Cathodal tDCS Over the Left Prefrontal Cortex Diminishes Choice-Induced Preference Change

Flavia Mengarelli[1,2], Silvia Spoglianti[2], Alessio Avenanti[1,2,3] and Giuseppe di Pellegrino[1,2]

[1]Dipartimento di Psicologia, Alma Mater Studiorum Università di Bologna, Bologna I-40127, Italy, [2]Centro Studi e Ricerche in Neuroscienze Cognitive, Polo scientifico-didattico di Cesena, Cesena I-47521, Italy, [3]Istituto di Ricovero e Cura a Carattere Scientifico Fondazione Santa Lucia, Roma I-00179, Italy

Address correspondence to Flavia Mengarelli, Centre de Neurosciences Cognitives, UMR 5229, CNRS, Bron, France.
Email: flavia.mengarelli@isc.cnrs.fr

In everyday life, people often find themselves facing difficult decisions between options that are equally attractive. Cognitive dissonance theory states that after making a difficult choice between 2 equally preferred options, individuals no longer find the alternatives similarly desirable. Rather, they often change their existing preferences to align more closely with the choice they have just made. Despite the relevance of cognitive dissonance in modulating behavior, little is known about the brain processes crucially involved in choice-induced preference change. In the present study, we applied cathodal transcranial Direct Current Stimulation (tDCS) with the aim of downregulating the activity of the left or the right dorsolateral prefrontal cortex (DLPFC) during a revised version of Brehm's (in 1956. Post-decision changes in the desirability of alternatives. J Abnorm Soc Psychol. 52:384–389) free-choice paradigm. We found that cathodal tDCS over the left, but not over the right, DLPFC caused a reduction of the typical behavior-induced preference change relative to sham stimulation. Our findings highlight the role of prefrontal cortex in cognitive dissonance and provide evidence that left DLPFC plays a necessary role in the implementation of choice-induced preference change.

Keywords: attitude change, cognitive control, decision-making, prefrontal cortex, transcranial direct current stimulation

Introduction

Behaviors can create, not only reflect, people's attitudes. Several studies highlight how decisions can alter, rather than follow from, individuals' preferences (Izuma et al. 2010). Making difficult choices between options that are equally attractive to us is an ever-present part of our everyday life, like deciding between jobs offered by 2 different companies or selecting a new car among the different alternatives. Notably, after such a choice between equally preferred options is made, people no longer find the alternatives similarly desirable (Brehm 1956; Harmon-Jones and Harmon-Jones 2002), and they like the selected option more and the rejected option less than they initially did. The preference change serves to settle the psychological conflict due to the cognitions in contradiction with the choice executed: the positive attributes of the rejected alternative are dissonant with not having chosen it, and the negative attributes of the preferred alternative are dissonant with having chosen it (Aronson et al. 1995). Adjusting preferences to support prior decisions is a well-established phenomenon that has attracted the attention of scholars in the area of decision-making and social cognition for decades. This phenomenon has been mostly investigated at a behavioral level and has been explained by the influential theory of cognitive dissonance (Festinger 1957). According to this theory, inconsistent (dissonant) behaviors and attitudes result in a psychologically uncomfortable state of arousal that motivates people to reduce the dissonance by changing their original attitudes to be more consonant with the displayed behavior.

Despite the broad relevance of cognitive dissonance and dissonance reduction processes for different research traditions in psychology, knowledge about their neural substrates is still meager. Recent functional magnetic resonance imaging (fMRI) studies have suggested that the detection of the cognitive conflict generated by the inconsistency between attitudes and actions may be related to activity in the dorsal anterior cingulate cortex (dACC) (van Veen et al. 2009; Izuma et al. 2010), while the associated aversive autonomic arousal would be linked to activity in the anterior insula (van Veen et al. 2009; Qin et al. 2011). Once conflict is detected by the dACC and dissonance is aroused, decision-related attitude change may occur rapidly (Harmon-Jones, Harmon-Jones, et al. 2008). A number of evidence supports the involvement of dorsolateral prefrontal cortex (DLPFC), a region known to be involved in implementation of control and conflict resolution (Botvinick et al. 2001, 2004), in this process. Previous research has shown that activity in the left, right, or bilateral DLPFC may be associated with decision-induced preference change, however to date none have used noninvasive brain stimulation methods to draw causal inference from brain to behavior. For example, Qin et al. (2011) showed that postchoice neural activity in frontal regions (including the left DLPFC) predicted individual difference in the postchoice change in preferences, the so called "spread", reflecting the increase of preference for the chosen items and the decrease of preference for the rejected items. Notably, Harmon-Jones, Gerdjikov, et al. (2008) manipulated left DLPFC activity by EEG biofeedback training and found that participants who received neurofeedback training to decrease-left frontal cortical activity showed a significant reduction in the postdecision preference changes, suggesting an important role of left DLPFC in this behavior. Although the above-mentioned studies focused on the role of the left DLPFC in cognitive dissonance reduction processes, there are also studies reporting frontal cortex activations in the right hemisphere. For example, Jarcho et al. (2010) examined brain activity while participants were making difficult decisions in a neuroimaging study and they noticed that greater decision-related attitude change was associated with increased activity of right inferior frontal gyrus and with decreased activity in right anterior insula. Moreover, Izuma et al. (2010) found that, during the postchoice rerating of the items, activity in bilateral

DLPFC was predicted by the interindividual differences in the postdecision preference change.

Taken together these studies have suggested that DLPFC may be involved in resolving the conflict between actions and attitudes by bringing our attitudes into line with previous behavior. However, although DLPFC activity was associated with decision-related attitude change, this does not necessarily mean that DLPFC is also crucial for this process. A central aim of neuroscience is to explain how brain activity gives raise to cognition and behavior and this requires recurring lesion and brain stimulation methods that allow establishing causal links between brain and functions. Thus, to prove the critical role of DLPFC in choice-induced preference changes, we applied cathodal transcranial Direct Current Stimulation (tDCS) to the left or the right DLPFC during a revised version of Brehm's free-choice paradigm (Brehm 1956). Cathodal tDCS is a noninvasive brain stimulation technique known to decrease cortical excitability in the targeted brain region and to interfere with its processing, thus potentially leading to changes in behavior (Nitsche and Paulus 2001; Ardolino et al. 2005; Nitsche et al. 2008; Priori et al. 2009). In addition, we included a control condition where we applied sham stimulation to the right or left DLPFC. Each subject participated in only 1 of the 3 conditions (active tDCS over left DLPFC, active tDCS over right DLPFC, and sham tDCS). In this procedure, participants were first required to rank 2 sets of art prints, from most liked to least liked. Then, they were asked to choose between pairs of prints, among which 2 pairs comprised images they had seen and rated nearly equally before. Finally, after tDCS, they ranked the 2 sets of prints again.

We expect that in normal physiological condition (i.e., after sham tDCS) participants would exhibit the typical postdecision attitude change, with increased preference for the chosen pairs and decreased preference for the rejected pairs. Moreover, we hypothesize that if DLPFC is necessary for adjusting attitudes into line with behavior, active tDCS over this region might lead participants to reduce or not show any postdecision preference change. In particular, since cognitive dissonance implies some degree of rationalization and self-control (Brehm 1956; Festinger 1957; Aronson et al. 1995; Harmon-Jones and Harmon-Jones 2002; Harmon-Jones, Harmon-Jones, et al. 2008; van Veen et al. 2009; Izuma et al. 2010; Jarcho et al. 2010; Qin et al. 2011) and the left hemisphere is particularly involved in such processes (Ramachandran 1995, 1996; Gazzaniga et al. 1996; Tomarkenand and Keener 1998; Boggio et al. 2008; Ochsner and Gross 2008; Berkman and Lieberman 2009), we hypothesized that participants' ratings would remain relatively stable over time after stimulation of left, but not right, DLPFC.

Materials and Methods

Participants

Forty-eight healthy volunteers (28 women; mean age = 24.7; range: 20–38; mean years of education = 16.9; range: 13–21), recruited through posted advertisements, participated in the experiment. Participants were not taking psychoactive medications, and they were free of current or past psychiatric or neurological illnesses as determined by history. None of the participants had contraindications to brain stimulation (Poreisz et al. 2007; Rossi et al. 2009). All were naïves to tDCS and to the nature of the experiment, and at the beginning they were not explicitly informed about the experimental variables tested. All participants gave informed written consent before entering the study.

The experiment was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki, and was approved by the Ethical Committee of the Department of Psychology, University of Bologna.

Transcranial Direct Current Stimulation

Participants were randomly assigned to receive either unilateral active stimulation with the cathode electrode over the left DLPFC ($N = 16$), unilateral active stimulation with the cathode electrode over the right DLPFC ($N = 16$), or sham stimulation over the same cortical areas (Sham or control group; $N = 16$, with 8 and 8 participants with the cathode electrode over the left and the right DLPFC, respectively). In all 3 conditions, the anode electrode was placed over the contralateral supraorbital area. This electrode arrangement has been shown effective in various studies (Kincses et al. 2004; Fregni et al. 2005). Participants in the 3 groups (Left DLPFC, Right DLPFC, and Sham) did not differ for sex ($\chi^2_2 = 1.75, P = 0.41$), age ($F_{2,45} = 1.82, P = 0.17$), and years of education ($F_{2,45} = 0.87, P = 0.42$).

The left and the right DLPFC were targeted with reference to the F3 and F4 positions of the international EEG 10/20 system, respectively (Fecteau, Knoch, et al. 2007; Fecteau, Pascual-Leone, et al. 2007; Knoch et al. 2008; Keeser et al. 2011). Previous studies have estimated that Talairach coordinates corresponding to F3 are $x = -37$, $y = 27$, and $z = 44$ (BA 8/9), and those corresponding to F4 are $x = 39$, $y = 26$, and $z = 43$ (BA 8/9) (Herwig et al. 2003). The scalp positions corresponding to such coordinates were identified on each participant's head with the SoftTaxic Navigator system (Electro Medical Systems, Bologna, Italy) as in previous research (Bertini et al. 2010; Serino et al. 2011; Avenanti, Annella, Candidi, et al. 2013; Jacquet and Avenanti 2015; Tidoni et al. 2013). Skull landmarks (nasion, inion, and 2 preauricular points) and ~100 points providing a uniform representation of the scalp were digitized by means of a Polaris Vicra digitizer (Northern Digital Inc., ON, Canada). Talairach coordinates were automatically estimated by the SoftTaxic Navigator from an MRI-constructed stereotaxic template and the F3 or F4 position was individuated on participants' scalp.

For active stimulation, cathodal direct current, generated by a battery-driven electrical stimulator, was constantly delivered for 15 min at 1 mA intensity (current density: 0.028 mA/cm²) through 2 saline-soaked surface sponge electrodes (35 cm²). We ramped current up over the first 40 s of the stimulation and down over the last 40 s. For sham stimulation, instead, the stimulator was turned on only for 15 s. Thus, participants felt the initial itching sensation associated with active tDCS, but received no active current for the rest of the stimulation period. This method of sham stimulation has been shown to be reliable in naïve and experienced subjects (Gandiga et al. 2006).

Procedure

We adapted the Lieberman et al. (2001) modified version of Brehm's free-choice paradigm (Brehm 1956); see also Chen and Risen (2010) and Izuma and Murayama (2013), for a detailed and critical discussion of this well-established paradigm.

As cover story, on entering the testing room participants were informed that they would be performing some tasks designed to assess the influence of brain stimulation on esthetic preferences. All tasks were completed in a single session divided into 4 phases (see Fig. 1).

In Phase 1, participants were given 2 sets of 15 art prints (size 9 × 9 cm) and were asked to rank them (from 1 = the most liked to 15 = the least liked). Participants sorted a set of 15 cards that reproduced seascape paintings from French impressionism, and a second set of 15 cards that reproduced Aboriginal art paintings. The order in which these 2 sets were sorted was counterbalanced across participants, and the second set was always referred to as the critical set. As soon as the rankings were completed, the participants were asked to relax and listen to classical music for 15 min, before tDCS. In the meanwhile, the experimenter removed 2 pairs of prints from the critical set (critical pairs): one pair consisted of the fourth- and 10th- ranked prints (referred to as the 4–10 pair), while the other pair consisted of the sixth- and 12th-ranked prints (referred to as the 6–12 pair). Hence, the 4–10 and 6–12 pairs represented relatively liked and disliked prints, respectively.
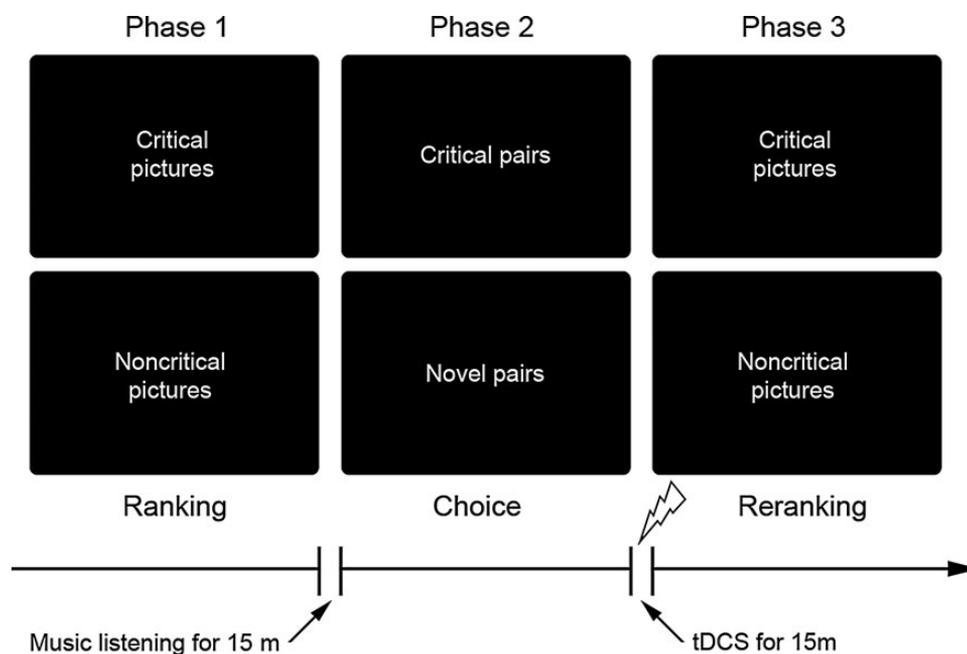
Figure 1. Schematic representation of the task procedure: In Phase 1, participants ranked in the order of their preference 2 sets of 15 art prints, i.e., the critical and noncritical pictures. Then, they listened to music for 15 min. In Phase 2, participants were presented with 2 pairs of art prints and chose which pair they would prefer if they could have full-size reproductions of that pair to take home with them. Participants made 6 choices for each set of prints. For the critical set, one choice involved the critical pairs and 5 choices involved novel pairs of prints. For the noncritical set, all the choices included novel pairs of prints. After completing Phase 2, active/sham tDCS was administered for 15 min. In Phase 3, participants reranked in the order of their preference the 2 initial sets of art prints. Finally, in Phase 4 (not shown in the figure), participants completed some control tasks, including explicit memory tests and assessment of discomfort experienced during tDCS (see text for more details).

In Phase 2, participants were informed that they were now going to complete another esthetic task. More specifically, they were presented with 2 pairs of art prints placed on the table (one on the left, the other on the right side) and asked to choose which they would prefer if they could have full-size reproductions of that pair to take home with them. Participants made 6 choices for each set. For the critical set, one choice involved the critical pairs and 5 choices involved novel pairs of prints of the same art category. For the noncritical set, all the choices included novel pairs of prints. The pair the participants indicated to prefer was designated as the "selected pair". The other pair was designated as the "rejected pair". The pairs of prints used for the participant's fourth choice in the critical set were the 2 critical pairs drawn from the first ranking. The relative spatial location in which the critical (4–10 and 6–12) pairs were placed as well as the order of presentation of the 2 (critical and noncritical) sets, were counterbalanced across participants. Active/sham tDCS started immediately after the last choice was made and lasted for 15 min during which the participant was required to remain seated and relaxed.

Phase 3 started 1 min before the stimulation was over and it was similar to Phase 1. The participants were asked to rerank each set of prints in order of their preference. It was specified that this was not a memory test and that they had to classify the pictures according to their preferences in that particular moment. The order of presentation of the 2 sets followed that one of Phase 2, so it was counterbalanced across participants as well.

In the last phase, Phase 4, participants were shown the 15 prints from the critical set (either the seascape set or the Aboriginal set) and asked to identify the 4 prints that had appeared in Phase 2 (memory of the critical pairs). As a test of memory for their previous choice, participants were also asked to recall which pair they had selected and which pair they had rejected during Phase 2. Finally, participants indicated their level of discomfort during the tDCS on a 7-point Likert scale ranging from 1 ("no discomfort") to 7 ("severe discomfort").

Data Analysis

To assess preference changes in the critical set, we measured the mean ranks of the selected and rejected pairs in Phase 1 and Phase 3. An increase in the mean ranks of the selected pair (more liking) and a decrease in the mean ranks of the rejected pair (less liking) in Phase 3 compared with the Phase 1, respectively, would indicate the typical choice-induced attitude change. Mean ranks in the critical set were analyzed using a Phase (Phase 1, Phase 3) × Pair (selected, rejected) × Group (Left DLPFC, Right DLPFC, and Sham) mixed-model analysis of variance (ANOVA).

The same Phase × Pair × Group ANOVA was carried out on data from the noncritical set. For this set, we considered as "selected pairs" and "rejected pairs" those pairs of prints with initial ranks equivalent to the ranks of the selected and rejected prints from the critical set (for similar method see Lieberman et al. 2001). Note that prints from the noncritical sets were ranked twice with no intervening choice, so that they provided baseline levels of attitude change in the absence of choice. In all the ANOVAs, post hoc analysis was carried out using Newman–Keuls test.

To test whether tDCS changed the magnitude of noise (i.e., random variation) during ranking (Izuma and Murayama 2013), a further analysis was carried out. For each subject, the Spearman's rank-order correlation coefficient (r_s) between ranking in Phase 1 and 3 was computed separately for the critical and noncritical sets. The coefficient was calculated both on all the art prints (r_s) and on a subset of them in which the critical pairs were excluded (r_s'). Then, 2 Set (critical, non critical) × Group (Left DLPFC, Right DLPFC, and Sham) mixed-model ANOVA were carried out, one for each coefficient.

In addition, a series of 1-way ANOVA with Group as the between-subjects factor were used to ensure that participants in the 3 groups did not differ in the ability to remember the critical pairs and their choice or in the discomfort felt during tDCS.

Results

A preliminary analysis revealed that the higher-ranked pair 4–10 was chosen 81% of the time by the Left DLPFC group, 69% of the time by the Right DLPFC group, and 75% of the time by the Sham group. The 3 stimulation groups did not significantly differ in the choice of the 4–10 pair ($\chi^2_2 = 3.12$, $P = 0.20$). These percentages were consistent with those reported

in the literature: for instance, in the [Lieberman et al.'s 2001](#) study, 64% and 75% of participants chose the higher-ranked pair in the first and the second experiment, respectively; moreover, [Gerard and White (1983)](#) reported that 75% of their participants chose the 4–10 pair. Note that eliminating the data of those participants who selected the lower-ranked pair (6–12 pair) did not change our results, so we chose to include them in our analysis.

Critical Set ("Rank, Choose, and Rerank")

The Phase × Pair × Group ANOVA yielded a significant main effect of Pair ($F_{1,45} = 43.11$, $P < 0.0001$), with higher mean ranks for the selected ($M = 7.17$) relative to the rejected ($M = 8.93$) pairs, and a significant 2-way Phase × Pair interaction ($F_{1,45} = 16.90$, $P < 0.0001$): relative to Phase 1, in Phase 3 the selected pairs increased in ranking (from $M = 7.50$ to $M = 6.83$; $P < 0.05$) and the rejected pairs decreased in ranking (from $M = 8.50$ to $M = 9.35$; $P < 0.01$). Critically, the 3-way Phase × Pair × Group interaction was significant ($F_{2,45} = 3.04$, $P < 0.05$; see Fig. 2). No other significant main effect or interaction was found in the ANOVA (all $F < 0.98$, $P > 0.38$).

To uncover the source of the significant 3-way interaction, 3 separate 2-way Phase × Pair repeated measures ANOVAs were performed, one for each stimulation group.

The ANOVAs on the Sham and the Right DLPFC groups (Fig. 2 left and right panels) showed a main effect of Pair (Sham: $F_{1,15} = 33.53$, $P < 0.0001$; Right DLPFC: $F_{1,15} = 14.69$, $P < 0.001$), and no main effect of Phase (all $F_{1,15} < 1.80$, $P > 0.20$). Most importantly, both analyses revealed a significant Phase × Pair interaction (Sham: $F_{1,15} = 9.42$, $P < 0.01$; Right DLPFC: $F_{1,15} = 31.49$, $P < 0.0001$). Post hoc comparisons showed a significant difference between ratings for selected and rejected pairs across Phases 1 and 3: the mean rank of the rejected pair indicated less liking in Phase 3 than in Phase 1 (Sham: $P < 0.01$; Right DLPFC: $P < 0.01$), whereas the mean rank of the selected pair indicated more liking in Phase 3 than in Phase 1 (Sham: $P = 0.18$; Right DLPFC: $P < 0.001$). That is, for participants under both Sham and Right DLPFC conditions, the chosen pair tended to increase in ranking (liking), and the rejected pair decreased in ranking (disliking), following decision.

The same analysis on the Left DLPFC group showed only a main effect of Pair ($F_{1,15} = 6.80$, $P < 0.05$; Fig. 2, middle panel), and no main effect of Phase ($F_{1,15} = 0.28$, $P = 0.60$). Critically, the Phase × Pair interaction was also not significant ($F_{1,15} = 0.09$, $P = 0.76$), suggesting that participants did not show any changes in preference from Phase 1 to Phase 3, and consequently showed no attitude change. Hence, participants who received cathodal tDCS over the left DLPFC did not present the typical choice-induced attitude change, as compared with participants who received active tDCS over the right DLPFC or sham stimulation.

To directly compare postdecision attitude changes in the 3 groups, we computed the spread between chosen and rejected pairs in Phases 1 and 3 (increase in rank for the selected pairs minus decrease in rank for the rejected pairs; [Lieberman et al. 2001](#); [Harmon-Jones, Harmon-Jones, et al. 2008](#).). Planned comparisons revealed that spread in the Sham and Right DLPFC groups was significantly greater than in the Left DLPFC group ($P < 0.05$; Fig. 3).

Noncritical Set ("Rank and Rerank")

The Phase × Pair × Group ANOVA indicated only a significant main effect of Pair ($F_{1,45} = 12.53$, $P < 0.001$; Fig. 4), showing that the mean ranks of the "selected" pair ($M = 7.55$) were significantly higher than those of the "rejected" pair ($M = 8.52$). Note that the "selected" pair in the noncritical set was ranked higher than the "rejected" pair because of the choices made in the critical set, where participants chose more frequently the 4–10 pair than the 6–12 pair. The ANOVA did not exhibit any other significant main effect or interaction (all $F < 0.60$, $P > 0.55$), suggesting that participants' ranking of images in the noncritical set remained stable across the study. Thus, the differences shown by the 3 groups in the attitude change in the critical set could not be ascribed to chance variations in preferences because there were no changes in the rankings of the corresponding prints in the noncritical set.

Control Analysis

Scholars have suggested that the free-choice paradigm is potentially influenced by artifacts and may measure a pattern of choice-induced preference changes (as predicted by
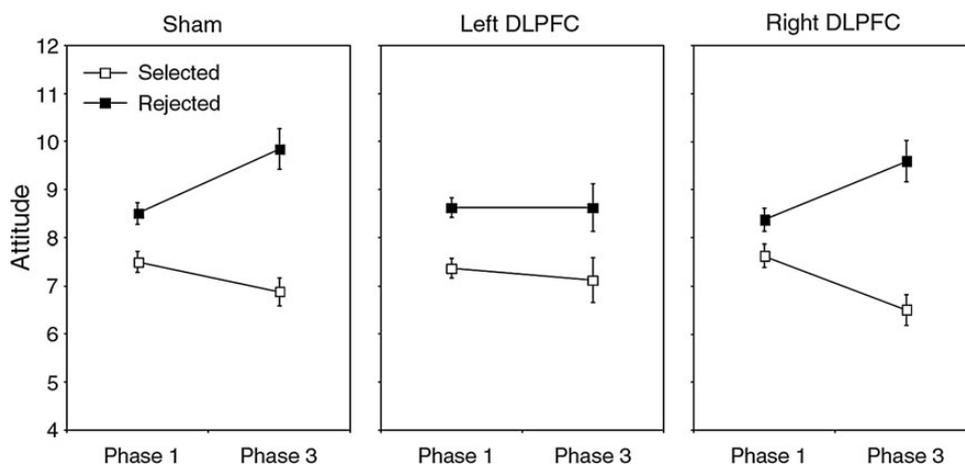
Figure 2. Preference for selected and rejected pairs of the critical set (prints ranked and reranked with an intervening choice) in Phase 1 and Phase 3, as a function of stimulation condition. Left, middle, and right panels show data from Sham, Left DLPFC, and Right DLPFC groups. Error bars reflect standard error. Note that higher number in rank indicates less liking, while lower number indicates more liking.

cognitive dissonance theory) without any change in true preferences. This notion was empirically supported (Chen and Risen 2010; Izuma et al. 2010) as well as demonstrated in a simulation study (Izuma and Murayama 2013). According to the arguments proposed by Chen and Risen (2010), it may be possible that, in our study, the tDCS affected the magnitude of noise (i.e., random variation) in the ranking and/or choice phases rather than cognitive dissonance processes. This, in turn, could have produced the differences in the spread across groups (see also Izuma and Murayama 2013 for a detailed discussion of this point). Thus, to demonstrate that tDCS specifically affected cognitive dissonance processes it is important to show that similar noise could be detected in the 3 groups.

It should be noted that the preliminary analysis already revealed that the higher-ranked pair 4–10 was chosen with similar frequency in the 3 groups, indicating similar consistency between participants' first ranking and their choice. This suggests that there is no difference in the magnitude of noise in the first ranking and choice phases across the 3 tDCS conditions. However, this is not surprising as tDCS was administered after the choice and participants were randomly assigned to the 3 groups. Thus, to further assure that suppression of left DLPFC affected postdecision attitude changes without
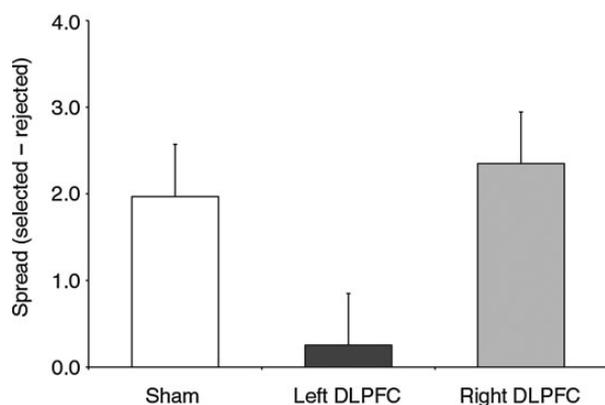
increasing the magnitude of noise during the second ranking phase, we tested whether the relationship between the first and the second ranking was different in the critical set of the Left DLPFC group relative to the other conditions. Table 1 shows that the correlation between the 2 rankings was high in both sets for all groups. Moreover, a Set × Group ANOVA on correlation coefficients showed no significant effect (all $F < 1.19$, $P > 0.3$), suggesting that tDCS over left DLPFC specifically prevented the change in attitude after the choice and did not alter rankings in an unspecific manner.

Control Tests

A series of additional analyses were performed on control tests. The 3 groups had some difficulty in identifying the 4 prints they evaluated in Phase 2 (i.e., the critical pairs), from the set of 15. Indeed, accuracy was 50% in the Left DLPFC group, 55% in the Right DLPFC group, and 45% in the Sham group. Moreover, of the pictures correctly identified as critical prints, the Left DLPFC group categorized 53% of the prints correctly as selected or rejected, the Right DLPFC group 71%, and Sham group 45%. Critically, participants in the 3 groups did not differ in their memory of the critical pairs ($F_{2,45} = 0.32$, $P = 0.72$), or of their choice ($F_{2,45} = 2.12$, $P = 0.13$). Moreover, discomfort ratings were low and statistically comparable in the 3 groups (Left DLPFC: $M = 2.63$; Right DLPFC: $M = 2.38$; Sham group: $M = 2.38$; $F_{2,45} = 0.22$, $P = 0.80$). These findings suggest that the lack of postdecision preference change in the Left DLPFC group cannot be ascribed to any difference in memory performance or in the discomfort felt by participants from this group relative to the Right DLPFC or Sham groups.

Discussion

After making a choice between equally attractive options, people no longer find the alternatives similarly desirable, and they often change their existing preferences to align more closely with the choice they have just made. In line with the previous literature (Brehm 1956; Lieberman et al. 2001; Kitayama et al. 2004; Izuma et al. 2010), our behavioral results showed the typical attitude change that follows a difficult choice between 2 similarly likable options. After making a

Figure 3. Mean Spread (selected − rejected) in the critical set for Sham, Left, and Right DLPFC stimulation condition. Error bars reflect standard error.
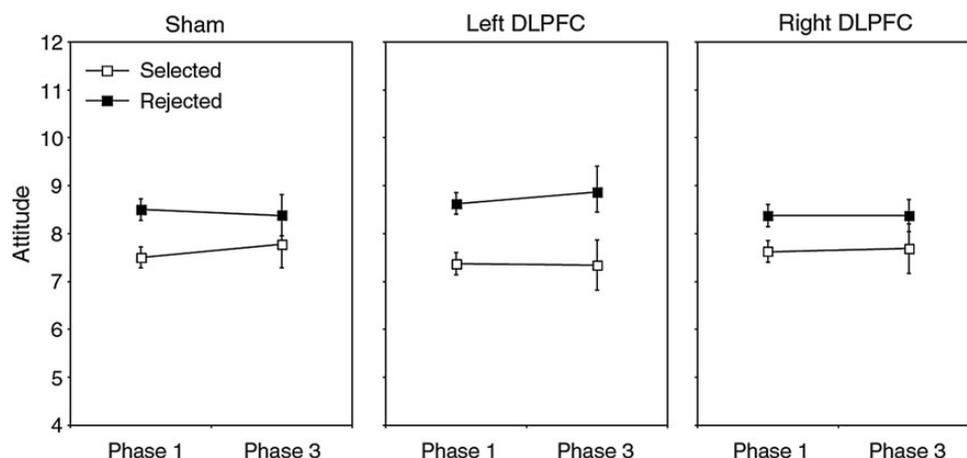
Figure 4. Preference for selected and rejected pairs of the noncritical set (prints ranked and reranked without an intervening choice) in Phase 1 and Phase 3, as a function of stimulation condition left, middle, and right panels show data from Sham, Left DLPFC, and Right DLPFC groups. Error bars reflect standard error. Note that in Phase 1, pairs with the same ranks as those a participant selected and rejected in the critical set were designated as selected and rejected, respectively, in the noncritical set for comparison purposes.

Table 1
Mean correlation' coefficients between the first and the second rankings computed for the critical and the noncritical sets

	Sham	Left DLPFC	Right DLPFC
Critical set (r_s)	0.79	0.85	0.78
Non critical set (r_s)	0.79	0.83	0.82
Critical set (r'_s)	0.81	0.90	0.81
Non critical set (r'_s)	0.82	0.87	0.84

r_s: Spearman's rank-order correlation computed on all items and r'_s: Spearman's rank-order correlation computed without items 4, 6, 10, and 12.

choice, participants who were in normal physiological conditions (i.e., in the Sham condition) tended to increase their liking for the chosen paintings and to decrease their liking for the rejected ones.

The major point of novelty of our study is that noninvasive stimulation of the left but not of the right DLPFC disrupts this choice-related attitude change. Previous functional imaging studies suggested that activity in the left (Harmon-Jones, Harmon-Jones, et al. 2008; Izuma et al. 2010) or the right DLPFC (Jarcho et al. 2010), is associated with choice-induced preference change. Nevertheless, to date, the majority of studies provided correlational evidence which does not allow establishing whether neural processing in the DLPFC is also necessary for choice-induced preference change. In the current study, we applied for the first time a cathodal stimulation protocol that is known to decrease cortical excitability (Nitsche and Paulus 2001; Ardolino et al. 2005; Nitsche et al. 2008) in the left and right DLPFC during a revised version of free-choice paradigm to investigate the causal relation between DLPFC and postdecision attitude change.

According to cognitive dissonance theory (Festinger 1957), inconsistency between behavior and previous attitudes triggers an unpleasant emotional state requiring that cognitive processes step in for its reduction. In accordance with this theory, van Veen et al. (2009) found that during a counter-attitudinal argument the magnitude of dACC activity, which serves the function to monitor conflicts between incompatible streams of information or processes (Botvinick et al. 2001, 2004), predicted the final attitude change of participants in the dissonance condition. In line with previous imaging studies, suggesting that DLPFC is implicated in postdecisional attitude change (Harmon-Jones, Harmon-Jones, et al. 2008; Izuma et al. 2010; Jarcho et al. 2010), and consistent with theories on engagement of DLPFC in cognitive control (Miller 2000; Carter and van Veen 2007), emotion regulation (Ochsner and Gross 2005), as well as self-control (Hare et al. 2009), here we hypothesized a pivotal role of DLPFC in the processes responsible for dissonance reduction.

Our results showed that cathodal tDCS impaired cognitive dissonance reduction processes only when applied on the left DLPFC. Indeed, only participants who received active stimulation of this region did not display any differences between the mean ranks of the critical set in Phase 3 relative to Phase 1, suggesting that the tDCS could have interfered with cognitive processes required to change preferences following a difficult choice. In sharp contrast, participants who received sham tDCS or active cathodal tDCS over the right DLPFC showed the typical postdecision attitude change, ruling out the possibility of a widespread effect of the tDCS *per se*. That tDCS had not a general and unspecific effect on stimulus evaluation *per se* is

further suggested by the fact that in the noncritical set of prints, which were ranked and reranked without an intervening choice, the mean ranks of the corresponding pairs remained stable from Phase 1 to Phase 3 in all 3 stimulation groups.

It is unlikely that our results could be attributed to other factors such as memory of the critical pairs and memory of the choice made in Phase 2, as memory accuracy in the Left DLPFC group was comparable to that of the other 2 groups. Consistently, previous studies suggested that behavior-induced preference change occurs in a relatively automatic fashion, and neither explicit memory for, nor consciously controlled processing of, the discrepancy between subjects' past decisions and their preference, were considered to be responsible for this phenomenon (Lieberman et al. 2001; but see Chen and Risen 2010 and Izuma and Murayama 2013 for a critical view). Lastly, the level of discomfort experienced during active tDCS was very low and comparable to sham tDCS (Gandiga et al. 2006). Thus, the lack of postdecision preference change after stimulation of the left DLPFC cannot also be ascribed to any unpleasant scalp sensations evoked by tDCS.

Our findings are consistent with several prior observations. Previous research has associated left prefrontal cortical activity to a reduction in the amount of spreading of alternatives that typically occurs following a difficult decision (Harmon-Jones, Harmon-Jones, et al. 2008; Harmon-Jones, Gerdjikov, et al. 2008). For example, Qin et al. (2011) found that after a difficult decision, neural activity in left DLPFC predicted postdecision attitude change. Importantly, Harmon-Jones, Gerdjikov, et al. (2008) measured attitude change after participants made a difficult choice and their left DLPFC activity was manipulated using EEG biofeedback training. Participants who received neurofeedback to decrease, as compared with increase, left frontal activity showed a significant reduction in changing their attitudes after the difficult choice, suggesting a critical role of left DLPFC in such behavior. According to Harmon-Jones, Gerdjikov, et al. (2008), these results indicate that left DLPFC is causally involved in dissonance reduction processes. Although in line with our findings, this study lacks a control condition in which other cortical regions (i.e., the right PFC) are likewise manipulated through neurofeedback. Moreover, no sham condition was used to compare the performance of the decrease-left and the increase-left frontal groups. Our study significantly expands previous evidence on 2 fundamental aspects: it includes the critical control conditions and, most importantly, it employs direct stimulation of DLPFC, thus enabling us to claim a causal role of DLPFC activity in dissonance reduction processes and in postdecision attitude change.

Furthermore, our results allow refining the neural network underlying cognitive dissonance processes, by showing that the left, but not the right, DLPFC provides a critical neural substrate for choice-induced preference change and dissonance reduction. We suggest that cognitive processes mediated by left DLPFC (i.e., rationalization processes) occur in order to cope with the inconsistency between behavior and attitudes, and lead to consequential attitude change. The notion of left hemisphere involvement in rationalization is well established. Based on studies on split-brain patients, Gazzaniga et al. (1996) proposed that the left hemisphere contains an "interpreter" which helps to grant a sense of order to our lives, allowing us to settle our present attitudes with our past actions and feelings and vice versa. Similarly, Ramachandran (1995,

1996) suggested that, once an anomaly or discrepancy is detected by the right hemisphere (which generates the appropriate emotion too), the left hemisphere tries to restore self-consistency by ignoring or suppressing the dissonant evidence. Such perspective is consistent with previous theories of the role of DLPFC in cognitive control and behavioral adjustment following the experience of conflict (Miller and Cohen 2001). Accordingly, imaging studies have previously shown involvement of the left DLPFC areas in processes aimed at resolving cognitive conflict and that more activity in this region is associated with conflict decrease (MacDonald 2000). On this view, the left DLPFC might work by modulating activity in valuations regions (e.g., medial prefrontal regions; Sellitto et al. 2010), via inputs into valuation areas, thereby inducing a shift toward choice-consistent attitudes and facilitating dissonance reduction processes (Izuma et al. 2010).

Studies suggest an important role of left DLPFC in self-regulation processes (Tomarkenand and Keener 1998), as well as in affective modulation (Boggio et al. 2008). In an fMRI study, Hare et al. (2009) examined neural processes responsible for the deployment of self-control in dieters making real decisions about which food to eat. Greater activity in left DLPFC was found during implementation of self-control strategies and in those participants who were more capable to regulate food-intake. In addition, Figner et al. (2010) demonstrated that disruption of the left, but not right, DLPFC led to increased impatient choice for immediate but less valuable rewards. Additional EEG and fMRI evidence indicated high levels of baseline left prefrontal activation to be associated with increased capacity to voluntarily suppress negative emotions (Peña-Gómez et al. 2011). Importantly, studies indicate that a left-lateralized frontal network, including the left DLPFC, is consistently activated during reappraisal of emotions (Ochsner and Gross 2008; Berkman and Lieberman 2009). These studies suggest that emotion regulation recruits top-down executive control, possibly mediated by the left DLPFC. Our results are in line with these evidence and further support the notion that the left DLPFC is a crucial neural substrate for self-control and self-regulation.

Potential concerns with the tDCS protocol used need also to be addressed. First, we applied 1 mA cathodal stimulation and, in our interpretation of the results, have assumed that this would interfere with the computations carried out by the targeted DLPFC area. This assumption is justified on the basis of the findings of several previous studies that have found such interference effects in a wide range of behavioral paradigms (Nitsche et al. 2003; Antal et al. 2004; Dieckhöfer et al. 2006) and inhibitory effects in experiments combining TMS (Schmidt et al. 2013), as well as functional neuroimaging (Zheng et al. 2011), with tDCS. More specifically, several previous studies have found inhibitory effects of applying cathodal tDCS to the DLPFC in a variety of tasks, including personal (Fecteau, Knoch, et al. 2007; Fecteau, Pascual-Leone, 2007) and social (Knoch et al. 2008; Fumagalli et al. 2010) decision-making, verbal fluency (Vannorsdall et al. 2012), categorization (Lupyan et al. 2012), set shifting (Leite et al. 2011), and declarative memory (Javadi and Walsh 2012). Thus a large body of evidence supports our assumption.

A second concern is a lack of detailed knowledge about the spatial resolution of the technique. Although we centered our stimulation over the left and right DLPFC sectors shown to be involved in cognitive dissonance and postdecisional attitude changes (Harmon-Jones, Harmon-Jones, et al. 2008; Izuma et al. 2010; Qin et al. 2011), it is possible that additional sectors of the prefrontal cortex (e.g., the inferior frontal gyrus; Jarcho et al. 2010) were influenced by tDCS due the relatively poor spatial resolution of this technique (Nitsche et al. 2008; Priori et al. 2009). Moreover, several studies have shown that brain stimulation techniques can modulate activity in remote regions connected to the region being stimulated (Stagg et al. 2009; Keeser et al. 2011; Avenanti, Annella, et al. 2012; Avenanti, Candidi, et al. 2013). Thus, it is possible that regions interconnected to the left DLPFC were influenced by cathodal tDCS and may have contributed to the observed effects. In particular, modulating activity in frontal regions may have transcallosal (and opposite) effects on the activity of their homolog in the contralateral (unstimulated) hemisphere (Fecteau et al. 2007; Nowak et al. 2009; Avenanti, Coccia, et al. 2012). Thus the present data cannot establish whether the impact on cognitive dissonance is solely attributable to downmodulation of activity in the left DLPFC, or whether the behavioral effects are the results of a change in the balance of activity across both DLPFCs and interconnected regions. At any rate, our study shows a clear dissociation between the stimulation of left and right DLPFC in cognitive dissonance and attitude change following a difficult decision.

To sum up, we have found that applying cathodal tDCS over the left DLPFC affects the degree to which individuals change their attitude to be more consistent with the choice that they have just made. These results are consistent with the possibility that DLPFC is crucially implicated in dissonance reduction processes and, that the left, but not right, DLPFC plays a causal role in attitude change after a difficult decision. Thus, our findings suggest that this dissonance-induced preference change recruits the same neural network underlying the implementation of cognitive control, emotion regulation, and the deployment of self-control.

Notes

Conflict of Interest: None declared.

References

Antal A, Varga ET, Kincses TZ, Nitsche MA, Paulus W. 2004. Oscillatory brain activity and transcranial direct current stimulation in humans. Neuroreport. 15:1307–1310.

Ardolino G, Bossi B, Barbieri S, Priori A. 2005. Non-synaptic mechanisms underlie the after-effects of cathodal transcutaneous direct current stimulation of the human brain. J Physiol. 568:653–663.

Aronson J, Blanton H, Cooper J. 1995. From dissonance to disidentification: selectivity in the self-affirmation process. J Pers Soc Psychol. 68:986–996.

Avenanti A, Annella L, Candidi M, Urgesi C, Aglioti SM. 2013. Compensatory plasticity in the action observation network: virtual lesions of STS enhance anticipatory simulation of seen actions. Cereb Cortex. 23:570–580.

Avenanti A, Annella L, Serino A. 2012. Suppression of premotor cortex disrupts motor coding of peripersonal space. Neuroimage. 63:281–288.

Avenanti A, Candidi M, Urgesi C. 2013. Vicarious motor activation during action perception: beyond correlational evidence. Front Hum Neurosci. 7:185.

Avenanti A, Coccia M, Ladavas E, Provinciali L, Ceravolo MG. 2012. Low-frequency rTMS promotes use-dependent motor plasticity in chronic stroke: a randomized trial. Neurology. 78:256–264.

Berkman ET, Lieberman MD. 2009. Using neuroscience to broaden emotion regulation: theoretical and methodological considerations. Soc Pers Psychol Compass. 3:475–493.

Bertini C, Leo F, Avenanti A, Làdavas E. 2010. Independent mechanisms for ventriloquism and multisensory integration as revealed by theta-burst stimulation. Eur J Neurosci. 31:1791–1799.

Boggio PS, Rigonatti SP, Ribeiro RB, Myczkowski ML, Nitsche MA, Pascual-Leone A, Fregni F. 2008. A randomized, double-blind clinical trial on the efficacy of cortical direct current stimulation for the treatment of major depression. Int J Neuropsychopharmacol. 11:249–254.

Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. 2001. Conflict monitoring and cognitive control. Psychol Rev. 108:624–652.

Botvinick MM, Cohen JD, Carter CS. 2004. Conflict monitoring and anterior cingulate cortex: an update. Trends Cogn Sci. 8:539–546.

Brehm J. 1956. Post-decision changes in the desirability of alternatives. J Abnorm Soc Psychol. 52:384–389.

Carter CS, van Veen V. 2007. Anterior cingulate cortex and conflict detection: an update of theory and data. Cogn Affect Behav Neurosci. 7:367–379.

Chen M, Risen J. 2010. How choice affects and reflects preferences: revisiting the free-choice paradigm. J Pers Soc Psychol. 99:573–594.

Dieckhöfer A, Waberski TD, Nitsche M, Paulus W, Buchner H, Gobbelé R. 2006. Transcranial direct current stimulation applied over the somatosensory cortex—differential effect on low and high frequency SEPs. Clin Neurophysiol. 117:2221–2227.

Fecteau S, Knoch D, Fregni F, Sultani N, Boggio P, Pascual-Leone A. 2007. Diminishing risk-taking behavior by modulating activity in the prefrontal cortex: a direct current stimulation study. J Neurosci. 27:12500–12505.

Fecteau S, Pascual-Leone A, Zald DH, Liguori P, Théoret H, Boggio PS, Fregni F. 2007. Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making. J Neurosci. 27:6212–6218.

Festinger L. 1957. A theory of cognitive dissonance. Evanston (IL): Row, Peterson.

Figner B, Knoch D, Johnson EJ, Krosch AR, Lisanby SH, Fehr E, Weber EU. 2010. Lateral prefrontal cortex and self-control in intertemporal choice. Nat Neurosci. 13:538–539.

Fregni F, Boggio PS, Nitsche M, Bermpohl F, Antal A, Feredoes E, Marcolin MA, Rigonatti SP, Silva MT, Paulus W et al. 2005. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. Exp Brain Res. 166:23–30.

Fumagalli M, Vergari M, Pasqualetti P, Marceglia S, Mameli F, Ferrucci R, Mrakic-Sposta S, Zago S, Sartori G, Pravettoni G et al. 2010. Brain switches utilitarian behavior: does gender make the difference? PLoS One. 5:e8865.

Gandiga PC, Hummel FC, Cohen LG. 2006. Transcranial direct current stimulation (tDCS): a tool for double-blind sham-controlled clinical studies in brain stimulation. Clin Neurophysiol. 117:845–850.

Gazzaniga MS, Eliassen JC, Nisenson L, Wessinger CM, Fendrich R, Baynes K. 1996. Collaboration between the hemispheres of a callosotomy patient: emerging right hemisphere speech and the left hemisphere interpreter. Brain. 119:1255–1262.

Gerard HB, White GL. 1983. Post-decisional reevaluation of choice alternatives. Pers Soc Psychol Bull. 9:365–369.

Hare TA, Camerer CF, Rangel A. 2009. Self-control in decision-making involves modulation of the vmPFC valuation system. Science. 324:646–648.

Harmon-Jones E, Gerdjikov T, Harmon-Jones C. 2008. The effect of induced compliance on relative left frontal cortical activity: a test of the action-based model of dissonance. Eur J Soc Psychol. 38:35–45.

Harmon-Jones E, Harmon-Jones C. 2002. Testing the action-based model of cognitive dissonance: the effect of action orientation on post-decisional attitudes. Pers Soc Psychol Bull. 28:711–723.

Harmon-Jones E, Harmon-Jones C, Fearn M, Sigelman JD, Johnson P. 2008. Left frontal cortical activation and spreading of alternatives: tests of the action-based model of dissonance. J Pers Soc Psychol. 94:1–15.

Herwig U, Satrapi P, Schönfeldt-Lecuona C. 2003. Using the international 10–20 EEG system for positioning of transcranial magnetic stimulation. Brain Topogr. 16:95–99.

Izuma K, Matsumoto M, Murayama K, Samejima K, Sadato N, Matsumoto K. 2010. Neural correlates of cognitive dissonance and choice-induced preference change. Proc Natl Acad Sci USA. 107:22014–22019.

Izuma K, Murayama K. 2013. Choice-induced preference change in the free-choice paradigm: a critical methodological review. Front Psychol. 4:41. doi:10.3389/fpsyg.2013.00041

Jacquet PO, Avenanti A. 2015. Perturbing the action observation network during perception and categorization of actions' goals and grips: state-dependency and virtual lesion TMS effects. Cereb Cortex. 25:598–608.

Jarcho JM, Berkman ET, Lieberman MD. 2010. The neural basis of rationalization: cognitive dissonance reduction during decision-making. Soc Cogn Affect Neurosci. 6:460–467.

Javadi AH, Walsh V. 2012. Transcranial direct current stimulation (tDCS) of the left dorsolateral prefrontal cortex modulates declarative memory. Brain Stimul. 5:231–241.

Keeser D, Meindl T, Bor J, Palm U, Pogarell O, Mulert C, Brunelin J, Möller HJ, Reiser M, Padberg F. 2011. Prefrontal transcranial direct current stimulation changes connectivity of resting-state networks during fMRI. J Neurosci. 31:15284–15293.

Kincses TZ, Antal A, Nitsche MA, Bártfai O, Paulus W. 2004. Facilitation of probabilistic classification learning by transcranial direct current stimulation of the prefrontal cortex in the human. Neuropsychologia. 42:113–117.

Kitayama S, Snibbe AC, Markus HR, Suzuki T. 2004. Is there any "free" choice? Self and dissonance in two cultures. Psychol Sci. 15:527–533.

Knoch D, Nitsche MA, Fischbacher U, Eisenegger C, Pascual-Leone A, Fehr E. 2008. Studying the neurobiology of social interaction with transcranial direct current stimulation. The example of punishing unfairness. Cereb Cortex. 18:1987–1990.

Leite J, Carvalho S, Fregni F, Gonçalves ÓF. 2011. Task-specific effects of tDCS-induced cortical excitability changes on cognitive and motor sequence set shifting performance. PLoS One. 6:e24140.

Lieberman MD, Ochsner KN, Gilbert DT, Schacter DL. 2001. Do amnesic exhibit cognitive dissonance reduction? The role of explicit memory and attention in attitude change. Psychol Sci. 12:135–140.

Lupyan G, Mirman D, Hamilton R, Thompson-Schill SL. 2012. Categorization is modulated by transcranial direct current stimulation over left prefrontal cortex. Cognition. 124:36–49.

MacDonald AW. 2000. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science. 288:1835–1838.

Miller EK. 2000. The prefrontal cortex and cognitive control. Nat Rev Neurosci. 1:59–65.

Miller EK, Cohen JD. 2001. An integrative theory of prefrontal cortex function. Annu Rev Neurosci. 24:167–202.

Nitsche MA, Cohen LG, Wassermann EM, Priori A, Lang N, Antal A, Paulus W, Hummel F, Boggio PS, Fregni F et al. 2008. Transcranial direct current stimulation: State of the art 2008. Brain Stimul. 1:206–223.

Nitsche MA, Nitsche MS, Klein CC, Tergau F, Rothwell JC, Paulus W. 2003. Level of action of cathodal DC polarisation induced inhibition of the human motor cortex. Clin Neurophysiol. 114:600–604.

Nitsche MA, Paulus W. 2001. Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. Neurology. 57:1899–1901.

Nowak DA, Grefkes C, Ameli M, Fink GR. 2009. Interhemispheric competition after stroke: brain stimulation to enhance recovery of function of the affected hand. Neurorehabil Neural Repair. 23:641–656.

Ochsner KN, Gross JJ. 2008. Cognitive emotion regulation, insight from social cognitive and affective neuroscience. Curr Dir Psychol Sci. 17:153–158.

Ochsner KN, Gross JJ. 2005. The cognitive control of emotion. Trends Cogn Sci. 9:242–249.

Peña-Gómez C, Vidal-Piñeiro D, Clemente IC, Pascual-Leone A, Bartrés-Faz D. 2011. Down-regulation of negative emotional processing by transcranial direct current stimulation: effects of personality characteristics. PloS One. 6:e22812.

Poreisz C, Boros K, Antal A, Paulus W. 2007. Safety aspects of transcranial direct current stimulation concerning healthy subjects and patients. Brain Res Bull. 72:208–214.

Priori A, Hallett M, Rothwell JC. 2009. Repetitive transcranial magnetic stimulation or transcranial direct current stimulation? Brain Stimul. 2:241–245.

Qin J, Kimel S, Kitayama S, Wang X, Yang X, Han S. 2011. How choice modifies preference: neural correlates of choice justification. Neuroimage. 55:240–246.

Ramachandran VS. 1995. Anosognosia in parietal lobe syndrome. Conscious Cogn. 4:22–51.

Ramachandran VS. 1996. The evolutionary biology of self-deception, laughter, dreaming and depression: some clues from anosognosia. Med Hypotheses. 47:347–362.

Rossi S, Hallett M, Rossini PM, Pascual-Leone A, Safety of TMS Consensus Group. 2009. Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. Clin Neurophysiol. 120:2008–2039.

Schmidt S, Fleischmann R, Bathe-Peters R, Irlbacher K, Brandt SA. 2013. Evolution of premotor cortical excitability after cathodal inhibition of the primary motor cortex: a sham-controlled serial navigated TMS study. PLoS One. 8:e57425.

Sellitto M, Ciaramelli E, di Pellegrino G. 2010. Myopic discounting of future rewards after medial orbitofrontal damage in humans. J Neurosci. 30:2516–2510.

Serino A, Canzoneri E, Avenanti A. 2011. Fronto-parietal areas necessary for a multisensory representation of peripersonal space in humans: an rTMS study. J Cogn Neurosci. 23:2956–2967.

Stagg CJ, O'Shea J, Kincses ZT, Woolrich M, Matthews PM, Johansen-Berg H. 2009. Modulation of movement-associated cortical activation by transcranial direct current stimulation. Eur J Neurosci. 30:1412–1423.

Tidoni E, Borgomaneri S, di Pellegrino G, Avenanti A. 2013. Action simulation plays a critical role in deceptive action recognition. J Neurosci. 33:611–623.

Tomarkenand A, Keener A. 1998. Frontal brain asymmetry and depression: a self-regulatory perspective. Cogn Emot. 12:387–420.

Vannorsdall TD, Schretlen DJ, Andrejczuk M, Ledoux K, Bosley LV, Weaver JR, Skolasky RL, Gordon B. 2012. Altering automatic verbal processes with transcranial direct current stimulation. Front Psychiatry. 3:73.

van Veen V, Krug MK, Schooler JW, Carter CS. 2009. Neural activity predicts attitude change in cognitive dissonance. Nat Neurosci. 12:1469–1474.

Zheng X, Alsop DC, Schlaug G. 2011. Effects of transcranial direct current stimulation (tDCS) on human regional cerebral blood flow. Neuroimage. 58:26–33.