Journal of Experimental Psychology: General
2016, Vol. 145, No. 12, 1702–1712

0096-3445/16/$12.00 http://dx.doi.org/10.1037/xge0000238

Noninvasive Stimulation Over the Dorsolateral Prefrontal Cortex Facilitates the Inhibition of Motivated Responding

Nicholas J. Kelley
Northwestern University

Brandon J. Schmeichel
Texas A&M University

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 DC 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, transcranial DC stimulation

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).

This article was published Online First October 13, 2016.

Nicholas J. Kelley, Department of Psychology, Northwestern University; and Brandon J. Schmeichel, Department of Psychology, Texas A&M University.

Correspondence concerning this article should be addressed to Nicholas J. Kelley, Department of Psychology, Northwestern University, 2029 Sheridan Road, Evanston, IL 60201. E-mail: nicholasjkelley@gmail.com

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., nonphobic) 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, 2010) 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, 2010) suggest that the association between approach-related traits (e.g., behavioral approach system, 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 nonhuman 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 DC 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 et al., 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 Miniussi (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 response times (RTs) 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. Furthermore, whereas the prior experiments have typically tested small samples of participants (e.g., 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 (vs. 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 (vs. right) frontal electrical activity should speed movements toward threats, whereas the right frontal inhibition hypothesis predicts that increasing right (vs. 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) × 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 contraindications for noninvasive 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 approach-avoidance task (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 $M = 19.10$ years, $SD = 1.50$) 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.[1] 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 approach condition participants saw 32 appetitive images and 32 neutral images presented in a randomized order across two blocks.[2]

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

[1] We began this study focusing on the avoidance motivation condition and added the approach motivation condition at the recommendation of Nicholas J. Kelley'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 (with ds ranging from 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 $d = 0.70$.

[2] *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, and 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.

consulted normative data regarding the rating of IAPS images on six 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 six discrete emotions.

Image sizes (1,024 × 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).

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' RTs to the same movements (pull in the avoidance condition, push in the approach condition) that served as the focal dependent variable in our main analyses. Reaction times to neutral images in Block 1 correlated with RTs on incongruent trials in Block 2, $r(199) = .65$, $p < .001$, so we controlled for baseline RTs 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 min 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 5 × 7 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 mA/cm^2, total charge of 0.0512 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

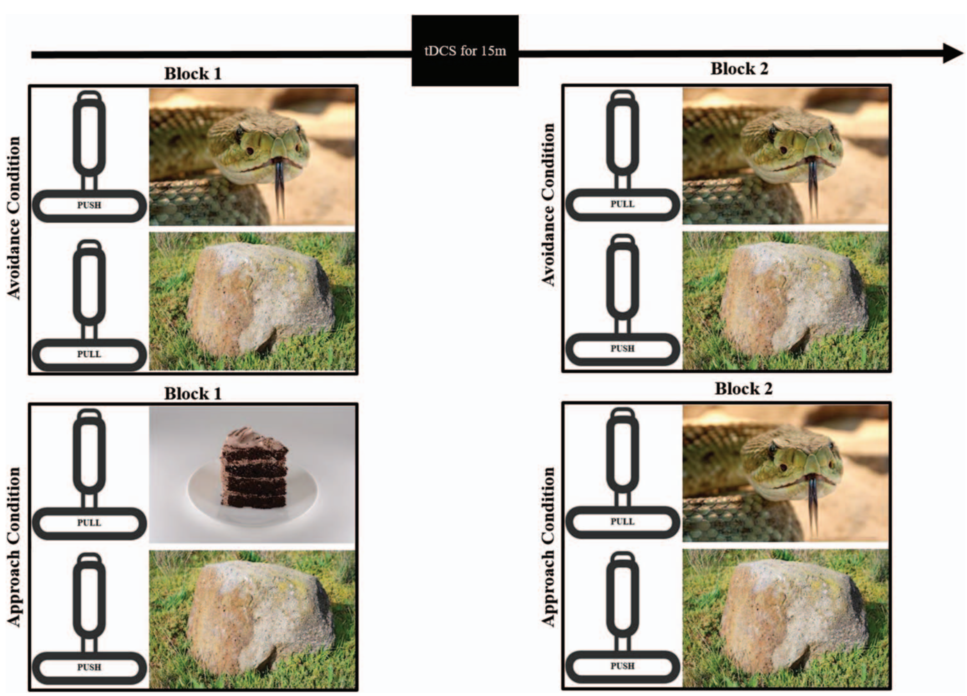

Figure 1. Schematic representation of the experimental procedure. Prior to transcranial DC stimulation (tDCS) (Block 1), participants in the avoidance condition pushed a joystick away from their body when they saw a negative image and pulled the joystick toward their body when they saw a neutral image. 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. See the online article for the color version of this figure.

sham condition all settings were identical to the other conditions except the stimulation duration (ramp-up: 5 s; stimulation: 30 s; ramp-down: 5 s). 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 poststimulation trials as incongruent trials henceforth because they entail motive-incongruent responses.

Results

Prestimulation Reaction Times

We analyzed RTs on the prestimulation AAT in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (motivation condition: approach vs. avoidance) × 2 (trial type: neutral vs. congruent) mixed-model analysis of variance. The main effect of trial type indicated that participants were slower on neutral trials (M = 1,310.91, SD = 293.14) than on congruent trials (M = 1,191.11, 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 = 1,309.00, SD = 271.99) were slower to react than those in the avoidance condition (M = 1,224.39, SD = 270.06), $F(1, 195) = 4.34$, $p = .04$, $\eta_p^2 = .02$. Faster responding in the avoidance (vs. 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, RTs prior to stimulation did not differ as a function of stimulation condition or the Stimulation × Motivation Condition interaction, suggesting successful random assignment.[3]

Poststimulation Reaction Times

We analyzed RTs on the poststimulation AAT in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (motivation condition: approach vs. avoidance) × 2 (trial type: neutral vs. congruent) mixed-model analysis of covariance, controlling for RTs to prestimulation 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 = 1,174.09, SD = 192.93) were faster to react relative to participants who received tDCS to increase left frontal activity (M = 1,240.45, SD = 187.60) and those who received sham stimulation (M = 1,255.54, SD = 183.36; ps < .05). The latter two groups did not differ ($p = .64$).

We also observed a significant Motivation Condition × Trial Type interaction, $F(1, 194) = 24.37$, $p < .001$, $\eta_p^2 = .11$. Follow-up analyses revealed that participants in the avoidance motivation condition were slower to react to neutral (M = 1,285.80, SD = 332.27) compared to motivationally incongruent trials (M = 1,140.81, 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 × 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 = 1,077.42, SD = 207.93) were significantly faster to perform motive-incongruent responses compared to those who received stimulation to increase left frontal activity (M = 1,220.86, SD = 302.50) or sham stimulation (M = 1,239.99, 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 RTs ($F < 1$, $p > .65$).

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 versus neutral trials (ps = .06 and .08), respectively (see Figure 2).

The three-way interaction among motivation condition, tDCS condition, and trial type was nonsignificant, $F(2, 199) = 0.42$, $p = .66$. 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 RTs 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 = 1,041.40, SD = 214.70) were faster to react to incongruent trials compared to those who received stimulation to increase left frontal activity (M = 1,158.52, SD = 336.70), or sham stimulation (M = 1,225.16, SD = 387.50; ps < .05, ds = 0.41 and 0.59), respectively.

The simple main effect of tDCS condition on RTs 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 fron-

[3] Error rates did not vary as a function of tDCS Condition × Motivation Condition × Trial Type interaction prior to stimulation or after stimulation (Fs < 1, ps > .40).

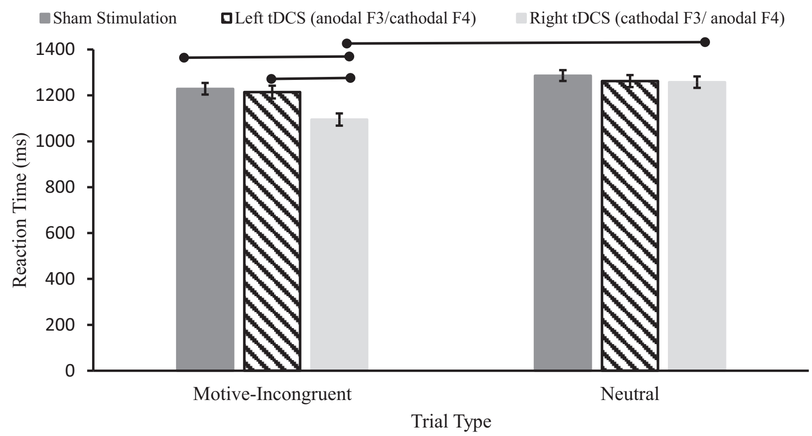

Figure 2. Reaction times to motive-incongruent trials and neutral trials as a function of stimulation condition. The left transcranial DC stimulation (tDCS) stimulus condition is stimulation to increase relative left frontal activity. The right tDCS is stimulation to increase relative right frontal activity. In motive-incongruent trials, participants pulled negative images toward the self (avoidance condition) and pushed positive images away from the self (approach condition). In neutral trials, there was opposite motor response. Error bars represent standard errors of the mean. ●—● = $p < .05$.

tal activity (M = 1,162.07, SD = 166.81) were significantly faster to react to incongruent trials compared to those who received stimulation to increase left frontal activity (M = 1,345.47, SD = 164.13) or sham stimulation (M = 1,265.79, 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., 2010). With regard to avoidance motivation, some studies have found a strong positive correlation between behavioral inhibition system 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 functional MRI (fMRI) evidence linking activity in right frontal cortex (specifically, right inferior frontal gyrus [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, 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 RTs 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 prepotent motor response inhibition observed in the current experiment remains unclear (see Buckholtz, 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 dorsolateral prefrontal cortex (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 et al., 2015; see also Gianotti et al., 2009). However, few fMRI studies have tested for asymmetric patters 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, Yun, 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, Iordan, & 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 (Schutter & 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.

References

Allen, J. J., Harmon-Jones, E., & Cavender, J. H. (2001). Manipulation of frontal EEG asymmetry through biofeedback alters self-reported emotional responses and facial EMG. *Psychophysiology, 38,* 685–693. http://dx.doi.org/10.1111/1469-8986.3840685

Amodio, D. M. (2009). Intergroup anxiety effects on the control of racial stereotypes: A psychoneuroendocrine analysis. *Journal of Experimental Social Psychology, 45,* 60–67. http://dx.doi.org/10.1016/j.jesp.2008.08.009

Amodio, D. M., Master, S. L., Yee, C. M., & Taylor, S. E. (2008). Neurocognitive components of the behavioral inhibition and activation systems: Implications for theories of self-regulation. *Psychophysiology, 45,* 11–19.

Aron, A. R. (2007). The neural basis of inhibition in cognitive control. *The Neuroscientist, 13,* 214–228. http://dx.doi.org/10.1177/1073858407299288

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences, 8,* 170–177. http://dx.doi.org/10.1016/j.tics.2004.02.010

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: One decade on. *Trends in Cognitive Sciences, 18,* 177–185. http://dx.doi.org/10.1016/j.tics.2013.12.003

Baumeister, R. F., Bratslavsky, E., Finkenauer, C., & Vohs, K. D. (2001). Bad is stronger than good. *Review of General Psychology, 5,* 323–370. http://dx.doi.org/10.1037/1089-2680.5.4.323

Baumeister, R. F., Vohs, K. D., & Tice, D. M. (2007). The strength model of self-control. *Current Directions in Psychological Science, 16,* 351–355. http://dx.doi.org/10.1111/j.1467-8721.2007.00534.x

Behan, B., Stone, A., & Garavan, H. (2015). Right prefrontal and ventral striatum interactions underlying impulsive choice and impulsive responding. *Human Brain Mapping, 36,* 187–198. http://dx.doi.org/10.1002/hbm.22621

Berkman, E. T., Burklund, L., & Lieberman, M. D. (2009). Inhibitory spillover: Intentional motor inhibition produces incidental limbic inhibition via right inferior frontal cortex. *NeuroImage, 47,* 705–712. http://dx.doi.org/10.1016/j.neuroimage.2009.04.084

Berkman, E. T., & Lieberman, M. D. (2010). Approaching the bad and avoiding the good: Lateral prefrontal cortical asymmetry distinguishes between action and valence. *Journal of Cognitive Neuroscience, 22,* 1970–1979. http://dx.doi.org/10.1162/jocn.2009.21317

Buckholtz, J. W. (2015). Social norms, self-control, and the value of antisocial behavior. *Current Opinion in Behavioral Sciences, 3,* 122–129. http://dx.doi.org/10.1016/j.cobeha.2015.03.004

Buss, K. A., Schumacher, J. R., Dolski, I., Kalin, N. H., Goldsmith, H. H., & Davidson, R. J. (2003). Right frontal brain activity, cortisol, and withdrawal behavior in 6-month-old infants. *Behavioral Neuroscience, 117,* 11–20. http://dx.doi.org/10.1037/0735-7044.117.1.11

Carver, C. S. (2005). Impulse and constraint: Perspectives from personality psychology, convergence with theory in other areas, and potential for integration. *Personality and Social Psychology Review, 9,* 312–333. http://dx.doi.org/10.1207/s15327957pspr0904_2

Chapman, L. J., & Chapman, J. P. (1987). The measurement of handedness. *Brain and Cognition, 6,* 175–183. http://dx.doi.org/10.1016/0278-2626(87)90118-7

Chen, M., & Bargh, J. A. (1999). Consequences of automatic evaluation: Immediate behavioral predispositions to approach or avoid the stimulus. *Personality and Social Psychology Bulletin, 25,* 215–224. http://dx.doi.org/10.1177/0146167299025002007

Chib, V. S., Yun, K., Takahashi, H., & Shimojo, S. (2013). Noninvasive remote activation of the ventral midbrain by transcranial direct current stimulation of prefrontal cortex. *Translational Psychiatry, 3,* e268. http://dx.doi.org/10.1038/tp.2013.44

Chikazoe, J., Konishi, S., Asari, T., Jimura, K., & Miyashita, Y. (2007). Activation of right inferior frontal gyrus during response inhibition across response modalities. *Journal of Cognitive Neuroscience, 19,* 69–80. http://dx.doi.org/10.1162/jocn.2007.19.1.69

Coan, J. A., & Allen, J. J. (2003). Frontal EEG asymmetry and the behavioral activation and inhibition systems. *Psychophysiology, 40,* 106–114. http://dx.doi.org/10.1111/1469-8986.00011

Coan, J. A., Allen, J. J., & Harmon-Jones, E. (2001). Voluntary facial expression and hemispheric asymmetry over the frontal cortex. *Psychophysiology, 38,* 912–925. http://dx.doi.org/10.1111/1469-8986.3860912

Cunillera, T., Fuentemilla, L., Brignani, D., Cucurell, D., & Miniussi, C. (2014). A simultaneous modulation of reactive and proactive inhibition processes by anodal tDCS on the right inferior frontal cortex. *PLoS ONE, 9,* e113537. http://dx.doi.org/10.1371/journal.pone.0113537

Dambacher, F., Schuhmann, T., Lobbestael, J., Arntz, A., Brugman, S., & Sack, A. T. (2015). Reducing proactive aggression through non-invasive brain stimulation. *Social Cognitive and Affective Neuroscience, 10,* 1303–1309. http://dx.doi.org/10.1093/scan/nsv018

Davidson, R. J. (2004). What does the prefrontal cortex "do" in affect: Perspectives on frontal EEG asymmetry research. *Biological Psychology, 67,* 219–234. http://dx.doi.org/10.1016/j.biopsycho.2004.03.008

Davidson, R. J., Kalin, N. H., & Shelton, S. E. (1992). Lateralized effects of diazepam on frontal brain electrical asymmetries in rhesus monkeys. *Biological Psychiatry, 32,* 438–451. http://dx.doi.org/10.1016/0006-3223(92)90131-I

Davidson, R. J., Kalin, N. H., & Shelton, S. E. (1993). Lateralized response to diazepam predicts temperamental style in rhesus monkeys. *Behavioral Neuroscience, 107,* 1106–1110. http://dx.doi.org/10.1037/0735-7044.107.6.1106

Davidson, R. J., & Rickman, M. (1999). Behavioral inhibition and the emotional circuitry of the brain: Stability and plasticity during the early childhood years. In L. A. Schmidt & J. Schulkin (Eds.), *Extreme fear, shyness, and social phobia: Origins, biological mechanisms, and clinical outcomes* (pp. 67–87). New York, NY: Oxford University Press. http://dx.doi.org/10.1093/acprof:oso/9780195118872.003.0005

Denson, T. F., DeWall, C. N., & Finkel, E. J. (2012). Self-control and aggression. *Current Directions in Psychological Science, 21,* 20–25. http://dx.doi.org/10.1177/0963721411429451

De Pascalis, V., Varriale, V., & D'Antuono, L. (2010). Event-related components of the punishment and reward sensitivity. *Clinical Neurophysiology, 121,* 60–76. http://dx.doi.org/10.1016/j.clinph.2009.10.004

Dolcos, F., Iordan, A. D., & Dolcos, S. (2011). Neural correlates of emotion–cognition interactions: A review of evidence from brain imaging investigations. *Journal of Cognitive Psychology, 23,* 669–694. http://dx.doi.org/10.1080/20445911.2011.594433

Elliot, A. J. (2006). The hierarchical model of approach–avoidance motivation. *Motivation and Emotion, 30,* 111–116. http://dx.doi.org/10.1007/s11031-006-9028-7

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. *Journal of Neuroscience, 27,* 12500–12505. http://dx.doi.org/10.1523/JNEUROSCI.3283-07.2007

Fischer, P., Greitemeyer, T., & Frey, D. (2008). Self-regulation and selective exposure: The impact of depleted self-regulation resources on confirmatory information processing. *Journal of Personality and Social Psychology, 94,* 382–395. http://dx.doi.org/10.1037/0022-3514.94.3.382

Fishbach, A., & Shah, J. Y. (2006). Self-control in action: Implicit dispositions toward goals and away from temptations. *Journal of Personality and Social Psychology, 90,* 820–832. http://dx.doi.org/10.1037/0022-3514.90.5.820

Fox, N. A., Henderson, H. A., Marshall, P. J., Nichols, K. E., & Ghera, M. M. (2005). Behavioral inhibition: Linking biology and behavior within a developmental framework. *Annual Review of Psychology, 56,* 235–262. http://dx.doi.org/10.1146/annurev.psych.55.090902.141532

Fregni, F., Orsati, F., Pedrosa, W., Fecteau, S., Tome, F. A., Nitsche, M. A., . . . Boggio, P. S. (2008). Transcranial direct current stimulation of the prefrontal cortex modulates the desire for specific foods. *Appetite, 51,* 34–41. http://dx.doi.org/10.1016/j.appet.2007.09.016

Friese, M., Hofmann, W., & Wänke, M. (2008). When impulses take over: Moderated predictive validity of explicit and implicit attitude measures in predicting food choice and consumption behaviour. *British Journal of Social Psychology, 47,* 397–419. http://dx.doi.org/10.1348/014466607X241540

Gable, P. A., Mechin, N. C., Hicks, J. A., & Adams, D. L. (2015). Supervisory control system and frontal asymmetry: Neurophysiological traits of emotion-based impulsivity. *Social Cognitive and Affective Neuroscience, 10,* 1310–1315. http://dx.doi.org/10.1093/scan/nsv017

Gandiga, P. C., Hummel, F. C., & Cohen, L. G. (2006). Transcranial DC stimulation (tDCS): A tool for double-blind sham-controlled clinical studies in brain stimulation. *Clinical Neurophysiology, 117,* 845–850. http://dx.doi.org/10.1016/j.clinph.2005.12.003

Garavan, H., Ross, T. J., & Stein, E. A. (1999). Right hemispheric dominance of inhibitory control: An event-related functional MRI study. *Proceedings of the National Academy of Sciences of the United States of America, 96,* 8301–8306. http://dx.doi.org/10.1073/pnas.96.14.8301

Gianotti, L. R. R., Knoch, D., Faber, P. L., Lehmann, D., Pascual-Marqui, R. D., Diezi, C., . . . Fehr, E. (2009). Tonic activity level in the right prefrontal cortex predicts individuals' risk taking. *Psychological Science, 20,* 33–38. http://dx.doi.org/10.1111/j.1467-9280.2008.02260.x

Gold, A. L., Morey, R. A., & McCarthy, G. (2015). Amygdala–prefrontal cortex functional connectivity during threat-induced anxiety and goal distraction. *Biological Psychiatry, 77,* 394–403. http://dx.doi.org/10.1016/j.biopsych.2014.03.030

Goldman, R. L., Borckardt, J. J., Frohman, H. A., O'Neil, P. M., Madan, A., Campbell, L. K., . . . George, M. S. (2011). Prefrontal cortex transcranial direct current stimulation (tDCS) temporarily reduces food cravings and increases the self-reported ability to resist food in adults with frequent food craving. *Appetite, 56,* 741–746. http://dx.doi.org/10.1016/j.appet.2011.02.013

Grimshaw, G. M., & Carmel, D. (2014). An asymmetric inhibition model of hemispheric differences in emotional processing. *Frontiers in Psychology, 5,* 489. http://dx.doi.org/10.3389/fpsyg.2014.00489

Harmon-Jones, E., & Allen, J. J. (1997). Behavioral activation sensitivity and resting frontal EEG asymmetry: Covariation of putative indicators related to risk for mood disorders. *Journal of Abnormal Psychology, 106,* 159–163. http://dx.doi.org/10.1037/0021-843X.106.1.159

Harmon-Jones, E., Gable, P. A., & Peterson, C. K. (2010). The role of asymmetric frontal cortical activity in emotion-related phenomena: A review and update. *Biological Psychology, 84,* 451–462. http://dx.doi.org/10.1016/j.biopsycho.2009.08.010

Harmon-Jones, E., Harmon-Jones, C., & Price, T. F. (2013). What is approach motivation? *Emotion Review, 5,* 291–295. http://dx.doi.org/10.1177/1754073913477509

Harmon-Jones, E., & Sigelman, J. (2001). State anger and prefrontal brain activity: Evidence that insult-related relative left-prefrontal activation is associated with experienced anger and aggression. *Journal of Personality and Social Psychology, 80,* 797–803. http://dx.doi.org/10.1037/0022-3514.80.5.797

Hewig, J., Hagemann, D., Seifert, J., Naumann, E., & Bartussek, D. (2006). The relation of cortical activity and BIS/BAS on the trait level. *Biological Psychology, 71,* 42–53. http://dx.doi.org/10.1016/j.biopsycho.2005.01.006

Hofman, D., & Schutter, D. J. (2009). Inside the wire: Aggression and functional interhemispheric connectivity in the human brain. *Psychophysiology, 46,* 1054–1058. http://dx.doi.org/10.1111/j.1469-8986.2009.00849.x

Hofmann, W., Friese, M., & Gschwendner, T. (2009). Men on the "pull": Automatic approach–avoidance tendencies and sexual interest behavior. *Social Psychology, 40,* 73–78. http://dx.doi.org/10.1027/1864-9335.40.2.73

Hofmann, W., Friese, M., & Strack, F. (2009). Impulse and self-control from a dual-systems perspective. *Perspectives on Psychological Science, 4,* 162–176. http://dx.doi.org/10.1111/j.1745-6924.2009.01116.x

Hofmann, W., Rauch, W., & Gawronski, B. (2007). And deplete us not into temptation: Automatic attitudes, dietary restraint, and self-regulatory resources as determinants of eating behavior. *Journal of Experimental Social Psychology, 43,* 497–504. http://dx.doi.org/10.1016/j.jesp.2006.05.004

Hortensius, R., Schutter, D. J., & Harmon-Jones, E. (2012). When anger leads to aggression: Induction of relative left frontal cortical activity with transcranial direct current stimulation increases the anger–aggression relationship. *Social Cognitive and Affective Neuroscience, 7,* 342–347. http://dx.doi.org/10.1093/scan/nsr012

Impett, E. A., Peplau, L. A., & Gable, S. L. (2005). Approach and avoidance sexual motives: Implications for personal and interpersonal well-being. *Personal Relationships, 12,* 465–482. http://dx.doi.org/10.1111/j.1475-6811.2005.00126.x

Inzlicht, M., & Gutsell, J. N. (2007). Running on empty: Neural signals for self-control failure. *Psychological Science, 18,* 933–937. http://dx.doi.org/10.1111/j.1467-9280.2007.02004.x

Jackson, D. C., Mueller, C. J., Dolski, I., Dalton, K. M., Nitschke, J. B., Urry, H. L., . . . Davidson, R. J. (2003). Now you feel it, now you don't: Frontal brain electrical asymmetry and individual differences in emotion regulation. *Psychological Science, 14,* 612–617. http://dx.doi.org/10.1046/j.0956-7976.2003.psci_1473.x

Jha, A., Nachev, P., Barnes, G., Husain, M., Brown, P., & Litvak, V. (2015). The frontal control of stopping. *Cerebral Cortex, 25,* 4392–4406. http://dx.doi.org/10.1093/cercor/bhv027

Kahan, D., Polivy, J., & Herman, C. P. (2003). Conformity and dietary disinhibition: A test of the ego-strength model of self-regulation. *International Journal of Eating Disorders, 33,* 165–171. http://dx.doi.org/10.1002/eat.10132

Kalin, N. H., Larson, C., Shelton, S. E., & Davidson, R. J. (1998). Asymmetric frontal brain activity, cortisol, and behavior associated with fearful temperament in rhesus monkeys. *Behavioral Neuroscience, 112,* 286–292. http://dx.doi.org/10.1037/0735-7044.112.2.286

Kelley, N. J., Eastwick, P. W., Harmon-Jones, E., & Schmeichel, B. J. (2015). Jealousy increased by induced relative left frontal cortical activity. *Emotion, 15,* 550–555. http://dx.doi.org/10.1037/emo0000068

Kelley, N. J., Hortensius, R., & Harmon-Jones, E. (2013). When anger leads to rumination: Induction of relative right frontal cortical activity with transcranial direct current stimulation increases anger-related rumination. *Psychological Science, 24,* 475–481. http://dx.doi.org/10.1177/0956797612457384

Kinsbourne, M. (1974). Mechanisms of hemispheric interaction in man. In M. Kinsbourne & W. L. Smith (Eds.), *Hemispheric disconnection and cerebral function* (pp. 260–285). Springfield, IL: C. C. Thomas.

Klein, A. M., Becker, E. S., & Rinck, M. (2011). Approach and avoidance tendencies in spider fearful children: The approach–avoidance task. *Journal of Child and Family Studies, 20,* 224–231. http://dx.doi.org/10.1007/s10826-010-9402-7

Knoch, D., & Fehr, E. (2007). Resisting the power of temptations: The right prefrontal cortex and self-control. *Annals of the New York Academy of Sciences, 1104,* 123–134. http://dx.doi.org/10.1196/annals.1390.004

Knoch, D., Gianotti, L. R., Pascual-Leone, A., Treyer, V., Regard, M., Hohmann, M., & Brugger, P. (2006). Disruption of right prefrontal cortex by low-frequency repetitive transcranial magnetic stimulation induces risk-taking behavior. *Journal of Neuroscience, 26,* 6469–6472. http://dx.doi.org/10.1523/JNEUROSCI.0804-06.2006

Kotabe, H. P., & Hofmann, W. (2015). On integrating the components of self-control. *Perspectives on Psychological Science, 10,* 618–638. http://dx.doi.org/10.1177/1745691615593382

Laham, S. M., Kashima, Y., Dix, J., & Wheeler, M. (2015). A meta-analysis of the facilitation of arm flexion and extension movements as a function of stimulus valence. *Cognition and Emotion, 29,* 1069–1090. http://dx.doi.org/10.1080/02699931.2014.968096

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2008). *International affective picture system (IAPS): Affective ratings of pictures and instruction manual* (Tech. Rep. No. A-8). Gainesville, FL: University of Florida.

Libkuman, T. M., Otani, H., Kern, R., Viger, S. G., & Novak, N. (2007). Multidimensional normative ratings for the international affective picture system. *Behavior Research Methods, 39,* 326–334. http://dx.doi.org/10.3758/BF03193164

Maxwell, J. S., & Davidson, R. J. (2007). Emotion as motion asymmetries in approach and avoidant actions. *Psychological Science, 18,* 1113–1119.

Mischel, W. (1958). Preference for delayed reinforcement: An experimental study of a cultural observation. *Journal of Abnormal and Social Psychology, 56,* 57–61. http://dx.doi.org/10.1037/h0041895

Mischel, W., Ebbesen, E. B., & Zeiss, A. R. (1972). Cognitive and attentional mechanisms in delay of gratification. *Journal of Personality and Social Psychology, 21,* 204–218. http://dx.doi.org/10.1037/h0032198

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100. http://dx.doi.org/10.1006/cogp.1999.0734

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., . . . Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America, 108,* 2693–2698. http://dx.doi.org/10.1073/pnas.1010076108

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., . . . Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation, 1,* 206–223. http://dx.doi.org/10.1016/j.brs.2008.06.004

Ostafin, B. D., Marlatt, G. A., & Greenwald, A. G. (2008). Drinking without thinking: An implicit measure of alcohol motivation predicts failure to control alcohol use. *Behaviour Research and Therapy, 46,* 1210–1219. http://dx.doi.org/10.1016/j.brat.2008.08.003

Peterson, C. K., Shackman, A. J., & Harmon-Jones, E. (2008). The role of asymmetrical frontal cortical activity in aggression. *Psychophysiology, 45,* 86–92.

Phillips, L. H., Henry, J. D., Hosie, J. A., & Milne, A. B. (2008). Effective regulation of the experience and expression of negative affect in old age. *Journals of Gerontology: Series B. Psychological Sciences and Social Sciences, 63,* 138–145. http://dx.doi.org/10.1093/geronb/63.3.P138

Pizzagalli, D. A., Sherwood, R. J., Henriques, J. B., & Davidson, R. J. (2005). Frontal brain asymmetry and reward responsiveness: A source-localization study. *Psychological Science, 16,* 805–813. http://dx.doi.org/10.1111/j.1467-9280.2005.01618.x

Powers, M. B., & Emmelkamp, P. M. (2008). Virtual reality exposure therapy for anxiety disorders: A meta-analysis. *Journal of Anxiety Disorders, 22,* 561–569. http://dx.doi.org/10.1016/j.janxdis.2007.04.006

Rodman, A. M., Kastman, E., Dorfman, H. M., Baskin-Sommers, A., Kiehl, K. A., Newman, J. P., & Buckholtz, J. W. (2016). Selective mapping of psychopathy and externalizing to dissociable circuits for inhibitory self-control. *Clinical Psychological Science, 4,* 559–571. http://dx.doi.org/10.1177/2167702616631495

Schmeichel, B. J. (2007). Attention control, memory updating, and emotion regulation temporarily reduce the capacity for executive control. *Journal of Experimental Psychology: General, 136,* 241–255. http://dx.doi.org/10.1037/0096-3445.136.2.241

Schmeichel, B. J., Harmon-Jones, C., & Harmon-Jones, E. (2010). Exercising self-control increases approach motivation. *Journal of Personality and Social Psychology, 99,* 162–173. http://dx.doi.org/10.1037/a0019797

Schmeichel, B. J., & Vohs, K. (2009). Self-affirmation and self-control: Affirming core values counteracts ego depletion. *Journal of Personality and Social Psychology, 96,* 770–782.

Schutter, D. J., & Harmon-Jones, E. (2013). The corpus callosum: A commissural road to anger and aggression. *Neuroscience and Biobehavioral Reviews, 37,* 2481–2488. http://dx.doi.org/10.1016/j.neubiorev.2013.07.013

Shamosh, N. A., Deyoung, C. G., Green, A. E., Reis, D. L., Johnson, M. R., Conway, A. R., . . . Gray, J. R. (2008). Individual differences in delay discounting: Relation to intelligence, working memory, and anterior prefrontal cortex. *Psychological Science, 19,* 904–911. http://dx.doi.org/10.1111/j.1467-9280.2008.02175.x

Silberman, E. K., & Weingartner, H. (1986). Hemispheric lateralization of functions related to emotion. *Brain and Cognition, 5,* 322–353. http://dx.doi.org/10.1016/0278-2626(86)90035-7

Solarz, A. K. (1960). Latency of instrumental responses as a function of compatibility with the meaning of eliciting verbal signs. *Journal of Experimental Psychology, 59,* 239–245. http://dx.doi.org/10.1037/h0047274

Sutton, S. K., & Davidson, R. J. (1997). Prefrontal brain asymmetry: A biological substrate of the behavioral approach and inhibition systems. *Psychological Science, 8,* 204–210. http://dx.doi.org/10.1111/j.1467-9280.1997.tb00413.x

Swick, D., Ashley, V., & Turken, U. (2011). Are the neural correlates of stopping and not going identical? Quantitative meta-analysis of two response inhibition tasks. *NeuroImage, 56,* 1655–1665. http://dx.doi.org/10.1016/j.neuroimage.2011.02.070

Tabibnia, G., Monterosso, J. R., Baicy, K., Aron, A. R., Poldrack, R. A., Chakrapani, S., . . . London, E. D. (2011). Different forms of self-control share a neurocognitive substrate. *Journal of Neuroscience, 31,* 4805–4810. http://dx.doi.org/10.1523/JNEUROSCI.2859-10.2011

Tangney, J. P., Baumeister, R. F., & Boone, A. L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of Personality, 72,* 271–324. http://dx.doi.org/10.1111/j.0022-3506.2004.00263.x

Tekin, S., & Cummings, J. L. (2002). Frontal-subcortical neuronal circuits and clinical neuropsychiatry: An update. *Journal of Psychosomatic Research, 53,* 647–654. http://dx.doi.org/10.1016/S0022-3999(02)00428-2

Tomarken, A. J., Davidson, R. J., & Henriques, J. B. (1990). Resting frontal brain asymmetry predicts affective responses to films. *Journal of Personality and Social Psychology, 59,* 791–801. http://dx.doi.org/10.1037/0022-3514.59.4.791

Tomarken, A. J., Davidson, R. J., Wheeler, R. E., & Doss, R. C. (1992). Individual differences in anterior brain asymmetry and fundamental dimensions of emotion. *Journal of Personality and Social Psychology, 62,* 676–687. http://dx.doi.org/10.1037/0022-3514.62.4.676

Trope, Y., & Fishbach, A. (2000). Counteractive self-control in overcoming temptation. *Journal of Personality and Social Psychology, 79,* 493–506. http://dx.doi.org/10.1037/0022-3514.79.4.493

Wacker, J., Chavanon, M. L., & Stemmler, G. (2010). Resting EEG signatures of agentic extraversion: New results and meta-analytic integration. *Journal of Research in Personality, 44,* 167–179. http://dx.doi.org/10.1016/j.jrp.2009.12.004

Received March 22, 2016
Revision received August 27, 2016
Accepted September 1, 2016 ■