SELF-CONTROL OF AVOIDANCE MOTIVATION: IMPLICATIONS FOR UNDERSTANDING FRONTAL CORTICAL ASYMMETRY

A Dissertation

by

NICHOLAS JOSEPH KELLEY

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Brandon J. Schmeichel
Committee Members,	Heather Lench
	Stephen Maren
	Suresh Ramanathan
Head of Department,	Douglas Woods

August 2015

Major Subject: Psychology

ABSTRACT

Self-control involves the inhibition of dominant response tendencies. Most research on self-control has examined the inhibition of approach-motivated tendencies, and previous research has found that right frontal cortical asymmetry facilitates the inhibition of approach-motivated behaviors. The current experiments tested the hypothesis that a manipulated increase in right frontal cortical asymmetry facilitates the inhibition of avoidance-motivated responses. In Experiment 1, participants used a joystick to pull neutral images toward and push threatening images away from the body and then received 15 minutes of transcranial direct current stimulation. Afterward participants pulled threatening images toward and pushed neutral images away from the body. This response required self-control insofar as pushing away (not pulling) threatening stimuli is the dominant response tendency. Stimulation to increase right frontal cortical asymmetry caused threats to be pulled toward the body faster. A second Experiment, using the same task as Experiment 1, directly compared the self-control of approach and avoidance impulses. Results revealed that stimulation to increase right frontal asymmetry facilitated the self-control of impulses regardless of their motivational direction, representing first evidence that inhibiting avoidance-motivated behaviors shares a common neural mechanism with inhibiting approach-related behaviors: right frontal cortical asymmetry.

DEDICATION

TO MY MOTHER

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Brandon Schmeichel, and my committee members, Dr. Lench, Dr. Maren, Dr. Ramanathan for their guidance and support throughout the course of this research. Thanks also go to my friends and colleagues and the social psychology faculty for creating an environment in which I was able to succeed. I also want to extend my gratitude to the undergraduate research assistants for their help with data collection, the Schmeichel laboratory for their constant support, and to all the Texas A&M University students who were willing to participate in these experiments. Finally, thanks to my mother for her sacrifice, constant support, and encouragement.

TABLE OF CONTENTS

Page

ABSTRACT ii

DEDICATION iii

ACKNOWLEDGEMENTS iv

TABLE OF CONTENTS v

LIST OF FIGURES vii

1. INTRODUCTION 1

1.1 Self-control and approach motivation 1
1.2 Self-control and avoidance motivation 2
1.3 Left frontal asymmetry and approach motivation 4
1.4 Right frontal asymmetry and avoidance motivation 6
1.5 Right frontal asymmetry and inhibitory control 8
1.6 Why does right frontal asymmetry increase self-control? 11
1.7 Motivational direction and embodied cognition 11
1.8 Goals and overview of the current experiments 13

2. EXPERIMENT 1 14

2.1 Method 14
2.1.1 Participants and design 14
2.1.2 Procedure 15
2.1.3 Approach-avoidance task block 1 16
2.1.4 tDCS 17
2.1.5 Approach-avoidance task block 2 18
2.2 Results 18
2.2.1 Data preparation 18
2.2.2 Baseline reaction time analyses 18
2.2.3 Baseline error analyses 19
2.2.4 Main analyses 20
2.2.5 Errors 22
2.3 Discussion 23

3. EXPERIMENT 2 25

3.1 Method 25
3.1.1 Participants and design 25
3.1.2. Procedure 26
3.1.3 Approach-avoidance task block 1 27
3.1.4 tDCS 28
3.1.5. Approach-avoidance task block 2 29
3.1.6 Joystick movements 30
3.2 Results 30
3.2.1. Baseline reaction time analyses 30
3.2.2. Baseline error analyses 32
3.2.3 Main analyses 33
3.2.4 Errors 36
3.2.5 Secondary analyses 37
3.2.6. Latency analysis. 39
3.3 Discussion 40

4. SUMMARY AND CONCLUSIONS 42

4.1 Summary 42
4.2 Right frontal asymmetry, avoidance, and inhibition 43
4.3 Limitations 44
4.4 Underlying mechanisms 45
4.5 Implications for self-control research 47
4.6 Implications for the conceptualization of behavioral inhibition sensitivity 49
4.7 Conclusion 49

REFERENCES 51

APPENDIX 66

LIST OF FIGURES

Page

Figure 1. Reaction times to pull negative images toward the body and push neutral images away from the body as a function of stimulation condition (Experiment 1). 21

Figure 2. Number of errors committed when pulling negative images toward the body and pushing neutral images toward the body as a function of stimulation condition (Experiment 1). 23

Figure 3. Reaction times to motivationally incongruent trials and neutral trials as a function of stimulation condition (Experiment 2). 34

Figure 4. Number of errors committed in response to motivationally incongruent trials and neutral trials as a function of stimulation condition (Experiment 2). 36

Figure 5. Joystick movements as a function of stimulation condition in the avoidance condition (Experiment 2). 38

Figure 6. Joystick movements as a function of stimulation condition in the approach condition (Experiment 2). 39

Figure 7. Response latencies to motivationally incongruent trials and neutral trials as a function of stimulation and motivation conditions (Experiment 2). 40

1. INTRODUCTION

The survival of any organism is contingent upon motivational systems of approach and avoidance. Acting appropriately in the face of appetitive stimuli (e.g., opportunities to mate or eat) and threatening stimuli (e.g., predators) could mean the difference between life and death. The capacity to control these motivationally-charged responses also contributes to behavioral flexibility in humans (e.g., Munakata, Snyder, & Chatham, 2012; Vaughn, Kopp, Krakow, 1984) and in many other species including non-human primates (e.g., Addessi, Paglieri, & Focaroli, 2011; Amici, Aureli, & Call, 2008), rats (Eisenberger, Weier, Masterson, & Theis, 1989), and dogs (Miller, Pattison, DeWall, Rayburn-Reeves, & Zentall, 2010). Self-control refers to effortful processes involved in inhibiting or overriding dominant response tendencies (Muraven & Baumeister, 2000). The vast majority of research on self-control has focused on the control of approach-motivated behaviors, whereas the self-control of avoidance behaviors has been relatively neglected (see Carver, 2005). The current research investigated the role of the right prefrontal cortex in controlling avoidance-motivated responding.

1.1 Self-control and approach motivation

Beginning with Walter Mischel's seminal work on delay of gratification (Mishel 1958; Mischel, Ebbesen, Zeiss, 1972), the practical and the theoretical implications of self-control have been important topics in psychological science (Metcalfe, & Mischel, 1999; Carver & Scheier, 1982; Muraven, & Baumeister, 2000). Most research on self-control has focused on the self-control of approach-motivated impulses. Approach motivation refers to the impulse to go toward a stimulus (see Harmon-Jones, Harmon-Jones, & Price, 2013). Behaviors that stem from approach-motivated impulses include the consumption of food (Kahan, Polivy, & Herman, 2003), alcohol use (Ostafin, Marlatt, & Greenwald, 2008), gambling (Schmeichel, Harmon-Jones, & Harmon-Jones, 2010), sexual behavior (Impett, Peplau, & Gable, 2005), spending (Baumeister, 2002; Vohs & Faber, 2007) and aggression (Harmon-Jones, & Sigelman, 2001). Failures to control approach-motivated impulses contribute to drug addiction, personal debt, obesity, and other outcomes that carry both personal and societal costs.

1.2 Self-control and avoidance motivation

Much less is known about the causes and consequences of the self-control of avoidance-motivated impulses. Avoidance motivation refers to the "energization of behavior by, or the direction of behavior away from negative stimuli" (Elliot, 2006, p. 112). Avoidance-motivated behaviors create distance (either physical or psychological) from negative or aversive stimuli.

Numerous phobias and psychopathologies may reflect poorly regulated avoidance motivation, so research on these topics may be relevant to understanding the self-control of avoidance motivation. In clinical psychology, research on exposure therapy for anxiety disorders (e.g., Forsyth, Barrios, Acheson, 2007), specific phobias (e.g., Hirai, Vernon, & Cochran, 2007), panic disorder (e.g., Craske, Brown, & Barlow, 1991), and post-traumatic stress disorder (e.g., Rothbaum & Schwartz, 2001) may all be relevant for understanding the self-control of avoidance-motivated impulses. Exposure therapy involves the "deliberate and planned exposure to a feared stimulus, or representation of the stimulus" (Richard, Lauterbach, & Gloster, 2007, p. 4). This therapy may require self-control insofar as the patient must tolerate exposure to the feared stimulus. Exposure-based forms of therapeutic treatment demonstrate some of the largest treatment effects in the clinical treatment literature (Richard et al., 2007; Powers & Emmelkamp, 2008), suggesting that even strong avoidance-motivated impulses may be amenable to control.

Another relevant line of evidence comes from experiments inspired by the resource model of self-control. This research uses 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 during emotional video clips (Haggar, Wood, Stiff, & Chatzisarantis, 2010). Many studies have found that suppressing emotional reactions to positive clips (e.g., Fischer, Greitemeyer, & Frey, 2007; 2008), aversive clips (e.g., Inzlicht & Gutsell, 2007; Schmeichel, 2007), or clips 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 task. Evidence from these emotion suppression studies thus indicates that controlling either approach- or avoidance-related emotions can induce ego depletion and undermine subsequent self-control. These results suggest that a common mechanism underlies the control of both avoidance-motivated and approach–motivated impulses.

1.3 Left frontal asymmetry and approach motivation

Asymmetric frontal cortical activity may reflect a person's motivational orientation and may be relevant for identifying a common neural mechanism for the self-control of approach and avoidance. Greater left frontal asymmetry is robustly related to approach-motivation. Using electroencephalographic (EEG) recordings, researchers have linked greater left than right frontal cortical activity with trait approach motivation (Coan & Allen, 2003; Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997) and with individual differences in approach-motivated emotions (Harmon-Jones & Allen, 1998; Tomarken, Davidson, Wheeler, & Doss, 1992). In addition to individual difference variables, the temporary experience of approach-motivated emotion has been correlated with greater left than right frontal cortical activity (Harmon-Jones, 2007; Harmon-Jones et al., 2002; Harmon-Jones, Lueck, Fearn, & Harmon-Jones, 2006; Harmon-Jones & Sigelman, 2001).

Experiments involving the manipulation of brain activity have also linked greater left than right frontal cortical activity to approach motivation. These experiments are important because they allow researchers to draw causal inferences about asymmetric activity in the frontal lobes (Schutter, van Honk & Panksepp, 2004). Accordingly, a number of studies using manipulations of frontal brain activity have found that increased left frontal cortical activity increases the experience and expression of approach motivation. For instance, Allen, Harmon-Jones, and Cavender (2001) manipulated frontal cortical asymmetry using biofeedback training and found that those who had trained to increase left frontal activity reacted more strongly (viz. more left frontal activity) to a positive affective film compared to those who had trained to increase right frontal cortical activity.

Other researchers have used transcranial direct current stimulation (tDCS) to manipulate asymmetric frontal cortical activity. Functionally, tDCS alters electrical activity in the brain by sending a weak electrical current between two electrodes fixed to the scalp. tDCS causes subthreshold changes in membrane potentials, which in turn leads to bidirectional changes in cortical excitability (Nitsche & Paulus, 2000). Anodal tDCS increases cortical excitability and cathodal tDCS decreases cortical excitability (Nitsche & Paulus, 2000). By combining anodal and cathodal stimulation over the frontal cortex, tDCS is particularly well suited for inducing frontal asymmetry. With strategically placed electrodes, tDCS allows researchers to increase activation (i.e., anodal stimulation) in one hemisphere while decreasing activity (i.e., cathodal stimulation) in the other hemisphere.

Using tDCS researchers have found additional support for a causal relationship between greater relative left frontal cortical activity and approach motivation. For example, research by Hortensius, Schutter, and Harmon-Jones (2012) found that after receiving tDCS to increase relative left frontal cortical activity individuals behaved more aggressively towards another participant when angry. Using the same stimulation parameters, Kelley, Eastwick, Harmon-Jones, and Schmeichel (in press) found that tDCS to increase relative left frontal cortical activity caused an increase in jealousy following social exclusion. Taken together these lines of evidence converge on the conclusion that increased relative left frontal cortical activity can increase approach motivation and approach-motivated states.

1.4 Right frontal asymmetry and avoidance motivation

The evidence linking left frontal cortical activity to approach motivation is relatively clear, but the same cannot be said for the motivational implications of relative right frontal cortical activity. Some evidence has implicated relative right frontal cortical activity in avoidance-related emotions and behaviors, whereas other work has related it to inhibitory control.

As discussed previously, avoidance motivation refers to the energization of behavior away from negative stimuli (Elliot, 2006). Prior research has linked relative right frontal cortical activity to negative emotions (e.g., fear, disgust) associated with withdrawal or avoidance motivation. One relevant line of evidence comes from studies of frontal EEG activity (Coan, Allen, & Harmon-Jones, 2001; Dawson, Panagiotides, Klinger, & Hill, 1992). In rhesus monkeys greater right frontal asymmetry has been associated with fear behaviors (Kalin, Larson, Shelton, & Davidson, 1998). In human infants right frontal brain asymmetry has been associated with increased negative emotional reactions (e.g., crying) in response to maternal separation. These results suggest that right frontal asymmetry predicts exaggerated avoidance-motivated reactions to aversive events. Consistent with these results, Tomarken, Davidson, and Henriques (1990) found a positive association between resting relative right frontal cortical asymmetry and negative affective responses to aversive film clips (see also Wheeler, Davidson, & Tomarken, 1993).

Evidence also suggests that state-like variation in negative emotional responding influences right frontal asymmetry. For example, Davidson, Ekman, Saron, Senulis, and Friesen (1990) recorded EEG activity while participants watched either a disgust-inducing film clip or a happiness-inducing clip. Results revealed that relative to the happiness clip, the disgust clip caused greater relative right frontal cortical activity. Further support for the right frontal asymmetry-avoidance link comes from the study of affect and motivation in depression. Depressed individuals have demonstrated greater right than left frontal cortical activity (Coan & Allen, 2003). Additionally, seasonal variation in depression (e.g., seasonal affective disorder) has also been associated with greater right than left frontal cortical activity (e.g., Allen, Iacono, Depue, & Arbisi, 1993). Taken together, converging evidence from human and animal studies, normal and psychopathological populations, and varied neuro-scientific measurement techniques point to the conclusion that increased right frontal cortical asymmetry is associated with avoidance motivation and related negative emotions.

A recent tDCS study on the consolidation of fear memories suggested that greater right than left frontal cortical activity may exert a causal influence on avoidance motivated responding. Mungee et al. (2014) paired a fear-conditioning paradigm with either cathodal stimulation (i.e., stimulation to decrease activity) over the right dorsolateral prefrontal cortex, anodal stimulation (i.e., stimulation to increase activity) over the right dorsolateral prefrontal cortex or sham stimulation. Fear was measured via skin conductance responses to the conditioned stimulus. Results revealed that anodal stimulation over the right dorsolateral prefrontal cortex increased memory for the conditioned feared stimulus as measured via skin conductance responses. These results suggested that increasing activation of the right dorsolateral prefrontal cortex increases fear memory consolidation. Thus, one of the components of right frontal cortical asymmetry (i.e., increased right frontal activity) enhances the consolidation of fear memories, which lends support to the hypothesis that right frontal cortical asymmetry increases avoidance motivation. However this study did not simultaneously pair anodal stimulation to the right dorsolateral prefrontal cortex with cathodal stimulation to the left dorsolateral prefrontal cortex to create an asymmetric pattern of activity. Given that the combined effects of anodal stimulation over the right dorsolateral prefrontal cortex and cathodal stimulation over the left dorsolateral prefrontal cortex have yet to be combined in the study of fear memory consolidation, the causal relationship between greater relative right frontal cortical asymmetry and avoidance motivation remains unclear.

1.5 Right frontal asymmetry and inhibitory control

Other evidence points to a link between greater right than left frontal cortical activity and inhibitory control. Inhibitory control is defined as the suppression of a prepotent response (Garavan, Ross, & Stein, 1999). Directional manipulations of frontal brain activity using tDCS have found that greater right than left frontal cortical activity decreases risk-taking in a gambling task (Fecteau et al., 2007), consistent with the idea that increased relative right frontal activity helps to inhibit approach-related reward seeking tendencies. A manipulated increase in right frontal cortical activity has also been found to decrease food cravings and calories ingested relative to a manipulated increase in left frontal cortical activity and sham stimulation conditions (Fregni et al., 2008).

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 function to stifle approach-motivated risk-seeking tendencies. Taken together the results from these brain stimulation studies suggest that increased right frontal cortical asymmetry may increase inhibition and self-control. However, all of these studies have examined the impact of relative right frontal activation and the control of approach-motivated impulses. The impact of relative right frontal activation on the control of avoidance-motivated responding has received much less attention.

Research on the relationship between behavioral inhibition sensitivity (BIS; Carver & White, 1994) and frontal asymmetry further highlights a possible link to response inhibition, but also increases ambiguity of the functional consequences of relative right frontal activity. Some researchers have found a strong positive association between BIS and relative right frontal activity (e.g., Sutton & Davidson, 1997), but others have observed only a weak positive association (e.g., Coan & Allen, 2003), and still others have observed no significant relationship (e.g., Harmon-Jones & Allen, 1997). The BIS scale appears to conflate avoidance with inhibition. The BIS scale includes items that reflect anxiety-related or inhibitory emotional responses (e.g., "I feel worried when I think I have done poorly at something important") and fear or avoidance-related responses (e.g., "I have very few fears compared to my friends"). Accordingly, Coan and Allen (2003) suggested that the relationship between right frontal asymmetry and BIS may be driven by withdrawal/avoidance tendencies or by inhibition. As documented above, many studies by Davidson and colleagues have examined the relationship between relative right frontal activity and withdrawal/avoidance tendencies (e.g., Davidson et al., 1990). However, due to a relative dearth of research on the possible link between right frontal asymmetry and inhibition it remains unclear whether increased right frontal asymmetry reflects mainly increased inhibition or increased avoidance.

Evidence from other brain measures further suggests links between the right prefrontal cortex and inhibitory control. One popular way researchers have studied inhibitory control is by using a Go/No-Go task. This task asks participants to respond to one stimulus (the *GO* stimulus) and to inhibit their response to another stimulus (the *NO-GO* stimulus). Neuroimaging studies have consistently found increased activation in parts of the right prefrontal cortex, notably the right inferior frontal gyrus, in response to the NO-GO stimulus (Chikazoe et al., 2007; Aron et al., 2004). Consistent with this evidence, Swick, Ashley, and Turken (2011) meta-analyzed 47 neuroimaging studies using a Go/No-Go task to study prefrontal activation during response inhibition. This meta-analysis suggested a broader pattern of right frontal cortical activation during response inhibition. Additional support for the link between the right prefrontal cortex and response inhibition comes from work using functional near-infrared spectroscopy (fNIRS,). fNIRS is a brain imaging technique that measures changes in oxygenated and deoxygenated hemoglobin, in contrast to fMRI which measures changes only in deoxygenated hemoglobin (Cui, Bray, Bryant, Glover, & Reiss, 2011). Research using fNIRS has also found greater right prefrontal cortical activation during response inhibition (Rodrigo et al., 2014).

1.6 Why does right frontal asymmetry increase self-control?

Whereas greater right than left frontal cortical activity has been observed to decrease impulsive behavior and approach-related responding (e.g., Fecteau et al., 2007. Fregni et al., 2008), ambiguity exists about why this decrease occurs. One explanation is that greater right than left frontal cortical activity enables self-control. The capacity to not consume cake or take unnecessary risks may have been greater than the impulse to act out those behaviors following stimulation to increase relative right frontal cortical activity. However, the behavior patterns could also be explained by an increase in avoidance motivation. For example, ingesting a slice of chocolate cake or taking a risk on a gambling task may be incompatible with one's goals (e.g., weight loss and financial security respectively), and thus consumption and risk-taking may have been viewed as stimuli to be avoided. Research into the self-control of avoidance-motivated impulses may help to disentangle the contributions of right frontal asymmetry to inhibitory control versus avoidance.

1.7 Motivational direction and embodied cognition

At its most basic level the key distinction between avoidance motivation and approach motivation is the direction of physical movement. Avoidance motivation stimulates movement away from a stimulus, whereas approach motivation stimulates movement toward a stimulus. This basic distinction is apparent even in single-celled organisms (Schneirla, 1959), suggesting that the relationship between physical movement and motivational tendencies is an elementary one.

Research and theory on embodied cognition also suggest close links among physical movements, motivation, and higher-level cognitive processes (Wilson, 2002; see Darwin, 1872). One way to examine the relationship between motor behavior, motivation, and higher-level processes involves assessing how quickly persons bring desired objects toward the self or push undesired objects away. Solarz (1960) was among the first to observe a connection between body movements and approach/avoidance motivation using this method. In his study participants viewed cards depicting words that were positively valenced or negatively valenced. Participants were randomly assigned to pull positive 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. That is to say, participants were fastest to push unpleasant words away and pull pleasant words toward themselves. This pattern was replicated by Chen and Bargh (1999), who also found that the effect holds in the absence of conscious processing. These results suggest the existence of a strong relationship between pulling and appetitive stimuli (e.g., sexual stimuli; Hofmann, Friese, & Gschwender, 2009) as well as between pushing and aversive stimuli (e.g., spiders; Klein, Becker, & Rinck, 2011). Many other researchers have replicated this same basic pattern of results (e.g., Krieglmeyer & Deutsch, 2010).

Given that self-control is required to override predominant response tendencies, the recruitment of self-control resources is required to perform motive-incongruent behaviors. On an approach/avoidance task (AAT), the motive incongruent pattern involves pulling unpleasant stimuli toward the self or pushing pleasant or desired stimuli away. The slowing of response latencies reported by Solarz (1960) for incongruent (e.g., pulling aversive stimuli toward the self) relative to congruent trials likely reflects the recruitment of self-control processes. However, as noted previously, self-control research has focused mainly on the control of approach-related impulses, and the mechanisms by which avoidance-related impulses are controlled are less clear. The current experiments tested one possible neural mechanism for the control of avoidance-motivated responses: asymmetric activity in the right prefrontal cortex.

1.8 Goals and overview of the current experiments

Prior research has focused extensively on the self-control of approach-oriented impulses. The main goal of the current research was to examine the self-control of avoidance motivated impulses. Specifically, these studies tested the whether a manipulated increase in right frontal asymmetry enhances avoidance-motivated impulses or the self-control of avoidance -motivated impulses. As reviewed above, activity in the right frontal cortex may enable self-control or it may increase avoidance motivation. Testing the role of greater right than left frontal activity in the self-control of avoidance-motivated impulses allows us to generate and test competing hypotheses about the role of the right frontal asymmetry in increasing inhibitory control or avoidance motivation, respectively.

2. EXPERIMENT 1

Investigating the self-control of avoidance-motivated responding may help to clarify the functional consequences of right frontal asymmetry. Fear of snakes and spiders appear to be evolutionarily hard-wired responses (Öhman & Mineka, 2001; Öhman & Mineka, 2003). Thus the prepotent response to such threatening stimuli is an avoidance-motivated impulse, and overriding this impulse would seem to require self-control. If increased right frontal asymmetry increases avoidance motivation, then increasing right frontal asymmetry via tDCS should facilitate the prepotent response and thus lead participants to pull feared images toward them more slowly. In contrast, if increased right frontal asymmetry enables inhibitory control, then increasing right frontal asymmetry via tDCS should increase participants' ability to override their prepotent response and thus enable them to pull feared images toward them more quickly. We tested these competing hypotheses using an approach-avoidance joystick task in conjunction with an experimental manipulation of asymmetrical frontal cortical activity.

2.1 Method

2.1.1 Participants and design

Participants were 88 healthy, right-handed undergraduates voluntarily participating in a double-blind between-subjects single factor design (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) in exchange for credit toward a course requirement. Participants were excluded based on contra-indications for non-invasive brain stimulation ($N = 3$, see Nische et al., 2008), including psychiatric or neurological history, damaged skin tissue, and medications (with the exception of women using oral contraceptives). In addition, we included only strongly right-handed participants, as is the norm in frontal asymmetry research (e.g., Sutton & Davidson, 1997).We excluded participants based their scores on Chapman and Chapman's (1987) handedness questionnaire. Specifically, we excluded those with a score above 17 on the handedness questionnaire who are considered either ambidextrous or left-handed (N =1). Participants were also excluded due to equipment failure (N = 3), failing to complete the pre-stimulation trials of the AAT (N = 1), and pulling sensors out during stimulation (N = 1). After exclusions, data from 79 participants (40 female) remained for analysis.

2.1.2 Procedure

Participants were led to believe they were participating in an experiment on brain activity and reactions to visual stimuli. Upon arrival participants completed a consent form, a handedness questionnaire (Chapman & Chapman, 1987), a safety screening, measures of behavioral approach and behavioral inhibition system sensitivities (Carver & White, 1994), trait self-control (Tangey, Baumeister, & Boone, 2004), disgust sensitivity (Tybur, Lieberman, & Griskevicius, 2009), and a self-report scale of emotional states (Harmon-Jones, Harmon-Jones, Abramson & Peterson, 2009). These measures were included on an exploratory basis and did not relate to the results reported below.

2.1.3 Approach-avoidance task block 1

Participants completed an approach-avoidance task (AAT; Chen & Bargh, 1999) in which they saw 32 negative images and 32 neutral images presented in a randomized order across two blocks. Images were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008). The negative images used were: 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. The neutral images used were: 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 7656. We used Libkuman, Otani, Kern, Viger, & Novak’s (2007) IAPS normative data to guide our image selection. This normative data set was of interest because images were rated on 6 discrete emotions: happiness, surprise, sadness, anger, disgust and fear. We selected images that primarily evoked fear; neutral images were rated low (below the midpoint) on all 6 discrete emotions.

Images appeared on a computer screen with a resolution of 1024×768 pixels. Each image remained on the screen until the participant moved a joystick. In the first block, participants were instructed by a research assistant to push a joystick away from them when they saw a negative image and to pull the joystick toward them when they saw a neutral image. These instructions were also displayed onscreen prior to the start of the task. Participants were told to read the instructions and continue when they were ready. The joystick was always placed between the participant and computer monitor such that the pushing and pulling of the joystick represented pushing the image away or pulling it toward the body, respectively. This first block served two purposes. First, it afforded a baseline estimate of participants' pull reaction times to be controlled in subsequent analyses.[1] Second, it reinforced pushing away negative images as a dominant response tendency. Immediately following the first block of the AAT participants received 15 minutes of tDCS.

2.1.4 tDCS

The current study 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. 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). A bipolar montage was used and electrodes were placed in wet sponges saturated with electrode-gel and fixed to the scalp positioned over left (F3) and right (F4) prefrontal regions (10-20 EEG system). Both experimenter 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 cortical activity (anodal over F3/cathodal over F4), increase in

---

[1] Reaction times for pulling neutral images in Block 1 correlated significantly with reaction times for pulling negative images in Block 2, r (77) = .59, $p < .001$.

relative right frontal cortical activity (cathodal over F3/anodal over F4), or sham. In the sham condition all settings except the stimulation duration (ramp-up: 5 sec; stimulation: 30 sec; ramp-down: 5 sec) were identical to the other conditions. This method has proven to be a reliable method of sham stimulation that does not result in consequential aftereffects (Gandiga, Hummel & Cohen, 2006).

2.1.5 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 were instructed to pull negative images toward the self and push neutral images away. Because pushing negative images away from the self is a predominant response tendency (e.g., Chen & Bargh, 1999; Marsh, Ambady, & Kleck, 2005), pulling negative images toward the self requires self-control to override the predominant tendency.

2.2 Results

2.2.1 Data preparation

Following Chen and Bargh (1999) all latencies greater than 4,000 ms (3.2 %) were considered outliers and omitted from analysis, and the reaction time data were log transformed to approximate normality. For ease of interpretation all means are reported in the original millisecond reaction latencies.

2.2.2 Baseline reaction time analyses

Recall that prior to brain stimulation participants pushed negative images away (i.e., engaged the dominant response tendency) and pulled neutral images toward the self on the AAT. One-way between-subjects ANOVA on participants' reaction times found no differences among tDCS conditions in the speed with which participants pushed threats away at baseline, F (2, 76) = 2.46, p = .09. Specifically, participants who went on to receive stimulation to increase relative right frontal cortical activity pushed negative images away from them non-significantly faster (M = 1064.96 ms, SD = 265.13) relative to participants who received stimulation to increase relative left frontal cortical activity (M = 1319.48 ms, SD = 419.56) and those who received sham stimulation (M = 1240.36 ms, SD = 478.29). The tDCS conditions also did not differ on the speed with which they pulled neutral images toward the self prior to stimulation, F (2, 76) = 0.42, p = .66. Specifically, participants who went on to receive stimulation to increase relative right frontal cortical activity were no faster (M = 1303.17 ms, SD = 318.17) than participants who received stimulation to increase relative left frontal cortical activity (M = 1323.03 ms, SD = 396.97) and those who received sham stimulation (M = 1409.83 ms, SD = 473.41), respectively.

2.2.3 Baseline error analyses

We analyzed the commission of errors in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (trial type: neutral vs. congruent) mixed-model ANOVA. The stimulation conditions did not differ in pre-stimulation errors, F (2, 77) = 0.48, p = .62. Moreover there was no effect of trial type on the commission of errors F (1, 77) = 0.16, p = .70. There was however a significant stimulation condition × trial type interaction, F (2, 77) = 4.16, p = .02. Specifically, participants who went on to receive tDCS to increase left frontal asymmetry had marginally more prestimulation errors when pushing negative images away (*M* = 1.29, *SD* = 1.64) compared to pulling neutral images toward the self (*M* = 0.52, *SD* = 0.75), t (20) = 2.02, p = .06. In addition, participants who went on to receive tDCS to increase right frontal asymmetry had marginally less prestimulation errors when pushing negative images away (*M* = 0.64, *SD* = 1.19) compared to pulling neutral images toward the self (*M* = 1.43, *SD* = 1.93), t (21) = 1.72, p = .09. There was no difference in the sham stimulation condition, t (30) = 0.89, p = .38.

2.2.4 Main analyses

After stimulation participants pulled negative images toward the self and pushed neutral images away. A one-way between-subjects ANCOVA found a main effect of stimulation type on participants' reaction times when pulling negative images toward the self, controlling for reaction times pulling neutral images toward the self prior to tDCS stimulation, F (2, 75) = 4.04, p = .02, η_p^2 = .10. Specifically, participants who received stimulation to increase relative right frontal cortical activity pulled negative images toward them significantly faster (*M* = 1084.33 ms, *SD* = 261.35) relative to participants who received stimulation to increase relative left frontal cortical activity (*M* = 1259.35 ms, *SD* = 260.89) and those who received sham stimulation (*M* = 1258.06 ms, *SD* = 261.92), *p*s < .03, *d*s = .67, respectively. The effects of stimulation to increase relative left frontal cortical activity and sham stimulation did not differ, p = .88. Please see Figure 1.

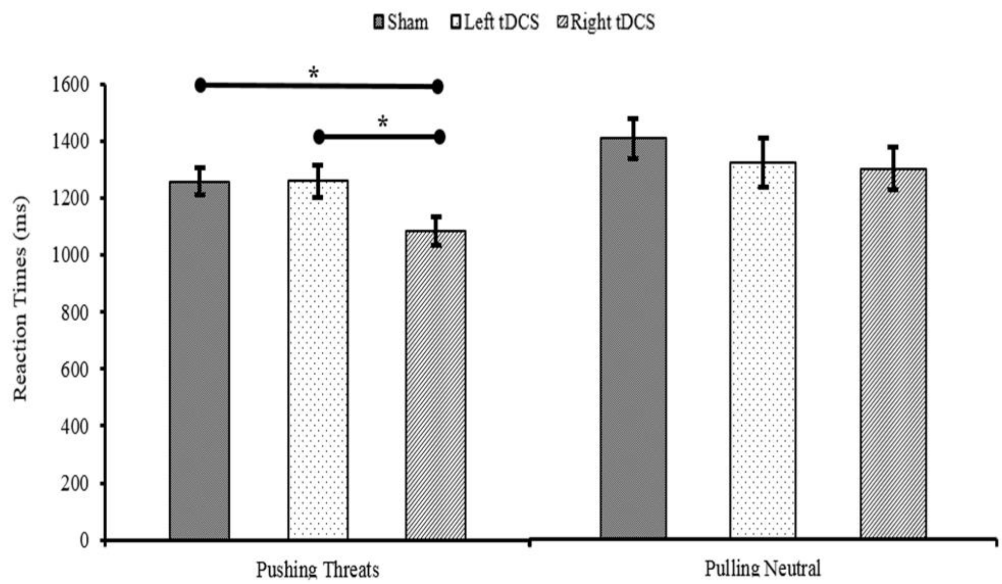

Figure 1. Reaction times to pull negative images toward the body and push neutral images away from the body as a function of stimulation condition (Experiment 1).

Stimulation condition did not influence pushing neutral images away from the self, *F* (2, 76) = 0.36, *p* = .70. Participants who received stimulation to increase relative right frontal cortical activity were no faster (*M* = 1319.40 ms, *SD* = 308.54) than participants who received stimulation to increase relative left frontal cortical activity (*M* = 1319.27 ms, *SD* = 379.43) and those who received sham stimulation (*M* = 1413.38 ms, *SD* = 467.63), respectively.

We also analyzed participants' reaction times to post-stimulation trials in a mixed model design in order to determine if stimulation affected both trial types similarly or not. We conducted a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (trial type: neutral vs. incongruent) mixed-model ANOVA. There was no main effect of stimulation condition, *F* (2, 77) =

1.81, $p = .17$. There was a main effect of trial type whereby participants were significantly faster to react to incongruent trials ($M = 1203.04$, $SD = 386.63$) compared to neutral trials ($M = 1355.78$, $SD = 392.62$) after stimulation, $F(1, 77) = 19.44$, $p < .001$. There was also a significant stimulation condition × trial type interaction, $F(2, 77) = 3.16$, $p = .048$. This interaction revealed the pattern noted above whereby stimulation did not influence reaction times to neutral trials but did influence reaction times to pulling negative images toward the self.

2.2.5 Errors

We analyzed the commission of errors in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (trial type: neutral vs. incongruent) mixed-model ANOVA. Stimulation did not influence errors on post-stimulation trials, $F(2, 77) = 0.11$, $p = .90$. Trial type did not influence error rates after stimulation, $F(2, 77) = 0.10$, $p = .94$. There was also no stimulation × trial type interaction, $F(2, 77) = 0.53$, $p = .59$. Please see Figure 2.

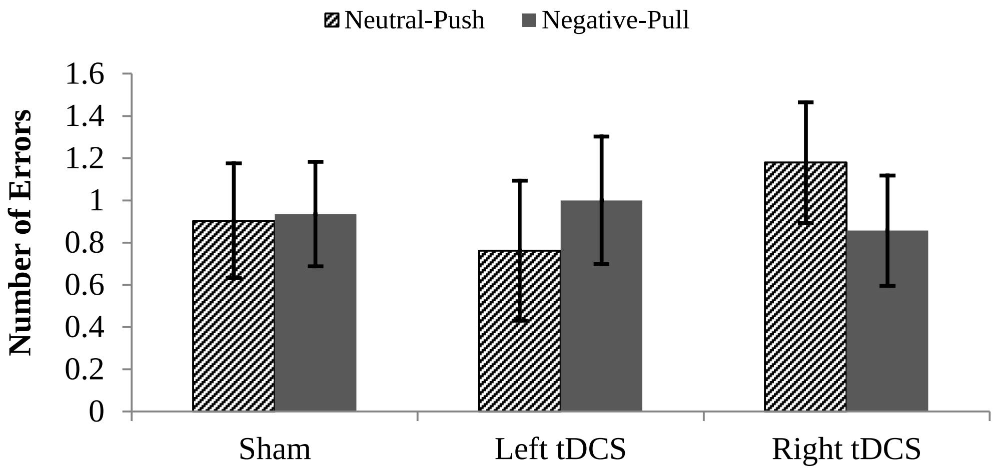

Figure 2. Number of errors committed when pulling negative images toward the body and pushing neutral images toward the body as a function of stimulation condition (Experiment 1).

2.3 Discussion

The first experiment tested competing hypotheses regarding the role of asymmetric frontal cortical activity in the self-control of avoidance motivation. If greater right than left frontal cortical activity enables inhibitory control, then increasing relative right frontal activity via tDCS should increase participants' ability to override their prepotent response tendencies and pull fearful images toward themselves more quickly. In contrast, if increasing relative right frontal asymmetry increases avoidance motivation, then increasing relative right frontal activity via tDCS should enhance the prepotent response to negative images and cause them to pull fearful images toward them more slowly. Consistent with the first hypothesis, participants in Experiment 1 were significantly faster to pull threats toward the self after a manipulated increase in right frontal asymmetry. This result represents the first evidence that increased relative right frontal cortical activity may enable the self-control of avoidance-motivated responding. However, one plausible alternative explanation is tDCS to increase right frontal asymmetry causes faster pulling behavior more generally. This first experiment was not designed to rule out this alternative explanation. Thus a second experiment was conducted in part to address this possibility.

3. EXPERIMENT 2

The purpose of the Experiment 2 was threefold. First, we sought a direct replication of the effect of increased relative right frontal cortical activity on the self-control of avoidance-motivated responding observed in Experiment 1. Second, we tested the hypothesis that a manipulated increase in right frontal asymmetry increases self-control of impulses irrespective of their motivational direction. To achieve this second goal Experiment 2 also included an approach–motivated responding condition wherein participants had to push appetitive images away (i.e., the motive-incongruent response) and pull neutral images toward the self following tDCS. The requirement to pull neutral images toward the self after stimulation allowed us to address the third purpose of Experiment 2 namely ruling out the alternative explanation that tDCS to increase right frontal asymmetry causes faster reaction times when pulling stimuli toward the self.

In summary, the main hypothesis driving Experiment 2 was that stimulation to increase relative right frontal cortical activity causes faster reaction times when participants must perform a motive-incongruent response regardless of whether this is an approach-oriented or avoidance-oriented motive-incongruent response (i.e., pushing rewards away or pulling threats toward the self). The secondary hypothesis was that stimulation does not simply hasten the pull responses.

3.1 Method

3.1.1 Participants and design

Experiment 2 sampled 129 healthy, right-handed undergraduates participating in a double-blind between-subjects design. The experimental design was a 2 (positive vs.

negative) × (3: 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) between subjects design. They received credit toward a course requirement for their participation. Participants were excluded based on contra-indications for non-invasive brain stimulation (*N* = 1, see Nitsche et al., 2008), including psychiatric or neurological history, damaged skin tissue, and medications (with the exception of women using oral contraceptives). In addition, we only included strongly right-handed participants as is the norm in frontal asymmetry research (e.g., Sutton & Davidson, 1997).We did not exclude participants based their scores on Chapman and Chapman's (1987) handedness questionnaire in Experiment 2 because all participants were strongly right-handed. Participants were also excluded due to equipment failure (*N* = 2) and sensors falling out during stimulation (*N* = 1). After exclusions, data from 125 participants (82 female) remained for analysis.

3.1.2. Procedure

The experimental procedure was identical to Experiment 1 with regard to the questionnaires and the tDCS stimulation parameters. Participants were randomly assigned to the avoidance condition of the AAT as in Experiment 1 or the approach condition, which was a new addition for Experiment 2. In the approach condition participants saw 32 appetitive images and 32 neutral images presented in a randomized order across two blocks. Images appeared on a computer screen with a resolution of 1024×768 pixels. In the first block participants were instructed to pull a joystick toward them when they saw an appetitive image and to push the joystick away them when they saw a neutral image. The joystick was always placed between the participant and computer monitor such that the pushing and pulling of the joystick represented pushing the image away or pulling it toward the body, respectively. Experiment 2 also recorded joystick data continuously during the experimental trials. As a result, each trial timed out at 2000 milliseconds if no response was detected.

3.1.3 Approach-avoidance task block 1

Participants completed an approach-avoidance task (AAT; Chen & Bargh, 1999) in which they saw 32 emotional (negative or positive) images and 32 neutral images presented in a randomized order across two blocks. Negative and neutral images were the same as in Experiment 1. Positive images were also taken from the IAPS database and the normative data from Libukman et al. (2009) was used to guide image selection. Specifically, we were interested in images that evoked happiness while also having low ratings on surprise, sadness, anger disgust and fear. The positive IAPS images used were: 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. Images appeared on a computer screen with a resolution of 1024×768 pixels. Each image remained on the screen until the participant moved a joystick. In the avoidance condition, in the first block, participants were instructed by a research assistant to push a joystick away from them when they saw a negative image and to pull the joystick toward them when they saw a neutral image. These instructions were also displayed onscreen prior to the start of the task. Participants were told to read the instructions and continue when they were ready.

In the avoidance condition, as in Experiment 1, the first block of the AAT involved pushing negative images away from the self (i.e., the motive-congruent response) and pulling neutral images toward the self. In the approach condition, in the first block participants were instructed by the experimenter to pull a joystick toward them when they saw a positive image (i.e., the motive-congruent response) and to push the joystick away from them when they saw a neutral image. These instructions were also displayed onscreen prior to the start of the task. Participants were told to read the instructions and continue when they were ready. This first block served two purposes. First, it afforded a baseline estimate of participants' push/pull reaction times to be controlled in subsequent analyses.[2] Second, it reinforced pushing away negative images and pulling positive images as a dominant response tendency in the avoidance and approach conditions respectively. Immediately following the first block of the AAT participants received 15 minutes of tDCS. As in Experiment 1, the joystick was always placed between the participant and computer monitor such that the pushing and pulling of the joystick represented pushing the image away or pulling it toward the body, respectively.

[2] Reaction times for neutral images in Block 1 correlated significantly with reaction times for incongruent trials in Block 2, r (121) = .48, $p < .001$.

3.1.4 tDCS

The current study used the same stimulation parameters as Experiment 1. Both d experimenter and participants were blind to the tDCS parameters, which were controlle by a separate investigator. Participants were randomly assigned to one of three r conditions: increase in relative left frontal cortical activity (anodal over F3/cathodal ove F4), increase in relative right frontal cortical activity (cathodal over F3/anodal over F4), or sham. In the sham condition all settings except the stimulation duration (ramp-up: 5 sec; stimulation: 30 sec; ramp-down: 5 sec) were identical to the other conditions. This method has proven to be a reliable method of sham stimulation that does not result in consequential aftereffects (Gandiga, Hummel & Cohen, 2006).

3.1.5. 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 push positive images away from their body. 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; Marsh, Ambady, & Kleck, 2005), pulling negative images toward the self (in the avoidance condition) and pushing positive images away from the self (in the approach condition) requires self-control to override the predominant tendency. For the sake of clarity, we refer to these post-stimulation trials as incongruent trials in subsequent analyses because they represent a motivationally-incongruent response requiring self-control.

3.1.6 Joystick movements

On an exploratory basis we also recorded participants' joystick movements to examine whether the pattern of movements differed as a function of stimulation condition. Specifically, we were interested in observing initial burst of movement in the motivationally-congruent direction on post-stimulation trials. Stated another way, we were interested in whether participants in the avoidance condition may initially push negative images away and correct themselves before pulling the images toward the self. Similarly, we were interested in whether those in the approach condition may initially pull post-stimulation positive images toward the self before correcting the behavior and pushing the images away. Joystick movements were scored on a 1-100 scale such that 1 = pulling toward the self, 50 = no movement toward or away from the self, and 100 = pushing away from the self. The joystick position on the 1-100 scale was recorded every 10 ms for up to 2000 ms on every trial. For ease of interpretation, in the analyses below we report the reaction times in 10 bins of 200 ms each.

3.2 Results

3.2.1. Baseline reaction time analyses

Recall that prior to brain stimulation participants in the avoidance condition pushed negative images away and pulled neutral images toward the self on the AAT, whereas participants in the approach condition pulled positive images toward the self and pushed neutral images away.

In the avoidance condition, a one-way between-subjects ANOVA on participants' reaction times found no differences among tDCS conditions in the speed with which participants pulled neutral images toward the self at baseline, F (2, 51) = 0.35, p = .97. Specifically, reaction times to pull neutral images toward the self did not differ among participants who went on to receive stimulation to increase relative right frontal cortical activity (M = 1218.84 ms, SD = 152.24), participants who received stimulation to increase relative left frontal cortical activity (M = 1200.43 ms, SD = 194.19), or those who received sham stimulation (M = 1212.34 ms, SD = 138.68), respectively.

An additional one-way between-subjects ANOVA on participants' reaction times found no differences among tDCS conditions in the speed with which participants in the avoidance condition pushed threats from the self at baseline, F (2, 52) = 0.03, p = .97. Specifically, reaction times to push negative images away did not differ among participants who went on to receive stimulation to increase relative right frontal cortical activity (M = 1103.95 ms, SD = 187.57), participants who received stimulation to increase relative left frontal cortical activity (M = 1085.51 ms, SD = 217.53), or those who received sham stimulation (M = 1087.40 ms, SD = 172.45), respectively. Thus, participants in the avoidance condition did not differ on reaction times to pre-stimulation AAT trials as a function of stimulation condition.

In the approach condition, a one-way between-subjects ANOVA on participants' reaction times found no differences among tDCS conditions in the speed with which participants pushed neutral images away from the self at baseline, F (2, 66) = 1.27, p =

.29. Specifically, reaction times to push neutral images away from the self did not differ among participants who went on to receive stimulation to increase relative right frontal cortical activity (*M* = 1325.82 ms, *SD* = 204.84), participants who received stimulation to increase relative left frontal cortical activity (*M* = 1432.44 ms, *SD* = 171.30), or those who received sham stimulation (*M* = 1310.71 ms, *SD* = 186.06), respectively.

An additional one-way between-subjects ANOVA on participants' reaction times found no differences among tDCS conditions in the speed with which participants pulled positive images toward themselves at baseline, F (2, 66) = 0.88, p = .42. Specifically, reaction times to pull positive images toward the self did not differ among participants who went on to receive stimulation to increase relative right frontal cortical activity (*M* = 1220.63 ms, *SD* = 175.20), participants who received stimulation to increase relative left frontal cortical activity (*M* = 1335.75 ms, *SD* = 157.54), or those who received sham stimulation (*M* = 1240.84 ms, *SD* = 210.47), respectively. Thus, participants in the approach condition did not differ on reaction times to pre-stimulation AAT trials as a function of stimulation condition on pre-stimulation trials.

3.2.2. Baseline error analyses

We analyzed the commission of errors 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 ANOVA. There was a main effect of trial type such that participants made significantly more errors on pre-stimulation neutral trials (*M* = 5.41, *SD* = 3.42) than congruent trials (*M* = 4.08, *SD* = 3.44), F (1,118) = 12.40, p < .001. There was also a main effect of motivation condition such that participants who were in the approach condition (*M* = 6.58, *SD* = 3.42) made significantly more than those in the avoidance condition (*M* = 3.95, *SD* = 2.65) prior to stimulation, *F* (1, 118) = 35.71, *p* < .001. No other main effects or interactive effects were significant.

3.2.3 Main analyses

Recall that after stimulation participants in the *avoidance condition* pulled negative images toward the self and pushed neutral images away. Participants in the *approach condition* pushed away appetitive images and pulled neutral images toward the self. A 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (motivation condition: approach vs. avoidance) between-subjects ANCOVA found a main effect of stimulation type on participants' reaction times to incongruent trials (pulling negative images toward the self in the avoidance condition or pushing appetitive images away in the approach condition), controlling for reaction times pulling neutral images toward the self prior to tDCS stimulation, *F* (2, 116) = 4.22, *p* = .02, η_p^2 = .07. Specifically, participants who received stimulation to increase relative right frontal cortical activity were significantly faster to react to incongruent trials (*M* = 1092.43 ms, *SD* = 177.45) relative to participants who received stimulation to increase relative left frontal cortical activity (*M* = 1209.43 ms, *SD* = 232.75) and those who received sham stimulation (*M* = 1199.90 ms, *SD* = 214.88), *p*s < .03, *d*s = 0.57 and 0.55, respectively. Please see Figure 3. The effects of stimulation to increase relative left frontal cortical activity and sham stimulation did not differ, *p* = .71.

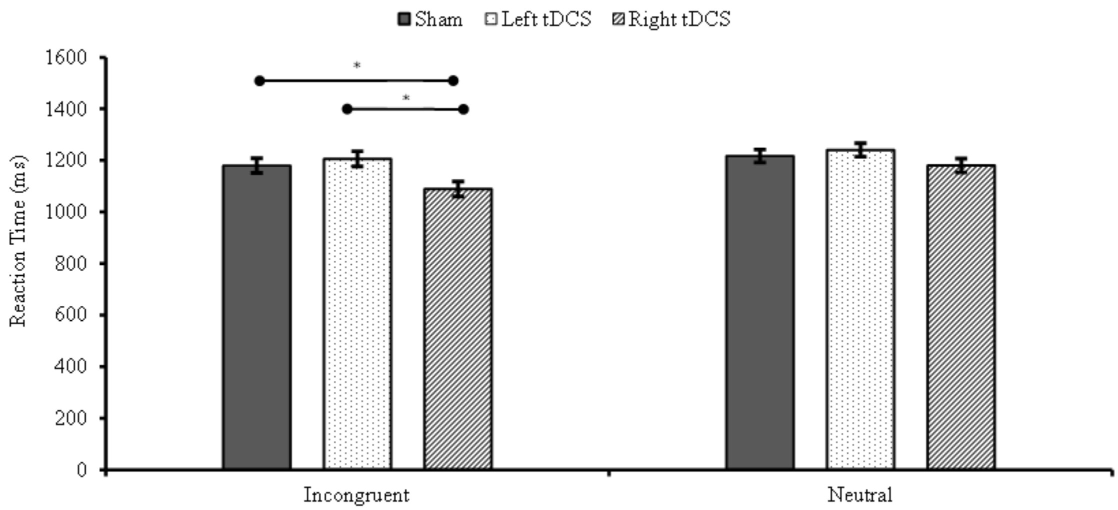

Figure 3. Reaction times to motivationally incongruent trials and neutral trials as a function of stimulation condition (Experiment 2).

The ANCOVA also revealed a main effect of motivation condition such that participants were faster to react to incongruent trials in the avoidance condition (M = 1060.36, SD = 196.76) compared to the approach condition (M = 1255.02, SD = 188.05), F (1, 116) = 16,26, p < .001. The stimulation × motivation condition interaction was not significant, F (2, 116) = .80, p = .45. Stimulation condition, motivation condition, and their interaction did not influence reactions to neutral images after stimulation, Fs < 1, ps > .40.

We also analyzed participants' reaction times to post-stimulation trials in a mixed model design in order to determine if stimulation affected both trial types (incongruent and neutral) similarly. We omitted motivation condition from this analysis in light of the non-significant stimulation condition × motivation condition interaction reported above. Consequently we conducted a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (trial type: neutral vs.

incongruent) mixed-model ANOVA. As predicted, there was a main effect of stimulation condition as was noted above, F (2, 120) = 3.06, p = .05. There was also a main effect of trial type whereby participants were significantly faster to react to incongruent trials (M = 1169.66, SD = 214.05) compared to neutral trials (M = 1214.58, SD = 168.43) after stimulation, F (1, 120) = 8.91, p = .003. There was no stimulation condition × trial type interaction, F (2, 120) = 1.69, p = .19. Post-hoc analyses revealed that stimulation to increase right frontal asymmetry led participants to reaction significantly faster to incongruent trials (M = 1094.44, SD = 179.30) compared to neutral trials (M = 1180.50, SD = 150.68), t (39) = 3.56, p < .001. There was no difference in reaction times to post-stimulation neutral trials and incongruent trials in either the stimulation to increase left frontal asymmetry, t (38) = 1.25, p = .22 or sham conditions, t (44) = 0.69, p = .49.

We next repeated the 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (trial type: neutral vs. incongruent) mixed-model ANOVA separately for the approach and avoidance conditions. In the approach condition, as predicted, there was a main effect of stimulation condition as was noted above, F (2, 65) = 5.57, p = .006. There was no main effect of trial type, F (1, 65) = 0.86, p = .36. There was no stimulation condition × trial type interaction, F (2, 65) = 0.84, p = .44. In the avoidance condition, there was no main effect of stimulation condition, F (2, 52) = 0.37, p =.70. There was a main effect of trial type, whereby participants were significantly faster to react to incongruent trials (M = 1060.36, SD = 196.76) compared to neutral trials (M = 11185.58, SD = 170.45) after stimulation, *F* (1, 52) = 33.98, *p* < .001.. There was no stimulation condition × trial type interaction, *F* (2, 52) = 0.59, *p* = .56.

3.2.4 Errors

We analyzed the commission of errors 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. incongruent) mixed-model ANOVA. As was the case with pre-stimulation trials, we observed a main effect of motivation condition such that participants who were in the approach condition (*M* = 4.48, *SD* = 3.15) made significantly more than those in the avoidance condition (*M* = 2.66, *SD* = 2.77) prior to stimulation, *F* (1, 118) = 29.57, *p* < .001. No other main effects or interactive effects were significant. Please see Figure 4.

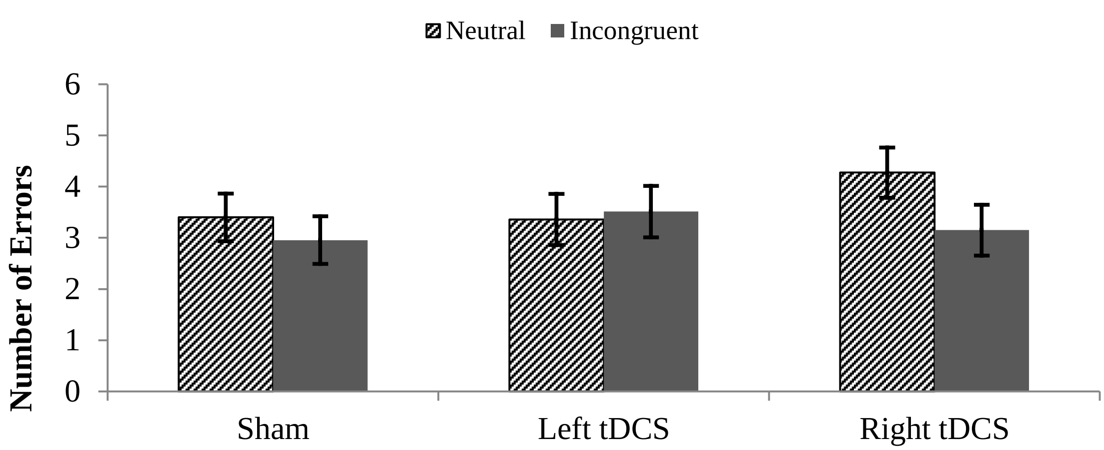

Figure 4. Number of errors committed in response to motivationally incongruent trials and neutral trials as a function of stimulation condition (Experiment 2).

3.2.5 Secondary analyses

On an exploratory basis we also examined participant's joystick movements to post-stimulation incongruent trials as a function of stimulation condition in a mixed model ANOVA. Because the patterns of joystick movements were going in opposite directions in the approach and avoidance conditions, the analysis was done separately for the approach and avoidance conditions. Participant's joystick movements recorded every 200 ms for a total of 2000 ms were assessed, resulting in 10 recordings. Thus, joystick movements were analyzed in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 10 (time: 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000) mixed-model ANOVA.

3.2.5.1. Avoidance condition

Joystick movements were scored on a 1-100 scale such that 1 = pulling toward the self and 100 = pushing away from the self. Unsurprisingly, there was a main effect of time such that as time progressed participants pulled negative images toward the self, $F(9, 495) = 15.46$, $p < .001$, as they had been instructed. Neither the main effect of stimulation condition nor the stimulation × time interaction were significant, *F*s < 1, *p*s > .60. This pattern suggests that participants' joystick movements did not vary as a function of stimulation condition. More importantly, at no point did joystick scores in any condition exceed 50. Thus, participants did not impulsively push negative images away prior to pulling the negative images toward the self. Please see Figure 5.

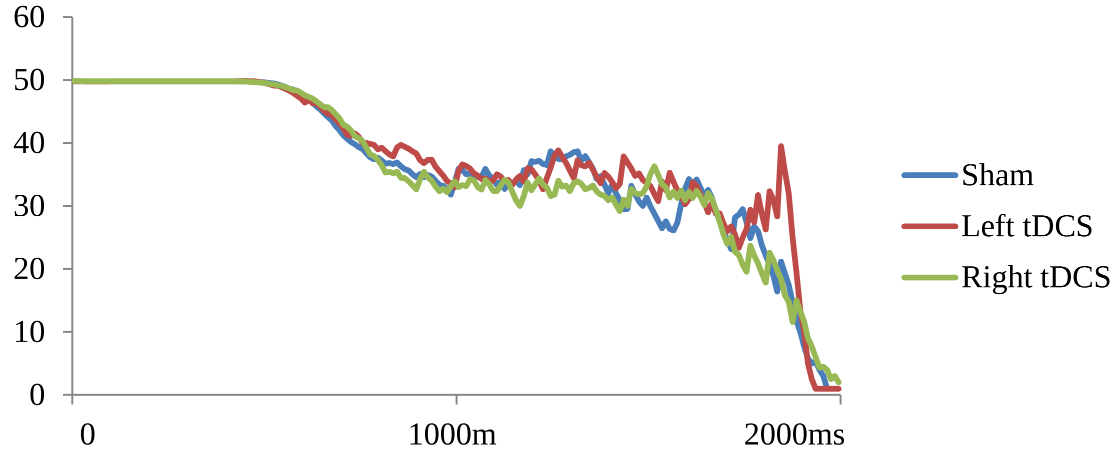

Figure 5. Joystick movements as a function of stimulation condition in the avoidance condition (Experiment 2).

3.2.5.2 Approach condition

A main effect of time indicated that as time progressed participants pushed appetitive images away from the self, F (9, 585) = 51.76, p < .001. Neither the main effect of stimulation condition nor the stimulation × time interaction was significant, Fs < 1, ps > .50. This pattern suggests that participants' joystick movements did not vary as a function of stimulation condition. More importantly, at no point did joystick scores in any condition exceed 50. This suggests that participants did not impulsively pull appetitive images toward the self prior to pushing appetitive images away. Please see Figure 6.

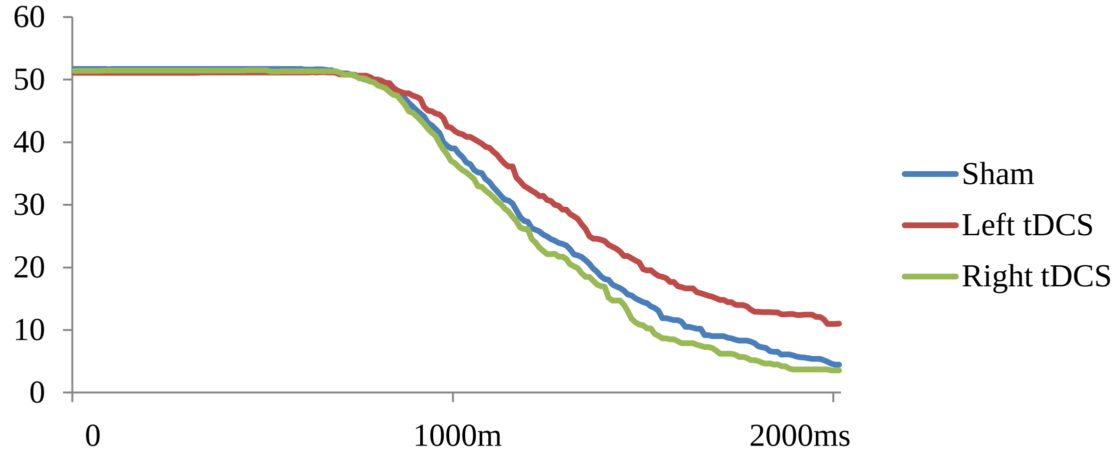

Figure 6. Joystick movements as a function of stimulation condition in the approach condition (Experiment 2).

3.2.6. Latency analysis

We also analyzed participants time to first movement of the joystick as a function of stimulation condition and motivation condition in a 3 (tDCS: sham, increase relative left frontal cortical activity, increase relative right frontal cortical activity) × 2 (motivation condition: approach vs. avoidance) between-subjects ANOVA. Results revealed a main effect of motivation condition such that participants had faster latencies to images in the avoidance condition (M = 456.06, SD = 211.07) compared to the approach condition (M = 572.73, SD = 371.92), F (1, 118) = 4.95, p = .03. There was no main effect of stimulation condition, F (2,118) = 0.24, p = .79 or a stimulation × motivation condition interaction, F (2, 118) = 1.55, p = .22. Please see Figure 7.

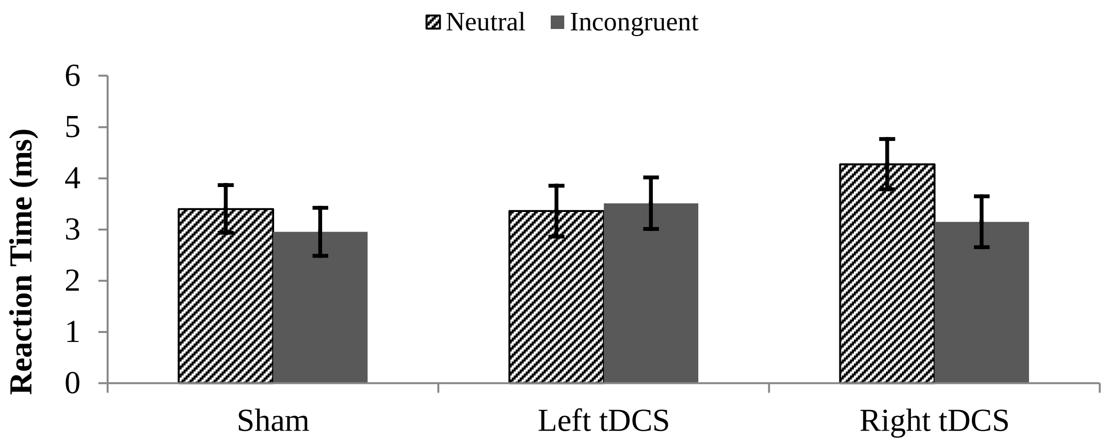

Figure 7. Response latencies to motivationally incongruent trials and neutral trials as a function of stimulation and motivation conditions (Experiment 2).

3.3 Discussion

The second experiment tested the hypothesis that right frontal asymmetric activity facilitates the self-control of impulses regardless of the motivational direction of those impulses. If greater right than left frontal cortical activity enables inhibitory control, then increasing relative right frontal activity via tDCS should increase participants' ability to override their prepotent response tendencies and pull fearful images toward themselves more quickly (in the avoidance condition) or push positive images away faster (in the approach condition). Consistent with this hypothesis, participants in Experiment 2 were significantly faster to react to post-stimulation incongruent trials after a manipulated increase in right frontal asymmetry. This result represents the first evidence that increased relative right frontal cortical activity may enable the self-control of impulses regardless of their motivational direction. Moreover, the fact that stimulation did not influence post-stimulation trials helps to rule out the alternative explanation that the effects of this first experiment were driven by faster pulling behavior

4. SUMMARY AND CONCLUSIONS

4.1 Summary

The current research had two main goals. The first goal was to test the hypothesis that both approach- and avoidance-motivated impulses are regulated by the same underlying brain mechanism (i.e., relative right frontal cortical activity). Experiment 1 found initial evidence in support of the role of relative right frontal cortical asymmetry in the self-control of avoidance motivation. Specifically, a manipulated increase in relative right frontal asymmetry (versus increased relative left frontal asymmetry and sham stimulation) caused participants to pull negative images towards themselves more quickly on an approach-avoidance joystick task. A second experiment directly compared the self-control of approach- and avoidance-motivated impulses within the same experiment. Experiment 2 found that participants who received stimulation to increase relative right frontal cortical activity were faster to react to motivationally incongruent trials (i.e., pulling negative images toward the self or pushing positive images away from the self) compared to stimulation to increase relative left frontal cortical activity or sham stimulation. Thus, the current experiments found evidence to support the hypothesis that increased relative right frontal cortical activity can enhance the self-control of both approach- and avoidance-motivated responding. Taken together with previous research (e.g., Fecteau et al., 2007; Fregni et al., 2008) this pattern suggests that right frontal asymmetry may enable inhibition regardless of the motivational direction of a behavior, consistent with the notion of a domain-general capacity for self-control (e.g., Muraven & Baumeister, 2000; Tabibnia et al., 2011).

4.2 Right frontal asymmetry, avoidance, and inhibition

The current studies linked right frontal asymmetry to response inhibition, whereas previous research had observed a link between right frontal asymmetry and avoidance motivation. How can these two seemingly divergent patterns of results be reconciled? First, it may be the case that the link between avoidance motivation and right frontal asymmetry is not as strong as previously thought. For example, several studies have failed to replicate the association between avoidance motivation and increased right prefrontal activation (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; Henriques & Davidson, 2000; Kline et al., 2000). Second, the current experiments did not test whether increased right frontal asymmetry increases avoidance-motivated responding when participants try to engage the avoidance-congruent behavior (i.e., we did not have a 'push negatives away' condition after stimulation). Thus, it is unclear the extent to which stimulation to increase right frontal activity promotes avoidance-motivated responding that individuals are not trying to control. Moreover, prior research on frontal asymmetry has yet to examine the relationship between asymmetry and the self-control of avoidance. From this perspective, rather than conflicting with prior research on frontal asymmetry, the results of the current experiments highlight the needs for continued work to clarify the role of right frontal asymmetry.

The results of the current experiments is consistent with prior research linking right frontal asymmetry to negative affect when considered thought the lens of the affective alarm model of control (Schmeichel & Inzlicht, 2013). This model theorizes that self-control is required to help resolve goal conflict – situations in which a goal is threatened or risks going unmet because it conflicts with another goal. For example, a person may have the impulse to eat a delicious dessert, but this impulse may conflict with the goal of losing weight. To further illustrate this point using avoidance motivated goal conflict as an example, a student's goal of avoiding public speaking may come into conflict with their goal of getting a good grade in a course. In situations like those described above, negative affect is typically evoked, signaling the need for control in order to prevent goal failure. From the perspective of the affective alarm model, right frontal asymmetry can be linked to both negative affect and self-control but at different time points. Immediately following goal conflict, negative affect may arise resulting in an increase in right frontal asymmetry. In turn this increased right frontal asymmetry may lead to an increase in self-control – specifically inhibition. This latter effect is what we observed in the current experiments. Future studies should continue to explore the complexities of the relationship between right frontal asymmetry, negative affect, and self-control from the perspective of the affective alarm model of self-control.

4.3 Limitations

Although the current experiments found evidence that increased right frontal asymmetry increases the self-control of impulses, the results do not speak to the role of right frontal asymmetry in motive-congruent responses to negative stimuli. That is to say, we did not test whether an increase in right frontal asymmetry speeds up reaction times when participants are asked to push negative images away – a motive-congruent response. Evidence that stimulation to increase right frontal asymmetry facilitates motive-incongruent responses but does not facilitate motive-congruent responses would represent even stronger evidence that increased right frontal asymmetry is about control rather than avoidance motivation. Future experiments should explore such a possibility.

As reviewed previously, tDCS is well-suited to manipulate frontal asymmetry because it allows researchers to increase activation in (i.e., anodal stimulation) in one hemisphere while decreasing activity (i.e., cathodal stimulation) in the contralateral hemisphere. Consistent with this viewpoint experiments have found support for a link between a manipulated increase in left frontal asymmetry via tDCS and approach motivation (e.g., Kelley et al., 2015). This is consistent with the EEG research linking left frontal asymmetry to approach motivation (e.g., Harmon-Jones, 2007; Harmon-Jones et al., 2002; Harmon-Jones & Sigelman, 2001). However, to date no experiments have paired tDCS with EEG to determine if tDCS over the frontal cortex induces asymmetric patterns of activity. As a result, we cannot say with certainty asymmetric patterns of activity were induced.

4.4 Underlying mechanisms

The present effects may be rooted in frontal cortical-subcortical interactions. A closed-loop circuit originates in the dorsolateral prefrontal cortex and projects to the thalamus through the striatum, globus pallidus and substantia nigra; this circuit has been implicated in executive functioning (see Tekin & Cummings, 2002). Inhibition is one of three major classes of executive functions (Miyake et al., 2000). Evidence from prior research pairing tDCS with functional magnetic resonance imaging found that stimulating the dorsolateral prefrontal cortex affects parts of the prefrontal circuit (e.g., the substantia nigra; Chib, Yub, Takahashi, & Shimojo, 2013). Chib and colleagues found that greater connectivity between the dorsolateral prefrontal cortex and the substantia nigra predicted greater attractiveness ratings of computer generated faces. As attraction is approach motivated in nature this may be interpreted as an increase in activation of the approach motivational system. There is to date no evidence pairing frontal cortical stimulation with neuroimaging to examine the circuitry involved in controlling approach or avoidance impulses. Future research pairing tDCS with imaging techniques should examine how 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).

Another possible brain mechanism is the corpus callosum, which connects complementary regions in the cerebral hemispheres (e.g., the left and right prefrontal cortices) and is critical for interhemispheric communication. Recent research suggests 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 correlated with increased attention toward angry faces in an emotional Stroop task. Based on this evidence, the link between left frontal cortical asymmetry and approach motivation may be driven by an increase interhemispheric signal transmission toward the left side of the brain. It may be the case that the right frontal asymmetry-inhibitory control link may be driven by an increase interhemispheric signal transmission toward the right side. Future work pairing tDCS with neuroimaging techniques should test this possibility.

4.5 Implications for self-control research

The current results may have implications for the treatment of conditions characterized by deficits in self-control. Failures to control approach-motivated impulses contribute to drug addiction, personal debt, obesity, and other outcomes that carry both personal and societal costs. Self-control training programs have been used to reduce the self-control of approach-motivated impulses in past research, notably anger and aggressive behavior. For example, Denson, Capper, Oaten, Friese, and Schofield (2011) used a 2-week training program to reduce aggression in response to insult or provocation amongst aggressive individuals. This training program asked participants to use their non-dominant hand to complete normal mundane behaviors (e.g., tooth brushing) between 8 am and 6 pm every day. Finkel, DeWall, Slotter, Oaten, and Foshee (2009) used the same training program and found that it decreased impulses to behave aggressively toward intimate partners.

Could tDCS to increase right frontal asymmetry be implemented into such training programs, or perhaps supplant them altogether? As reviewed previously, the self-control of avoidance motivated impulses has been studied within the clinical literature revealing two important findings. First, numerous phobias and psychopathologies may reflect poorly regulated avoidance motivation. Second, exposure-based treatments as some of the most effective treatments for a wide range of anxiety disorders including phobias, panic disorder, and post-traumatic stress disorder. Given that our results suggest that stimulation to increase right frontal asymmetry increase self-control of impulses, pairing this pattern of stimulation with exposure based treatments could allow mental health professionals to more efficiently treat a debilitating suite of anxiety disorders.

For example, the behavioral approach test (Arntz, Lavy, van den Berg, & van Rijsoort, 1993) is one task commonly used as part of exposure based treatments for phobia. Participants are scored on this task on a 13-point scale whereby higher scores reflect more engagement with the feared stimulus. In a study of spider phobics, Mulkens, de Jong, and Merckelbach (1996) used a version of the behavioral approach test in which a score of 0 indicated that the spider was 300 cm from the participant enclosed in a jar, and a score of 13 indicated that the spider was on the participant's hand. Garcia-Palacios, Hoffamn, Carlin, Furness, and Botella (2002) paired exposure therapy with a behavioral approach task in a group of spider phobics and found that compared to pre-treatment scores post treatment scores were significantly higher (i.e. participants were able to get closer to the spider). Could pairing tDCS to increase right frontal asymmetry facilitate this treatment effect? If a manipulated increase in right frontal asymmetry increases self-control as observed in the current experiments, and self-control is required for a spider phobic to approach a spider during the behavioral approach task, then such stimulation may help persons with spider phobias override their prepotent and approach the spider a quicker rate and to a greater degree than with treatment alone. Future research should explore the possibility of pairing tDCS with exposure therapy to test this possibility.

4.6 Implications for the conceptualization of behavioral inhibition sensitivity

Last, these results may have implications for how to conceptualize behavioral inhibition sensitivity in personality research. The results of the current research suggest that right frontal asymmetry reflects the inhibition of impulses rather than increased avoidance motivation. Recall that prior research on the relationship between behavioral inhibition sensitivity (BIS; Carver & White, 1994) and frontal asymmetry has been inconsistent. Some researchers have found a strong positive association between BIS and relative right frontal activity (e.g., Sutton & Davidson, 1997), but others have observed only a weak positive association (e.g., Coan & Allen, 2003), and still others have observed no significant relationship (e.g., Harmon-Jones & Allen, 1997). These inconsistent results may be due to the fact that the BIS scale includes items that reflect both avoidance and inhibition. Since the current results consistently found that increased right frontal asymmetry reflects the inhibition of impulses, researchers may be able to use the insights gleaned from these experiments to develop better measures of behavioral inhibition that robustly relate to right frontal asymmetry the way that measure of approach tendencies relate to left frontal asymmetry.

4.7 Conclusion

The survival of any organism is contingent upon motivational systems of approach and avoidance. Acting appropriately in the face of these stimuli has lasting survival costs. As a result, the capacity to control these impulses is ubiquitous and failures at control are arguably responsible, at least in part, for some of our greatest collective challenges as a species including - drug addiction, anxiety disorders, debt, obesity, and even climate change. The results of the current experiments suggest that stimulation to increase right frontal cortical asymmetry may facilitate self-control and in that way offer a building block toward solving some of these large scale societal issues.

REFERENCES

Addessi, E., Paglieri, F., & Focaroli, V. (2011). The ecological rationality of delay tolerance: Insights from capuchin monkeys. *Cognition*, *119*, 142-147.

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.

Allen, J. J., Iacono, W. G., Depue, R. A., & Arbisi, P. (1993). Regional electroencephalographic asymmetries in bipolar seasonal affective disorder before and after exposure to bright light. *Biological Psychiatry*, *33*, 642-646.

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.

Amici, F., Aureli, F., & Call, J. (2008). Fission-fusion dynamics, behavioral flexibility, and inhibitory control in primates. *Current Biology*, *18*, 1415-1419.

Arntz, A., Lavy, E., van den Berg, G., & Rijsoort, S. van (1993). Negative beliefs of spider phobics: A psychometric evaluation of the Spider Phobia Beliefs Questionnaire. *Advances in Behaviour Research and Therapy*, *15*, 257–277.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8*, 170-177

Baumeister, R. F. (2002). Yielding to temptation: Self-control failure, impulsive purchasing, and consumer behavior. *Journal of Consumer Research, 28*, 670-676.

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.

Carver, C. S., & Scheier, M. F. (1982). Control theory: A useful conceptual framework for personality–social, clinical, and health psychology. *Psychological Bulletin*, *92*, 111-135.

Cheng, K., Peña, J., Porter, M. A., & Irwin, J. D. (2002). Self-control in honeybees. *Psychonomic Bulletin & Review*, *9*, 259-263.

Carver, C. S., & White, T. L. (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS scales. *Journal of Personality and Social Psychology*, *67*, 319-333.

Chapman, L. J., & Chapman, J. P. (1987). The measurement of handedness. *Brain and Cognition*, *6*, 175-183.

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.

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

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.

Coan, J. A., & Allen, J. J. (2003). Frontal EEG asymmetry and the behavioral activation and inhibition systems. *Psychophysiology, 40*, 106-114.

Coan, J. A., Allen, J. J., & Harmon-Jones, E. (2001). Voluntary facial expression and hemispheric asymmetry over the frontal cortex. *Psychophysiology, 38*, 912-925.

Craske, M. G., Brown, T. A., & Barlow, D. H. (1991). Behavioral treatment of panic disorder: A two-year follow-up. *Behavior Therapy*, *22*, 289-304.

Cui, X., Bray, S., Bryant, D. M., Glover, G. H., & Reiss, A. L. (2011). A quantitative comparison of NIRS and fMRI across multiple cognitive tasks.*Neuroimage, 54*, 2808-2821.

Darwin, C. (1872). *The expression of emotions in man and animals*. New York: Philosophical Library.

Davidson, R. J., Ekman, P., Saron, C. D., Senulis, J. A., & Friesen, W. V. (1990). Approach-withdrawal and cerebral asymmetry: Emotional expression and brain physiology: I. *Journal of Personality and Social Psychology*, *58,* 330-341.

Dawson, G., Panagiotides, H., Klinger, L. G., & Hill, D. (1992). The role of frontal lobe functioning in the development of infant self-regulatory behavior. *Brain and Cognition*, *20*, 152-175.

Denson, T. F., Capper, M. M., Oaten, M., Friese, M., & Schofield, T. P. (2011). Self-control training decreases aggression in response to provocation in aggressive individuals. *Journal of Research in Personality*, *45*, 252-256.

Eisenberger, R., Weier, F., Masterson, F. A., & Theis, L. Y. (1989). Fixed-ratio schedules increase generalized self-control: Preference for large rewards despite high effort or punishment. *Journal of Experimental Psychology: Animal Behavior Processes*, *15*, 383-392.

Elliot, A. J. (2006). The hierarchical model of approach-avoidance motivation. *Motivation and Emotion*, *30*, 111-116.

Elliot, A. J., & McGregor, H. A. (1999). Test anxiety and the hierarchical model of approach and avoidance achievement motivation. *Journal of Personality and Social Psychology*, *76*, 628-644.

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. *The Journal of Neuroscience*, *27*, 12500-12505.

Finkel, E. J., DeWall, C. N., Slotter, E. B., Oaten, M., & Foshee, V. A. (2009). Self-regulatory failure and intimate partner violence perpetration. *Journal of Personality and Social Psychology*, *97*, 483-499.

Fischer, P., Greitemeyer, T., & Frey, D. (2007). Ego depletion and positive illusions: Does the construction of positivity require regulatory resources? *Personality and Social Psychology Bulletin*, *33*, 1306-1321.

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

Forsyth, J. P., Barrios, V., & Acheson, D. (2007). Exposure therapy and cognitive interventions for the anxiety disorders: Overview and newer third-generation perspectives. In D. C. S. Richard & D. Lauterbach (Eds.), *Handbook of the Exposure Therapies* (pp. 61-108). New York: Academic Press.

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.

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.

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.

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*, *96*, 8301-8306

Garcia-Palacios, A., Hoffman, H., Carlin, A., Furness, T. U., & Botella, C. (2002). Virtual reality in the treatment of spider phobia: a controlled study. *Behaviour Research and Therapy*, *40*, 983-993

Haggar, M. S., Wood, C., Stiff, C., & Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin*, *136*, 495-525.

Harmon-Jones, E. (2007). Trait anger predicts relative left frontal cortical activation to anger-inducing stimuli. *International Journal of Psychophysiology, 66,* 154–160.

Harmon-Jones, E., Abramson, L. Y., Sigelman, J., Bohlig, A., Hogan, M. E., & Harmon-Jones, C. (2002). Proneness to hypomania/mania or depression and asymmetrical frontal cortical responses to an anger-evoking event. *Journal of Personality and Social Psychology, 82*, 610-618.

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.

Harmon-Jones, E., & Allen, J. J. (1998). Anger and frontal brain activity: EEG asymmetry consistent with approach motivation despite negative affective valence. *Journal of Personality and Social Psychology*, *74*, 1310-1316.

Harmon-Jones, E., Harmon-Jones, C., Abramson, L., & Peterson, C. K. (2009). PANAS positive activation is associated with anger. *Emotion, 9*, 183-196.

Harmon-Jones, E., Harmon-Jones, C., & Price, T. F. (2013). What is approach motivation?. *Emotion Review*, *5*, 291-295.

Harmon-Jones, E., Lueck, L., Fearn, M., & Harmon-Jones, C. (2006). The effect of personal relevance and approach-related action expectation on relative left frontal cortical activity. *Psychological Science*, 17, 434-440.

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.

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.

Hofmann, W., Friese, M., & Gschwendner, T. (2009). Men on the "pull": Automatic approach-avoidance tendencies and sexual interest behavior. *Social Psychology*, *40*, 73-78.

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.

Hofman, D., & Schutter, D. J. (2009). Inside the wire: Aggression and functional interhemispheric connectivity in the human brain. *Psychophysiology*, *46*, 1054-1058.

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.

Hirai, M., Vernon, L. L., & Cochran, H. (2006). Exposure therapy for phobia. In D. Richard & D. Lauterbach (Eds.), *Handbook of the Exposure Therapies* (pp. 247-270). Burlington, MA: Academic Press.

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.

Inzlicht, M., & Gutsell, J. N. (2007). Running on empty: Neural signals for self-control failure. *Psychological Science, 18*, 933-937.

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.

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.

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.

Kelley, N. J., Eastwick, P. W., Harmon-Jones, E., & Schmeichel, B. J. (2015, April 6). Jealousy Increased by Induced Relative Left Frontal Cortical Activity. *Emotion*. Advance online publication.

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.

Kenrick, D. T., & Shiota, M. N. (2008). Approach and avoidance motivation(s): An evolutionary perspective. In A. J. Elliot (Ed.), *Handbook of Approach and Avoidance Motivation* (pp. 273-288). Mahwah, NJ: Lawrence Erlbaum Associates.

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.

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. *The Journal of Neuroscience*, *26*, 6469-6472.

Krieglmeyer, R., & Deutsch, R. (2010). Comparing measures of approach–avoidance behaviour: The manikin task vs. two versions of the joystick task. *Cognition and Emotion*, *24*, 810-828.

Lang, P.J., Bradley, M.M., & Cuthbert, B.N. (2008). International affective picture system (IAPS): Affective ratings of pictures and instruction manual. Technical Report A-8. University of Florida, Gainesville, FL.

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.

Marsh, A. A., Ambady, N., & Kleck, R. E. (2005). The effects of fear and anger facial expressions on approach-and avoidance-related behaviors. *Emotion, 5*, 119-124.

Metcalfe, J., & Mischel, W. (1999). A hot/cool-system analysis of delay of gratification: Dynamics of willpower. *Psychological Review, 106*, 3-19.

Miller, H. C., Pattison, K. F., DeWall, C. N., Rayburn-Reeves, R., & Zentall, T. R. (2010). Self-control without a "self"?: Common self-control processes in humans and dogs. *Psychological Science*, *21*, 534-538.

Mischel, W. (1958). Preference for delayed reinforcement: An experimental study of a cultural observation. *Journal of Abnormal and Social Psychology*, *56*, 57-61.

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.

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.

Mulkens, S. A., de Jong, P. J., & Merckelbach, H. (1996). Disgust and spider phobia. *Journal of abnormal psychology*, *105*(3), 464-468

Munakata, Y., Snyder, H. R., & Chatham, C. H. (2012). Developing Cognitive Control Three Key Transitions. *Current Directions in Psychological Science*, *21,* 71-77.

Mungee, A., Kazzer, P., Feeser, M., Nitsche, M. A., Schiller, D., & Bajbouj, M. (2014). Transcranial direct current stimulation of the prefrontal cortex: A means to modulate fear memories. *NeuroReport, 25*, 480-484.

Muraven, M., & Baumeister, R. F. (2000). Self-regulation and depletion of limited resources: Does self-control resemble a muscle?. *Psychological Bulletin*, *126*, 247-259.

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, *527*, 633-639.

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.

Oertig, D., Schüler, J., Schnelle, J., Brandstätter, V., Roskes, M., & Elliot, A. J. (2013). Avoidance goal pursuit depletes self-regulatory resources. *Journal of Personality*, *81*, 365-375.

Ohman, A., & Mineka, S. (2001). Fears, phobias, and preparedness: Toward an evolved module of fear and fear learning. *Psychological Review, 108*, 483-522.

Öhman, A., & Mineka, S. (2003). The malicious serpent: Snakes as a prototypical stimulus for an evolved module of fear. *Current Directions in Psychological Science*, *12*, 5-9.

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.

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.

Powers, M. B., & Emmelkamp, P. M. (2008). Virtual reality exposure therapy for anxiety disorders: A meta-analysis. *Journal of Anxiety Disorders*, *22*, 561-569.

Richard, D.C.S., Lauterbach, D., & Gloster, A.T. (2007). Description, mechanisms of action, and assessment. In D. C. S. Richard & D. Lauterbach (Eds.), *Handbook of the exposure therapies* (pp. 1-28). New York: Academic Press.

Rodrigo, A. H., Di Domenico, S. I., Ayaz, H., Gulrajani, S., Lam, J., & Ruocco, A. C. (2014). Differentiating functions of the lateral and medial prefrontal cortex in motor response inhibition. *Neuroimage*, *85*, 423-431.

Rothbaum, B. O., & Schwartz, A. C. (2001). Exposure therapy for posttraumatic stress disorder. *American Journal of Psychotherapy, 56*, 59-75.

Saunders, B., Milyavskaya, M., & Inzlicht, M. (in press). What does cognitive control feel like? Effective and ineffective cognitive control is associated with divergent phenomenology. *Psychophysiology.*

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.

Schmeichel, B. J., & Inzlicht, M. (2013). Incidental and integral effects of emotions on self-control. In M. D. Robinson, E. R. Watkins, and E. Harmon-Jones

(Eds.), *Handbook of Cognition and Emotion* (pp. 272-290). New York: Guilford Press.

Schneirla, T.C. (1959). An evolutionary and developmental theory of biphasic processes underlying approach and withdrawal. In M.R. Jones (Ed.) *Nebraska Symposium on Motivation* (pp.1-42). Lincoln: University of Nebraska Press.

Schutter, D. J., & Harmon-Jones, E. (2013). The corpus callosum: A commissural road to anger and aggression. *Neuroscience & Biobehavioral Reviews*, *37*, 2481-2488.

Schutter, D. J., Van Honk, J., & Panksepp, J. (2004). Introducing transcranial magnetic stimulation (TMS) and its property of causal inference in investigating brain-function relationships. *Synthese*, *141*, 155-173.

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.

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.

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.

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. *The Journal of Neuroscience*, *31*, 4805-4810.

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.

Tekin, S., & Cummings, J. L. (2002). Frontal–subcortical neuronal circuits and clinical neuropsychiatry: An update. *Journal of Psychosomatic Research*, *53*, 647-654.

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.

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.

Tybur, J. M., Lieberman, D., & Griskevicius, V. (2009). Microbes, mating, and morality: Individual differences in three functional domains of disgust. *Journal of Personality and Social Psychology*, *97*, 103-122.

Vaughn, B. E., Kopp, C. B., & Krakow, J. B. (1984). The emergence and consolidation of self-control from eighteen to thirty months of age: Normative trends and individual differences. *Child Development*, *55*, 990-1004.

Vohs, K. D., & Faber, R. J. (2007). Spent resources: Self-regulatory resource availability affects impulse buying. *Journal of Consumer Research*, *33*, 537-547.

Wheeler, R. E., Davidson, R. J., & Tomarken, A. J. (1993). Frontal brain asymmetry and emotional reactivity: A biological substrate of affective style. *Psychophysiology*, *30*, 82-89.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*, 625-636.

APPENDIX

QUESTIONAIRES

A-1. Handedness Questionnaire

With which hand do you:

Draw?	Left	Either	Right
Write?	Left	Either	Right
Use a Bottle Opener?	Left	Either	Right
Throw a Snowball to Hit a Tree? Left	Either	Right	
Use a Hammer?	Left	Either	Right
Use a Toothbrush?	Left	Either	Right
Use a Screwdriver?	Left	Either	Right
Use an Eraser on Paper?	Left	Either	Right
Use a Tennis Racket?	Left	Either	Right
Use Scissors?	Left	Either	Right
Hold a Match when Striking It?	Left	Either	Right
Stir a Can of Paint?	Left	Either	Right
On which shoulder do you rest			
a bat before swinging?	Left	Either	Right
Is anyone in your family left-handed?	Yes	No	

A-2 Safety Screening

Are you currently taking any medications for psychiatric or psychological problems? Yes No

Have you ever suffered a serious head injury (e.g., concussion)? Yes No

Have you ever been treated for a neurological (e.g., epilepsy) or psychiatric problem (e.g., major depression)? Yes No

Have you ever had any of the below (indicate yes or no in blank)?

___ psychotropic drugs, including cannabis, ecstasy, amphetamines and cocaine

___ epilepsy

___ metal in cranium

___ cardiac pacemaker

___ electronic hearing devices

___ skin disease

___ hearing disabilities or anomalies such as tinnitus

A-3. BIS/BAS Questionnaire

Please read each statement carefully, and then write the number that corresponds to your response in the blank provided at the beginning of the sentence. Thank you for your cooperation.

1	2	3	4
strongly disagree	disagree	agree	strongly agree

___ If I think something unpleasant is going to happen I usually get pretty "worked up."

___ When I get something I want, I feel excited and energized.

___ When I want something, I usually go all-out to get it.

___ I will often do things for no other reason than they might be fun.

___ I worry about making mistakes.

___ When I'm doing well at something, I love to keep at it.

___ I go out of my way to get things I want.

___ I crave excitement and new sensations.

___ Criticism or scolding hurts me quite a bit.

___ I'm always willing to try something new if I think it will be fun.

___ If I see a chance to get something I want, I move on it right away.

___ Even if something bad is about to happen to me, I rarely experience fear or nervousness.

___ When good things happen to me, it affects me strongly.

___ I feel pretty worried or upset when I think or know somebody is angry at me.

___ It would excite me to win a contest.

___ I feel worried when I think I have done poorly at something.

___ When I go after something I use a "no holds barred" approach.

___ I often act on the spur of the moment.

___ I have very few fears compared to my friends.

___ When I see an opportunity for something I like, I get excited right away.

A-4. Trait Self-Control

Please answer the following items as they apply to you. There are no right or wrong answers. Please choose a number, 1 through 5, that best represents what you believe to be true about yourself for each question. Use the following scale to refer to how much each question is true about you.

1	2	3	4	5
Not at all like me		Sometimes like me		Very much like me

____ 1. I have a hard time breaking bad habits.

____ 2. I am lazy.

____ 3. I say inappropriate things.
____ 4. I do certain things that are bad for me, if they are fun.
____ 5. I refuse things that are bad for me.
____ 6. I wish I had more self-discipline.
____ 7. I am good at resisting temptation.
____ 8. People would say that I have iron self-discipline.
____ 9. I have trouble concentrating.
____ 10. I am able to work effectively toward long-term goals.
____ 11. Sometimes I can't stop myself from doing something, even if I know it's wrong.
____ 12. I often act without thinking through all the alternatives.
____ 13. Pleasure and fun sometimes keep me from getting work done.

A-5 Three Domain Disgust Scale

The following items describe a variety of concepts. Please rate how disgusting you find the concepts described in the items, where 0 means that you do not find the concept disgusting at all, and 6 means that you find the concept extremely disgusting.

1. Shoplifting a candy bar from a convenience store	0	1	2	3	4	5	6
2. Hearing two strangers having sex	0	1	2	3	4	5	6
3. Stepping on dog poop	0	1	2	3	4	5	6
4. Stealing from a neighbor	0	1	2	3	4	5	6
5. Performing oral sex	0	1	2	3	4	5	6
6. Sitting next to someone who has red sores on their arm	0	1	2	3	4	5	6
7. A student cheating to get good grades	0	1	2	3	4	5	6
8. Watching a pornographic video	0	1	2	3	4	5	6
9. Shaking hands with a stranger who has sweaty palms	0	1	2	3	4	5	6
10. Deceiving a friend	0	1	2	3	4	5	6
11. Finding out that someone you don't like has sexual fantasies about you	0	1	2	3	4	5	6
12. Seeing some mold on old leftovers in your refrigerator	0	1	2	3	4	5	6
13. Forging someone's signature on a legal document	0	1	2	3	4	5	6
14. Bringing someone you just met back to your room to have sex	0	1	2	3	4	5	6
15. Standing close to a person who has body odor	0	1	2	3	4	5	6
16. Cutting to the front of a line to purchase the last few tickets to a show	0	1	2	3	4	5	6
17. A stranger of the opposite sex intentionally rubbing your thigh in an elevator	0	1	2	3	4	5	6
18. Seeing a cockroach run across the floor	0	1	2	3	4	5	6
19. Intentionally lying during a business transaction	0	1	2	3	4	5	6
20. Having anal sex with someone of the opposite sex	0	1	2	3	4	5	6
21. Accidentally touching a person's bloody cut	0	1	2	3	4	5	6