

Noninvasive stimulation over the dorsolateral prefrontal cortex facilitates the inhibition of  
motivated responding

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**Abstract**

Self-control involves the inhibition of dominant response tendencies. Most research on self-control has examined the inhibition of appetitive tendencies, and recent evidence suggests that stimulation to increase right frontal cortical activity helps to inhibit approach-motivated responses. The current experiment paired an approach-avoidance joystick task with transcranial direct current stimulation to test the effects of brain stimulation on the inhibition of both approach and avoidance response tendencies. Anodal stimulation over the right/cathodal stimulation over the left dorsolateral prefrontal cortex (compared to the opposite pattern of stimulation or sham stimulation) caused participants to initiate motive-incongruent movements more quickly, thereby suggesting a shared neural mechanism for the self-control of both approach- and avoidance-motivated impulses.

**Keywords:** self-control; inhibition; approach motivation; avoidance motivation; frontal asymmetry; transcranial direct current stimulation

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Self-control refers to the capacity to override or alter one's impulses (e.g., Tangney, Baumeister, & Boone, 2004). Most prior research on self-control, including Walter Mischel's seminal work on delay of gratification in children (Mischel 1958; Mischel, Ebbesen, Zeiss, 1972), has focused on the control of impulses to go toward stimuli or obtain rewards (i.e., approach-motivated impulses; see Harmon-Jones, Harmon-Jones, & Price, 2013). Behaviors that stem from approach-motivated impulses include eating (Kahan, Polivy, & Herman, 2003), alcohol use (Ostafin, Marlatt, & Greenwald, 2008), sexual behavior (Impett, Peplau, & Gable, 2005), and aggression (Harmon-Jones, & Sigelman, 2001). Failures to inhibit or control approach-motivated impulses thus contribute to obesity, drug addiction, unwanted pregnancies, and other outcomes that carry both personal and societal costs (e.g., Moffitt et al., 2011).

Less is known about the self-control of impulses to move away from stimuli or elude threats (i.e., avoidance-motivated impulses; see Elliot, 2006). Behaviors that stem from avoidance-motivated impulses include the evasion of threatening organisms (e.g., predators), situations (e.g., darkness), or states of being that could harm the self. But in some cases, painful or threatening stimuli (e.g., a medical procedure) must be endured in service of long-term goals (e.g., health; see Trope & Fishbach, 2000). In such instances a person may need to inhibit or alter avoidance-motivated impulses and stay near to or move toward aversive stimuli (Powers & Emmelkamp, 2008).

Because theory and research on self-control have focused almost exclusively on the self-control of approach-motivated impulses (e.g., Hofmann, Friese, & Strack, 2009; Kotabe & Hofmann, 2015; Schmeichel, Harmon-Jones, & Harmon-Jones, 2010), the self-control of

avoidance-motivated impulses among normal (i.e., non-phobic) individuals has received relatively little research attention (Carver, 2005). The current research examined the effects of noninvasive stimulation of electrical activity in the prefrontal cortex on the inhibition of both approach- and avoidance-oriented impulses.

### **Motivation and Electrical Activity in the Prefrontal Cortex**

Patterns of electrical activity in the prefrontal cortex may reveal a person's motivational orientation. Numerous studies using electroencephalographic (EEG) recordings have found a positive correlation between left frontal asymmetry (i.e., greater left than right frontal cortical activation) and both trait approach motivation (e.g., Coan & Allen, 2003; De Pascalis, Varriale, & D'Antuono, 2009) and states associated with high approach motivation (e.g., Harmon-Jones & Sigelman, 2001), although recent studies (e.g., Gable, Mechin, Hicks, & Adams, 2015) and meta-analytic evidence (e.g., Wacker, Chavanon, & Stemmler, 2009) suggest that the association between approach-related traits (e.g., BAS, extraversion) and frontal asymmetry is weaker than commonly assumed. Beyond self-reports of approach motivation, manipulations to increase left frontal asymmetry have been found to induce temporary changes in a person's motivational orientation. Experiments involving the manipulation of prefrontal cortical activity are important because they permit causal inferences about the consequences of frontal asymmetry. A growing number of studies have found that manipulations to increase left frontal asymmetry also increase approach-motivated responding (e.g., Allen, Harmon-Jones, & Cavender, 2001; Hortensius, Schutter, & Harmon-Jones, 2012; Kelley, Eastwick, Harmon-Jones, & Schmeichel, 2015).

In children and non-human primates, greater right frontal asymmetry has reliably been associated with trait-like differences in behavioral inhibition and anxious temperament (e.g., Buss et al., 2003; Davidson, Kalin, & Shelton, 1993; Davidson & Rickman, 1999; Kalin, Larson,

Shelton, & Davidson, 1998; Fox, Henderson, Marshall, Nichols, & Ghera, 2005). But in human adults the results are mixed. Some studies have found a positive correlation between greater right than left frontal cortical activation and avoidance-related traits and emotions (e.g., Coan, Allen, & Harmon-Jones, 2001; Tomarken, Davidson, & Henriques, 1990), whereas other studies have found little or no correlation between them (e.g., Amodio, Master, Yee, & Taylor, 2008; Coan & Allen, 2003; Harmon-Jones & Allen, 1997).

Rather than (or perhaps in addition to) influencing avoidance motivation, some evidence suggests that increasing activity in the right prefrontal cortex may increase inhibitory control (i.e., the capacity to suppress a prepotent response; Garavan, Ross, & Stein, 1999). For example, one study using transcranial direct current stimulation (tDCS) to manipulate frontal brain activity found that increasing right while decreasing left frontal cortical activity decreases risk-taking in a gambling task (Fecteau et al., 2007). A manipulated increase in right frontal activity with tDCS has also been found to decrease food cravings and caloric consumption relative to a manipulated increase in left frontal cortical activity and sham stimulation (Fregni et al., 2008; Goldman et al., 2011). More recently, increased right frontal asymmetry via tDCS has been found to decrease aggressive behavior (Dambacher et al., 2015), which is relevant insofar as decreasing aggression requires self-control (Denson, DeWall, & Finkel, 2012). Similarly, disruption of right frontal cortical activity via transcranial magnetic stimulation has been found to increase risky decision-making (Knoch et al., 2006), again suggesting that right frontal cortical activity may help to stifle approach-motivated tendencies (see Knoch & Fehr, 2007).

The results from prior brain stimulation studies thus suggest that manipulations to increase right frontal asymmetry may increase inhibition or self-control. However, that previous experiments only examined the impact of increased right frontal activation on approach-

motivated impulses and responses (i.e., reward seeking, eating, and aggression). How does a manipulated increase in right frontal activation influence avoidance-motivated responding?

According to an asymmetric inhibition model of frontal asymmetry (Grimshaw & Carmel, 2014; see also Kinsbourne, 1974; Silberman & Weingartner, 1986), cortical systems for approach and avoidance motivation are antagonists: Increased left frontal asymmetry inhibits the avoidance system and negative emotional information, whereas increased right frontal asymmetry inhibits the approach system and positive emotional information. Previous experiments using transcranial electrical stimulation have supported one side of the asymmetric inhibition model, namely the inhibition of approach-motivated responding by increased right frontal activity (e.g., Fecteau et al., 2007). But little if any evidence exists in humans to support the other side of the asymmetric inhibition model, namely the inhibition of avoidance motivation by increased left frontal activity (Grimshaw & Carmel, 2014). One of the major aims of the current experiment was to test both sides of the asymmetric inhibition model in a single study.

Another possibility—one that contradicts the asymmetric inhibition model of frontal asymmetry—is that increased right frontal asymmetry enables response inhibition generally (i.e., inhibition of both approach- and avoidance-motivated responding). This possible link between right frontal asymmetry and response inhibition has received relatively little attention in research using EEG but has been supported by numerous functional neuroimaging studies linking blood flow in the right inferior frontal cortex to response inhibition (e.g., Aron, Robbins, & Poldrack, 2004, 2014; Berkman, Burklund, & Lieberman, 2009; Jha, Nachev, Barnes, Husain, Brown, & Litvak, 2015). And one prior study using tDCS found evidence to link increased right frontal asymmetry to inhibition. Specifically, an experiment by Cunillera, Fuentemilla, Brignani, Cucurell, and Minussi (2014) paired bilateral tDCS to increase relative right frontal activity with

a go/no-go task and found that this asymmetric pattern of stimulation increases response inhibition. Taken as a group, these studies implicate the right prefrontal cortex as a source of successful response inhibition.

### **The current experiment**

In the current experiment we manipulated electrical activity in the frontal cortex using tDCS and then had participants attempt to override approach- or avoidance-oriented impulses. More specifically, after stimulation participants used a joystick to move away from images of rewards or move toward images of threats, respectively. Performing these motive-incongruent movements requires self-control, insofar as avoiding rewards and approaching threats requires one to override a predominant response tendency. This reasoning is supported by evidence that motive-congruent movements (i.e., moving toward rewards and moving away from threats) take less time to enact relative to motive-incongruent movements (Solarz, 1960; see also Chen & Bargh, 1999). The motive-incongruent movements are slower presumably because they require additional mental operations (e.g., inhibition).

To elaborate, Solarz (1960) was among the first to observe a connection between body movements and approach/avoidance motivation. He had participants view cards depicting words that were positive or negative in nature. Participants were randomly assigned to pull positive word cards toward the self and push negative cards away, or to engage the opposite patterns of response. Solarz found both faster reaction times and fewer errors when the stimulus and the response were compatible (i.e., when participants pulled pleasant words toward themselves and pushed unpleasant words away). This pattern was replicated by Chen and Bargh (1999), who further found that the effect held in the absence of conscious processing. As a group, these results suggest a strong relationship between pulling and appetitive stimuli (e.g., sexual stimuli;

Hofmann, Friese, & Gschwendner, 2009) as well as between pushing and aversive stimuli (e.g., spiders; Klein, Becker, & Rinck, 2011) (see Laham, Kashima, Dix, & Wheeler, 2015). At the neural level, arm flexions contextualized as pulling toward the self (as in the current experiment) have been associated with left frontal asymmetry, and arm extensions contextualized as pushing away from the self have been associated with right frontal asymmetry (Maxwell & Davidson, 2007). Accordingly, we reasoned that performing motive-incongruent responses (e.g., pulling aversive stimuli toward the self) would require the inhibition of motive-congruent tendencies (e.g., pushing aversive stimuli away) and thus require self-control.

The *asymmetric inhibition model of frontal asymmetry* makes two predictions pertaining to the speed of motive-incongruent movements. First, increasing left frontal activity should enable individuals to move toward threat images more quickly. This prediction, which has not been tested previously, follows from the idea that left frontal asymmetry inhibits avoidance-motivated impulses. If the impulse to move away from threats is inhibited, then individuals should be faster to approach threats.

Second, increasing right frontal activity should enable individuals to move away from rewards more quickly. This prediction follows from the idea that right frontal asymmetry inhibits approach-motivated impulses. If the impulse to approach rewards is inhibited, then individuals should be faster to avoid rewards. As reviewed above, prior experiments have provided indirect support for the idea that right frontal activity inhibits approach-related impulses (e.g., Fecteau et al., 2007). The current experiment thus seeks to extend prior support for this idea. Further, whereas the prior experiments have typically tested small samples of participants (for example, the study by Fecteau et al. on risk-taking included 12 participants per condition in a between



subjects-design), the current experiment included a larger sample of participants and thus had greater statistical power to detect tDCS effects.

The *right frontal inhibition hypothesis* makes different predictions. In this view, increasing right frontal activity should inhibit both approach-oriented and avoidance-oriented movements and thus speed movements toward threats and away from rewards, respectively. The right frontal inhibition hypothesis assumes that increasing left frontal activity has little or no effect on inhibition or self-control.

In summary, both the asymmetric inhibition model and the right frontal inhibition hypothesis predict that increasing right (versus left) frontal asymmetry with tDCS should reduce approach-motivated impulses and thus speed movements away from rewards. But the two views make competing predictions regarding the inhibition of avoidance-oriented movements. The asymmetric inhibition model predicts that increasing left (versus right) frontal electrical activity should speed movements toward threats, whereas the right frontal inhibition hypothesis predicts that increasing right (versus left) frontal activity should speed movements toward threats.

## Method

**Participants and design.** Two hundred seventeen right-handed undergraduate students attended a laboratory study in exchange for credit toward a course requirement. Participants reported to a study concerning brain activity and reactions to visual stimuli. The experimental design was a 2 (Motivation: approach vs. avoidance)  $\times$  3 (Stimulation: increase in relative left frontal cortical activity [anodal over F3/cathodal over F4], increase in relative right frontal cortical activity [cathodal over F3/anodal over F4], or sham) double-blind between-subjects design.

Upon arrival participants completed a consent form, a handedness questionnaire (Chapman & Chapman, 1987), and a safety screening. Participants were excluded from participating based on contra-indications for non-invasive brain stimulation ( $n = 4$ , see Nitsche et al., 2008), including psychiatric or neurological history, damaged skin tissue, and medications (with the exception of women using oral contraceptives). Participants were excluded from data analyses if they were ambidextrous or left-handed ( $n = 1$ ), did not follow directions ( $n = 2$ ), expressed suspicion about the experimental procedures ( $n = 1$ ), experienced equipment failure ( $n = 3$ ), failed to complete trials of the AAT ( $n = 2$ ), pulled sensors out ( $n = 1$ ), or had sensors fall out ( $n = 1$ ) during stimulation. After exclusions, data from 202 participants (107 female, 76 male, 19 not reporting) remained for analysis. Most participants (age  $M = 19.10$ ,  $SD = 1.50$ ) were Caucasian (61.4%) and non-Hispanic (69.8%).

**Approach-Avoidance Task Block 1.** Participants completed an approach-avoidance task (AAT; Chen & Bargh, 1999). The specifics of the AAT differed as a function of motivation condition. Participants in the *avoidance condition* ( $n = 134$ ) saw a mix of negative and neutral images, whereas participants in the *approach condition* ( $n = 68$ ) saw a mix of positive and neutral images.<sup>1</sup> Images were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008). In the avoidance condition participants viewed 32 negative images and 32 neutral images presented in a randomized order across two blocks. In the

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<sup>1</sup> We began this study focusing on the avoidance motivation condition and added the approach motivation condition at the recommendation of NJK's dissertation committee. We oversampled for the avoidance condition because no previous experiments had tested the effects of tDCS on avoidance impulses. With a sample of 134 participants in the avoidance condition we had .80 power to detect a medium-sized effect ( $d = 0.50$ ) of tDCS. By contrast, several experiments have tested the effects of tDCS on approach-related impulses and observed rather large effects of tDCS (ranging from  $d = 0.55$  to  $1.55$ ; Dambacher et al., 2015; Goldman et al., 2011; Kelley et al., 2015). A sample of 68 participants in the approach condition gave us .80 power to detect an effect equal to or greater than  $d = 0.70$ .

approach condition participants saw 32 appetitive images and 32 neutral images presented in a randomized order across two blocks.<sup>2</sup>

We used normative ratings of valence and arousal to guide image selection (Lang, Bradley, & Cuthbert, 2008). Normative ratings of valence varied as a function of picture type,  $F(2, 93) = 184.42, p < .001$ , such that positive images were rated as more positive ( $M = 6.85$   $SD = 0.52$ ) than neutral images ( $M = 5.45$   $SD = 0.82$ ), which in turn were rated as more positive than negative images ( $M = 3.78$   $SD = 0.53$ ),  $F(2, 93) = 184.42, p < .001$ . All pairwise comparisons were significant,  $ps < .001$ . Normative ratings of arousal also varied as a function of picture type,  $F(2, 93) = 146.05, p < .001$ . Both positive ( $M = 5.41$   $SD = 0.87$ ) and negative images ( $M = 5.99$   $SD = 0.66$ ) were rated as more arousing than neutral images,  $ps < .001$ . Negative images were rated more arousing than positive images,  $p = .01$ . We also consulted normative data regarding the rating of IAPS images on 6 discrete emotions: happiness, surprise, sadness, anger, disgust and fear (Libkuman, Otani, Kern, Viger, & Novak, 2007). The images we selected primarily evoked fear (in the avoidance condition) and happiness (in the approach condition), respectively; neutral images were rated below the midpoint on all 6 discrete emotions.

Image sizes ( $1024 \times 768$ ) were equivalent across conditions. All images were presented in the center of a 20-inch computer monitor with a gray background. Participants sat approximately 1-2 feet from the monitor during image viewing with the joystick always equidistant between the participant and the monitor. See Figure 1.

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<sup>2</sup> *Negative IAPS*: 1019, 1022, 1026, 1030, 1040, 1050, 1051, 1052, 1070, 1080, 1090, 1101, 1110, 1111, 1112, 1113, 1114, 1120, 1200, 1201, 1205, 1220, 1230, 1240, 1300, 1301, 1302, 1321, 1525, 6250, 6260, 6300. *Positive IAPS*: 4599, 4608, 4611, 4651, 4658, 4659, 4670, 4676, 4680, 4800, 7200, 7230, 7291, 7330, 7340, 7390, 7400, 7410, 7430, 7450, 7460, 7470, 7480, 7481, 7482, 7501, 7503, 7506, 8500, 8501, 8502, and 8503. *Neutral IAPS*: 1121, 1602, 1603, 1604, 1812, 1900, 1910, 2102, 2210, 2214, 2215, 2270, 2495, 5740, 5750, 5800, 6150, 7004, 7006, 7009, 7025, 7034, 7035, 7038, 7040, 7043, 7044, 7050, 7110, 7235, 7500, and 7546.

In the first block of the AAT, which occurred prior to tDCS, participants in the avoidance condition were instructed to push a joystick away from their body when they saw a negative image and pull the joystick toward their body when they saw a neutral image. In the approach condition participants were instructed to pull a joystick toward them when they saw a positive image and to push the joystick away when they saw a neutral image.

This first AAT block served two purposes. First, neutral image trials afforded a baseline estimate of participants' reaction times to the same movements (pull in the avoidance condition, push in the approach condition) that served as the focal DV in our main analyses. Reaction times to neutral images in Block 1 correlated with reaction times on incongruent trials in Block 2,  $r(199) = .65, p < .001$ , so we controlled for baseline reaction times to neutral images in subsequent analyses. Second, the first block of the AAT reinforced motive-congruent responses (i.e., pushing away negative images and pulling toward positive images) as the dominant response tendencies. Immediately following the first block of the AAT participants received 15 minutes of tDCS.

**tDCS.** We used the same stimulation parameters as Hortensius et al. (2012) and Kelley, Hortensius, and Harmon-Jones (2013). Stimulation was delivered using a battery-driven Magstim Eldith DC-stimulator Plus (NeuroConn GmbH, Ilmenau, Germany) with 5x7 cm conductive-rubber electrodes. The electrodes were placed on participants' scalps immediately after the first block of the AAT. Stimulation lasted for 15 min, with a current intensity of 2 mA (maximum current density:  $0.057 \text{ mA/cm}^2$ , total charge of  $0.0512 \text{ C/cm}^2$ , ramp-up/ramp-down: 5s). Prior to stimulation, stretch-lycra caps (Electro-Cap, Eaton, OH) were placed on participants' heads. A bipolar montage was used and electrodes were placed in wet sponges saturated with electrode gel and fixed to the scalp (underneath the cap) over left (F3) and right

(F4) prefrontal regions (10-20 EEG system). Both experimenters and participants were blind to the tDCS parameters, which were controlled by a separate investigator. Participants were randomly assigned to one of three conditions: *increase in relative left frontal activity* (anodal over F3/cathodal over F4), *increase in relative right frontal activity* (cathodal over F3/anodal over F4), or *sham stimulation*. In the sham condition all settings were identical to the other conditions except the stimulation duration (ramp-up: 5 sec; stimulation: 30 sec; ramp-down: 5 sec). This method has proven to be a reliable method of sham stimulation that does not result in consequential aftereffects (Gandiga, Hummel, & Cohen, 2006).

**Approach-Avoidance Task Block 2.** Immediately following stimulation participants completed a second block of the AAT in which the push/pull directions were reversed. Specifically, for the second block participants in the avoidance condition were instructed to pull negative images toward the self and push neutral images away. In the approach condition, participants were asked to pushed positive images away from their body and pull neutral images. Because pushing negative images away from the self and pulling positive images toward the self are considered dominant response tendencies (e.g., Chen & Bargh, 1999), making the opposite movement should require self-control to override the predominant tendency. For the sake of simplicity, we refer to these post-stimulation trials as incongruent trials henceforth because they entail motive-incongruent responses.

## Results

**Pre-Stimulation Reaction Times.** We analyzed reaction times on the pre-stimulation AAT in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity)  $\times$  2 (Motivation Condition: approach vs. avoidance)  $\times$  2 (Trial Type: neutral vs. congruent) mixed-model ANOVA. The main effect of trial type indicated that

participants were slower on neutral trials ( $M = 1310.91$ ,  $SD = 293.14$ ) than on congruent trials ( $M = 1191.11$ ,  $SD = 301.27$ ),  $F(1, 195) = 38.13$ ,  $p < .001$ ,  $\eta_p^2 = .16$ . The main effect of motivation condition indicated that participants in the approach condition ( $M = 1309.00$ ,  $SD = 271.99$ ) were slower to react than those in the avoidance condition ( $M = 1224.39$ ,  $SD = 270.06$ ),  $F(1, 195) = 4.34$ ,  $p = .04$ ,  $\eta_p^2 = .02$ . Faster responding in the avoidance (versus approach) motivation condition is consistent with the suggestion that negative stimuli are more salient and elicit stronger reactions than positive stimuli (e.g., Baumeister, Bratslavsky, Finkenauer, & Vohs, 2001). No other main effects or interactive effects were significant. In summary, reaction times prior to stimulation did not differ as a function of stimulation condition or the Stimulation  $\times$  Motivation condition interaction, suggesting successful random assignment.<sup>3</sup>

**Post-Stimulation Reaction Times.** We analyzed reaction times on the post-stimulation AAT in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity)  $\times$  2 (Motivation Condition: approach vs. avoidance)  $\times$  2 (Trial Type: neutral vs. congruent) mixed-model ANCOVA, controlling for reaction times to pre-stimulation neutral trials. The main effect of tDCS condition was significant,  $F(2, 194) = 3.55$ ,  $p = .03$ ,  $\eta_p^2 = .04$ . Participants who received tDCS to increase right frontal activity ( $M = 1174.09$ ,  $SD = 192.93$ ) were faster to react relative to participants who received tDCS to increase left frontal activity ( $M = 1240.45$ ,  $SD = 187.60$ ) and those who received sham stimulation ( $M = 1255.54$ ,  $SD = 183.36$ ),  $ps < .05$ . The latter two groups did not differ,  $p = .64$ .

We also observed a significant Motivation Condition  $\times$  Trial Type interaction,  $F(1, 194) = 24.37$ ,  $p < .001$ ,  $\eta_p^2 = .11$ . Follow-up analyses revealed that participants in the avoidance

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<sup>3</sup> Error rates did not vary as a function of tDCS condition  $\times$  Motivation Condition  $\times$  Trial Type interaction prior to stimulation or after stimulation,  $F_s < 1$ ,  $ps > .40$ .

motivation condition were slower to react to neutral ( $M = 1285.80$ ,  $SD = 332.27$ ) compared to motivationally incongruent trials ( $M = 1140.81$ ,  $SD = 327.44$ ) following stimulation,  $t(133) = 6.69$ ,  $p < .001$ . No such pattern occurred in the approach motivation condition,  $t(67) = 1.04$ ,  $p = .30$ .

Central to our hypotheses, we observed a Trial Type  $\times$  tDCS Condition interaction,  $F(2, 194) = 3.21$ ,  $p = .04$ ,  $\eta_p^2 = .03$ . For incongruent trials (i.e., pushing positive images away, pulling negative images toward the self) we observed a simple main effect of tDCS condition,  $F(2, 201) = 7.79$ ,  $p < .001$ ,  $\eta_p^2 = .07$ . Planned, follow-up analyses revealed that participants who received stimulation to increase right frontal activity ( $M = 1077.42$ ,  $SD = 207.93$ ) were significantly faster to perform motive-incongruent responses compared to those who received stimulation to increase left frontal activity ( $M = 1220.86$ ,  $SD = 302.50$ ) or sham stimulation ( $M = 1239.99$ ,  $SD = 328.71$ ),  $ps < .01$ ,  $ds = 0.55$  and  $0.59$  respectively. The latter two groups did not differ,  $p = .70$ . For neutral trials (i.e., pushing or pulling neutral images), tDCS condition did not influence reaction times,  $F < 1$ ,  $p > .65$ .

Follow-up paired samples t-tests within each tDCS condition revealed that participants reacted faster to incongruent compared to neutral trials only in the stimulation to increase right frontal activity condition,  $t(66) = 6.02$ ,  $p < .001$ ,  $d = .72$ . Neither stimulation to increase left frontal activity nor sham stimulation caused a significant difference in reactions times to incongruent vs. neutral trials,  $ps = .06$  and  $.08$ , respectively. Please see Figure 2.

The three-way interaction among motivation condition, tDCS condition, and trial type was non-significant,  $F(2, 199) = 0.42$ ,  $p = .66$ . Hence, whether participants were in the approach condition or the avoidance condition, tDCS to increase right frontal activity appeared to speed up

responding on motive-incongruent trials. Examining the effect of tDCS condition on incongruent trials in the approach and avoidance motivation conditions separately supported this conclusion.

In the avoidance motivation condition we observed a simple main effect of tDCS condition on reaction times to incongruent trials,  $F(2, 130) = 4.80, p < .01, \eta_p^2 = .07$ . Follow-up t-tests revealed that participants in the avoidance condition who received stimulation to increase relative right frontal activity ( $M = 1041.40, SD = 214.70$ ) were faster to react to incongruent trials compared to those who received stimulation to increase left frontal activity ( $M = 1158.52, SD = 336.70$ ), or sham stimulation ( $M = 1225.16, SD = 387.50$ ),  $ps < .05, ds = 0.41$  and  $0.59$  respectively.

The simple main effect of tDCS condition on reaction times to incongruent trials was also significant in the approach motivation condition,  $F(2, 63) = 4.01, p = .02, \eta_p^2 = .11$ . Participants in the approach condition who received stimulation to increase relative right frontal activity ( $M = 1162.07, SD = 166.81$ ) were significantly faster to react to incongruent trials compared to those who received stimulation to increase left frontal activity ( $M = 1345.47, SD = 164.13$ ) or sham stimulation ( $M = 1265.79, SD = 189.25$ ),  $ps < .05, ds = 1.11$  and  $0.58$  respectively.

### Discussion

Pairing brain stimulation over the frontal cortex with an approach-avoidance joystick task revealed that increasing right/decreasing left frontal activity increases the speed of motive-incongruent responses. More specifically, participants who received tDCS to increase relative right frontal cortical activity were faster to pull negative images toward the self and push positive images away, compared to participants who received tDCS to increase relative left frontal activity or sham stimulation. This pattern of results suggests that increased right frontal activity enables response inhibition regardless of the motivational direction of the response.



**Implications for theoretical models of frontal cortical asymmetry**

The asymmetric inhibition model of frontal asymmetry (Grimshaw & Carmel, 2014) assumes that cortical systems for approach and avoidance motivation function as antagonists, such that increasing left frontal asymmetry inhibits the avoidance system and increasing right frontal asymmetry inhibits the approach system. Previous experiments have supported one side of the asymmetric inhibition model, namely the inhibition of approach-motivated responding by a manipulation to increase right frontal activity (e.g., Fecteau et al., 2007), but to date no single study had tested both sides of the asymmetric inhibition model.

The current experiment tested both sides and found partial support for the asymmetric inhibition model. Consistent with previous research, cathodal stimulation over the right prefrontal cortex paired with anodal stimulation over the left prefrontal cortex facilitated the inhibition of approach-motivated impulses. But we did not find support for the other side of the model—that increasing left frontal activity inhibits avoidance-motivated responding. Rather, we found evidence to the contrary. The inhibition of avoidance-motivated responding was facilitated by increasing right frontal activity. The two findings together are congruent with a right frontal inhibition hypothesis, which suggests that right frontal activity enables response inhibition generally (i.e., inhibition of both approach and avoidance motivated responding).

Classic views associate left frontal asymmetry with positive affect and right frontal asymmetry with negative affect (e.g., Tomarken, Davidson, Wheeler, & Doss, 1992). A more recent motivational direction model associates left frontal asymmetry with approach motivation and right frontal asymmetry with avoidance or withdrawal (Davidson, 2004; Harmon-Jones, Gable, & Peterson, 2010). However, recent meta-analytic work suggests that the links between frontal asymmetry and motivational orientation may not be as clear as once assumed (cf. Wacker

et al., 2009). With regard to avoidance motivation, some studies have found a strong positive correlation between behavioral inhibition system (BIS) sensitivity (a putative measure of avoidance or withdrawal motivation) and right frontal asymmetry (e.g., Sutton & Davidson, 1997), but others have observed only a weak positive correlation (e.g., Coan & Allen, 2003), and still others have observed no significant relationship (e.g., Harmon-Jones & Allen, 1997). Many other studies have also failed to find an association between avoidance motivation and right frontal asymmetry (Amodio, Master, Yee, & Taylor, 2008; Hewig, Hagemann, Seifert, Naumann, & Bartussek, 2006; Pizzagalli, Sherwood, Henriques, & Davidson, 2005; Jackson et al., 2003; Coan, Allen, & Harmon-Jones, 2001), thereby casting doubt on the robustness of the link between right frontal asymmetry and avoidance motivation or negative emotion.

If right frontal asymmetry underlies avoidance motivation, then in the current experiment the manipulation to increase right frontal activity would have strengthened the impulse to move away from aversive stimuli and caused participants to be slower to enact the motive-incongruent response. But we found the opposite result—stimulation to increase right frontal activity caused participants to move toward aversive images more quickly. In further support of the view that right frontal asymmetry enables inhibition, we found that tDCS to increase right frontal activity also facilitates responses incongruent with approach-motivated impulses. The evidence that cathodal stimulation over the right prefrontal cortex paired with anodal stimulation over the left prefrontal cortex enables the inhibition of both approach- and avoidance-oriented responding is consistent with fMRI evidence linking activity in right frontal cortex (specifically right IFG, Aron et al., 2004) with performance on diverse tests of response inhibition. Thus, based on the current results using tDCS and the prior evidence from fMRI experiments, we suggest that right frontal asymmetry is more strongly associated with response inhibition than with avoidance

motivation or withdrawal. This perspective may help to account for the inconsistent results observed in prior studies that tried to link right frontal asymmetry with avoidance.

The evidence that cathodal stimulation over the right prefrontal cortex paired with anodal stimulation over the left prefrontal cortex enables the inhibition of both approach- and avoidance-motivated responding is consistent with domain general views of self-control capacity. One such view is the resource model of self-control (Baumeister, Vohs, & Tice, 2007). Research testing the resource model has used a sequential task paradigm whereby participants complete two self-control tasks in succession. The basic finding is that exercising self-control on the first task impairs performance on the second task. One common manipulation of self-control resources involves suppressing emotional responses. Many studies have found that suppressing positive emotional reactions (e.g., Fischer, Greitemeyer, & Frey, 2007; 2008), negative reactions (e.g., Inzlicht & Gutsell, 2007; Schmeichel, 2007), or reactions to stimuli that blend both positive and aversive elements (e.g., Friese, Hofmann, & Wanke, 2008; Hofmann, Rauch, & Gawronski, 2007) all lead to poorer performance on a subsequent self-control task. Evidence from these emotion suppression studies thus indicates that controlling either approach- or avoidance-related emotions can undermine subsequent self-control, which suggests that a common mechanism underlies the control of both avoidance-motivated and approach-motivated impulses. Viewed in light of the current findings, we speculate that this common mechanism may be greater right frontal cortical activity.

### **Limitations and future directions**

We observed that increasing right frontal activity increases self-control, but the role of right frontal activity in enacting avoidance-congruent responses to negative stimuli remains unclear. We did not test the extent to which increasing right frontal activity speeds up reaction

times to push negative images away. Evidence that stimulation to increase right frontal activity facilitates motive-incongruent responses but does not facilitate motive-congruent responses to negative stimuli would represent even stronger support for the idea that increased right frontal asymmetry primarily fosters self-control or inhibition rather than avoidance motivation. Future experiments should test the effects of brain stimulation on avoidance-congruent responses.

We defined self-control (following many other theorists) as overriding or altering a predominant response tendency. The motive-incongruent trials in our experiment entailed self-control under this definition insofar as the predominant response tendency is to approach appetitive images and avoid aversive ones. But numerous other forms of self-control exist, and it remains to be seen whether tDCS to increase right frontal activation influences these other forms of self-control, such as delay discounting (e.g., Shamosh et al., 2008), delay of gratification (e.g., Schmeichel & Vohs, 2009) resisting tempting foods (e.g., Fishbach & Shah, 2006), emotion suppression (Phillips, Henry, Hosie, & Milne, 2008), and the inhibition of racial biases (e.g., Amodio, 2009).

The real-world relevance of the type of pre-potent motor response inhibition observed in the current experiment remains unclear (see Buckholz, 2015; Rodman et al., 2016). Although motive-incongruent responses are not uncommon in some self-control challenges (e.g., dieters who move away from the dessert cart, first responders who go toward a burning building), we are aware of no previous research that has linked the kinds of motive-incongruent responses we studied with real-world self-control outcomes. Note, however, that anodal stimulation over the right DLPFC/cathodal stimulation over the left DLPFC has been found to reduce aggression (Dambacher et al., 2015), risky decision making (e.g., Fecteau et al., 2007), and caloric consumption (Fregni et al., 2008; Goldman et al., 2011)—all outcomes that are widely regarded

as consequential both inside and outside of the laboratory. Future research is needed to assess the extent to which these diverse forms of self-control tap a common underlying process (e.g., inhibition) and whether stimulation to increase right frontal cortical activity affects them all similarly, in addition to their ecological validity.

Because tDCS has two components—anodal stimulation and cathodal stimulation—the current study does not address whether stimulation over the left or right prefrontal cortex (or both) drives the effects observed in the current experiment. Much of the neuroimaging research in support of the right frontal inhibition hypothesis suggests that that increased right frontal activation is key to successful response inhibition (e.g., Aron et al., 2004, 2014; Berkman, Burklund, & Lieberman, 2009; Jha, Nachev, Barnes, Husain, Brown, & Litvak, 2015; see also Gianotti et al., 2009). However, few fMRI studies have tested for asymmetric patterns of DLPFC activation (Berkman & Lieberman, 2010). Future brain stimulation studies that manipulate right frontal and left frontal activity separately and neuroimaging studies that examine asymmetric activity patterns are needed to ascertain the contributions of increased right versus decreased left frontal activity to successful response inhibition.

Another limitation of the current study is that we assumed frontal asymmetry was modulated by the stimulation protocol we used, but we never assessed frontal asymmetry to verify the assumed change. Prior research using subtle psychological or psychosomatic interventions (e.g., contralateral hand contractions, see Peterson, Shackman, & Harmon-Jones, 2008) has observed that frontal asymmetry is readily modified, but we did not assess frontal EEG asymmetry either before or after stimulation in the current study. Although we would predict based on theory and research related to tDCS that asymmetric patterns of electrical activity were induced in the current experiment, we cannot say for certain that such patterns were induced. The

safest conclusion to draw from the current findings is that anodal stimulation over the right/cathodal stimulation over the left DLPFC modulates behaviors associated with frontal cortical asymmetry and self-control. Future studies pairing tDCS with concurrent EEG measurement are needed to verify that the effects of tDCS are indeed mediated by changes in frontal asymmetry.

### **Underlying Mechanisms**

The stimulation effects we observed may be rooted in frontal cortical-subcortical interactions—interactions that are better tested by methods other than tDCS or EEG. A closed-loop circuit originating in the dorsolateral prefrontal cortex projects to the thalamus through the striatum, globus pallidus, and substantia nigra; this circuit has been implicated in executive functioning (Tekin & Cummings, 2002). Inhibition is one major class of executive functions (Miyake et al., 2000). Evidence from prior research pairing tDCS with fMRI found that stimulating the dorsolateral prefrontal cortex affects parts of this prefrontal circuit. For example, research by Chib, Yub, Takahashi, and Shimojo (2013) found that greater connectivity between the dorsolateral prefrontal cortex and the substantia nigra predicts greater attractiveness ratings of computer generated faces. Insofar as attraction reflects approach motivation, this finding may be interpreted as evidence of an increase in activation of the approach system. We know of no studies pairing frontal cortical stimulation with neuroimaging to examine the circuitry involved in controlling or inhibiting approach or avoidance impulses. Future research pairing tDCS with imaging techniques should examine the extent to which a manipulated increase in right frontal asymmetry influences this prefrontal circuit during tasks requiring inhibitory control (e.g., perhaps by reducing connectivity between the prefrontal cortex and substantia nigra).

The inferior frontal gyrus is widely implicated in inhibitory control, particularly in the context of emotional evocative stimuli (Aron, 2007; Dolcos, Jordan, & Dolcos, 2011; Tabibnia et al 2011). The right IFG in particular appears to be relevant for successful inhibitory control (Aron et al., 2004; Chikazoe et al., 2007; Swick, Ashley, & Turken, 2011). Probing the connections between the right IFG and brain regions associated with reward and threat processing may help to clarify the underlying neural circuitry driving the current findings. With regard to rewarding or appetitive stimuli, successful inhibition during reward anticipation has been associated with increased activity in the right IFG, reduced activity in brain regions implicated in reward processing (i.e., the ventral striatum), and altered connectivity between the two regions (Behan, Stone, & Garavan, 2015). Additionally, greater functional connectivity between the right IFG and the right amygdala has been found to predict greater monetary winnings in a predator-prey task in which the participant is under threat of being shocked (Gold, Morey, & McCarthy, 2015). This evidence suggests that greater connectivity between the IFG and amygdala may allow persons to persist toward rewards in the face of possible threat. Taken together these neuroimaging studies suggest that successful inhibition of appetitive and aversive stimuli likely depends on functional connectivity between the IFG and both reward and threat processing regions of the brain. Future studies pairing prefrontal brain stimulation with emotional inhibitory control/self-control tasks should test whether the pattern of stimulation used in the current experiment influences connectivity between the IFG and reward and threat processing regions.

Another possible brain mechanism underlying the current findings is the corpus callosum, which connects complementary regions in the cerebral hemispheres (e.g., the left and right prefrontal cortices) and is thus crucial for interhemispheric communication. Recent research has

suggested that the corpus callosum may be a driving force underlying frontal cortical asymmetry and approach-motivated emotions and behaviors (Shutter & Harmon-Jones, 2013). For example, Hofman and Schutter (2009) used a callosal brain stimulation paradigm and measured visual attention toward angry faces. They found that higher levels of interhemispheric signal transmission from the right to the left side of the brain correlates with increased attention toward angry faces. Based on this evidence, it is plausible that the right frontal asymmetry-inhibitory control link may be driven by an increase in interhemispheric signal transmission toward the right side. Future work pairing tDCS with neuroimaging techniques should test this possibility.

### **Conclusion**

We used transcranial brain stimulation to test the effects of manipulated patterns of electrical activity in the prefrontal cortex on the inhibition of approach- and avoidance-motivated responses. Cathodal stimulation over the right prefrontal cortex paired with anodal stimulation over the left prefrontal cortex aided the inhibition of both types of motive-incongruent responses. This evidence suggests that increasing right frontal activity enables response inhibition rather than boosting withdrawal or avoidance motivation. The current findings suggest that increases in right frontal cortical activity may increase success at self-control challenges.



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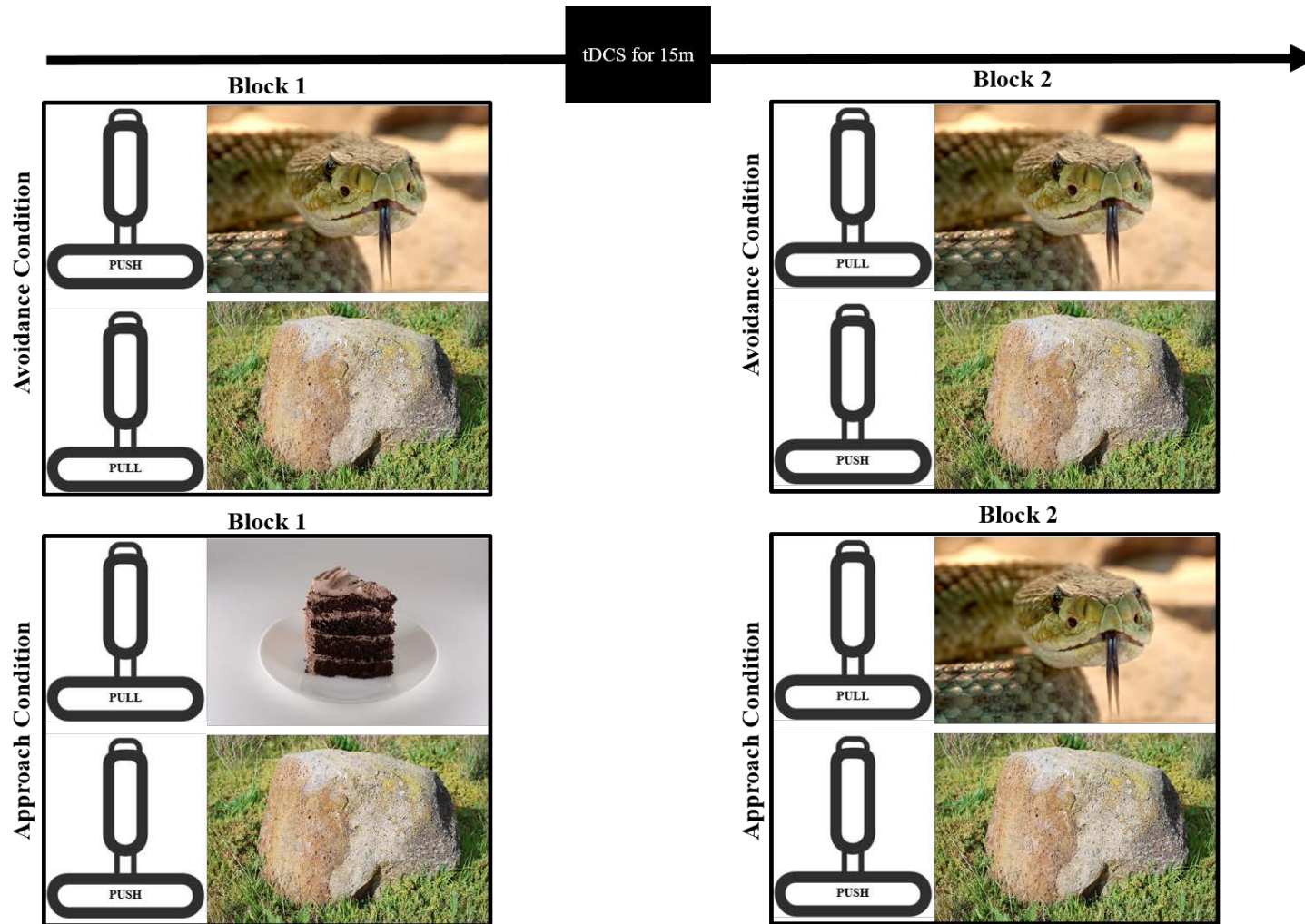
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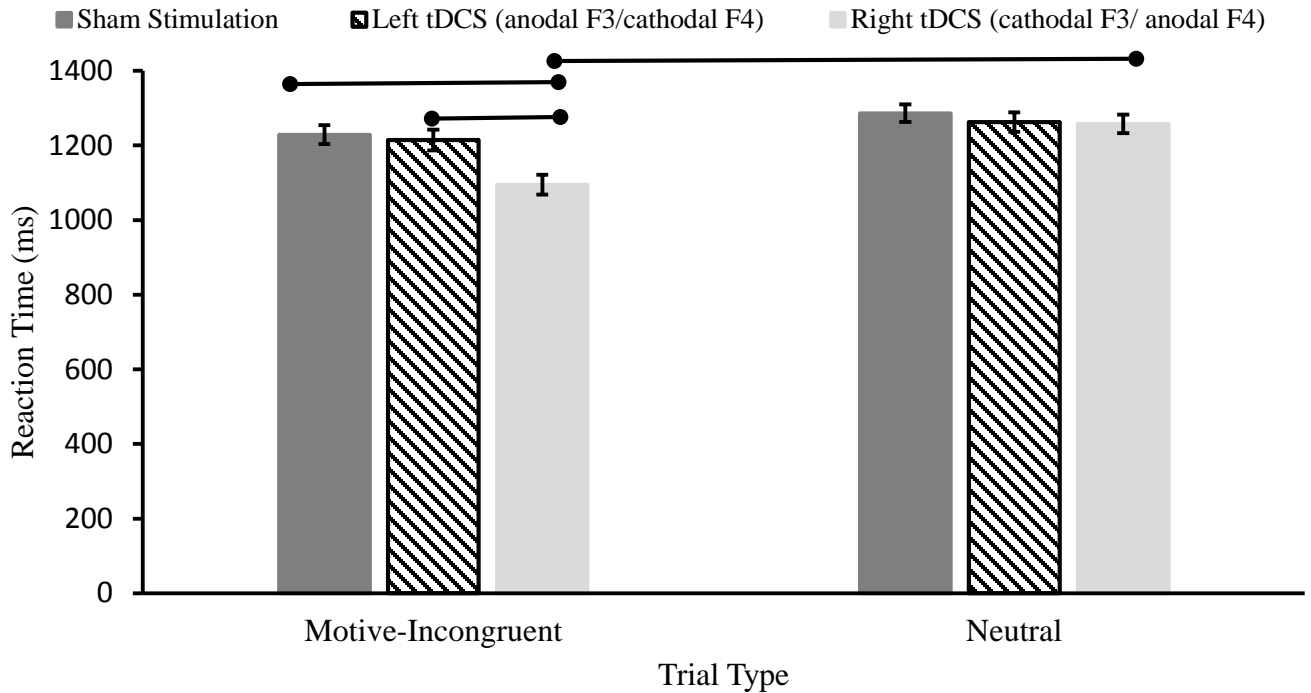
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**Figure 1.** Schematic representation of the experimental procedure. Prior to tDCS (Block 1) participants in the avoidance condition pushed a joystick away from their body when they saw a negative image and pulled the joystick toward their body when they saw a neutral image. In the approach condition participants pulled a joystick toward them when they saw a positive image and pushed the joystick away when they saw a neutral image. After tDCS (Block 2) the push/pull movements were reversed to require motive-incongruent movements.



**Figure 2.** Reaction times to motive-incongruent trials and neutral trials as a function of stimulation condition.



*Note.* **Left tDCS** = stimulation to increase relative left frontal activity. **Right tDCS** = stimulation to increase relative right frontal activity. **Motive incongruent** = pulling negative images toward the self (avoidance condition) and pushing positive images away from the self (approach condition). **Neutral** = opposite motor response to neutral trials. Error bars represent standard errors of the mean. ●● =  $p < .05$ .