_f_n_a, 128_m_f_n_a, 136_m_m_n_b, 149_m_m_n_b, 155_m_m_n_b, 156_m_f_n_a, 159_m_m_n_b,169_m_m_n_a, 180_m_f_n_a.

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