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The relationship of approach/avoidance motivation and asymmetric frontal cortical activity: A review of studies manipulating frontal asymmetry

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ABSTRACT

The balance between activity in the left and right frontal cortex, commonly referred to as asymmetric frontal cortical activity, has served as a proxy for an organism's motivational direction (i.e., approach vs. avoidance). Many studies have examined the influence of the manipulation of motivational direction on asymmetrical frontal cortical activity and found results consistent with the idea that greater relative left (right) frontal cortical activity is associated with approach (avoidance) motivation. We critically review literature employing physical (versus psychological) manipulations of frontal asymmetry using a variety of methodologies including neurofeedback training, muscular contractions, and non-invasive brain stimulation. These reviewed methods allow us to make stronger causal inferences regarding the role of asymmetric frontal cortical activity in approach and avoidance motivation.

1. Introduction

Approach and avoidance motivation are vital for survival. Approach motivation refers to the urge to go toward a stimulus (see Harmon-Jones et al., 2013).[1] This contrasts with avoidance motivation, which refers to the "energization of behavior by or the direction of behavior away from negative stimuli" (Elliot, 2006, p. 112). Thus, the "intended" direction of physical movement is a key feature distinguishing these two motivational orientations. Evidence of this distinction is apparent even in simple organisms. Dark-adapted earthworms contract their bodies in the presence of intense light to avoid aversive stimuli, and elongate their bodies in the presence of darkness to approach the safety signified by the darkness (Schneirla, 1959). For these earthworms and many more species, acting appropriately in the face of appetitive stimuli (e.g., seeking opportunities to mate or eat) and threatening stimuli (e.g., evading predators) could mean the difference between life and death, suggesting that motivational orientation is crucial to driving the behavior of most, in not all, organisms.

Whereas the functional significance of approach-avoidance behavior in simple organisms is tied to rudimentary survival concerns over physical safety, in more complex social species the functional significance of approach-avoidance motivation may revolve around the pursuit of reward and avoidance of punishment in social animals, according to some theorists (van Honk and Schutter, 2005, 2006). From this viewpoint, the approach-avoidance motivation continuum evolved from subcortical fight-flight mechanisms whereby approach behavior would entail attacking or thwarting an enemy in addition to the pursuit of foods and mates.

Whereas the presence of approach-avoidance behavior may be present across all organisms, its expression differs across species. One way in which motivational orientation is expressed in many vertebrate species is through cerebral lateralization. Indeed, approach-avoidance laterality effects are observed many species including in frogs (Rogers, 2002), toads (Lippolis et al., 2002), fish (Cantalupo et al., 1995), rats (Denenberg et al., 1978), and pigeons (Güntürkün et al., 2000). Indeed, cerebral lateralization appears to have functional significant across wide swaths of vertebrate species (Vallortigara et al., 1999).

In species with more of a cortex, the balance between activity in the left and right frontal cortex, commonly referred to as asymmetric frontal

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[1] Although many scientists define approach motivation as the urge to go toward desirable stimuli, Harmon-Jones et al. (2013) argued against including "desirable stimuli" in the definition based on much scientific evidence showing approach motivation in the absence of desirable stimuli.

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cortical activity, has served as a proxy for an organism's motivational orientation and the expression of approach-avoidance laterality effects. These laterality effects are presumed to have evolved to increase an organism's neural capacity and processing efficiency. These laterality patterns may prevent the simultaneous initiation of two antagonistic responses through inhibitory connections between the hemispheres (for review, see Schutter and Harmon-Jones, 2013; Vallortigara and Rogers, 2005). That is, cerebral lateralization would prevent an organism from simultaneously initiating an approach and avoidance response. Left-over-right and right-over-left frontal cortical activity patterns are related to contrasting motivation tendencies. Left-over-right dominance, or relative left frontal cortical activity, is associated with approach motivation, and right-over-left dominance, or relative right frontal activity, is associated with avoidance motivation. These patterns have been observed in a variety of organisms. For example, dogs demonstrate more exaggerated tail wagging toward the right in the presence of appetitive stimuli (e.g., their owners), whereas the presence of aversive stimuli (e.g., a dominant unfamiliar dog) elicits exaggerated tail wagging toward the left side. These behaviors are thought to recruit the left and right prefrontal cortex respectively (Quaranta et al., 2007). Similarly, dogs more quickly orient toward aversive stimuli (e.g., snakes) in the left hemifield and slower to resume approach-motivated behavior after seeing aversive stimuli in the left hemifield (e.g., Siniscalchi et al., 2010). Similar effects occur in marsupials (Lippolis et al., 2005).

Even stronger evidence comes from work on non-human primates. Anxiolytic drugs reduce anxious temperament and reduce relative right frontal asymmetry in rhesus monkeys (Kalin and Shelton, 1989; Davidson et al., 1992, 1993). Kalin et al. (1998) demonstrated that rhesus monkeys with greater relative right frontal activity also have greater cortisol concentrations. In contrast, monkeys with greater relative left frontal cortical activity showed reduced cortisol concentrations. These associations occurred at both one and three years of age. Moreover, greater relative right frontal activity was associated with greater defensive responses (e.g., freezing). This work on non-human primates highlights the role of greater relative right frontal activity in activating avoidance motivation and greater relative left frontal activity in reducing the activation of avoidance motivation.

Using electroencephalographic (EEG) recordings, researchers have linked relative left frontal cortical activity with trait approach motivation (Coan and Allen, 2003; Harmon-Jones and Allen, 1997; Sutton and Davidson, 1997) and with individual differences in approach-motivated emotions (Harmon-Jones and Allen, 1998; Tomarken et al., 1992). Similarly, relative right frontal cortical activity is associated with avoidance motivation (Coan et al., 2001; Dawson et al., 1992). In addition to individual difference variables, the temporary experience of approach-motivated emotion has been correlated with relative left frontal cortical activity (Harmon-Jones, 2007, 2002, 2006; Harmon-Jones and Sigelman, 2001). Likewise, state variation in avoidance-motivated emotion influences has been correlated with relative right frontal cortical activity. For example, Davidson et al. (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. Taken together, converging evidence suggests that greater relative left frontal cortical activity is associated with approach motivation, whereas greater relative right frontal cortical activity is associated with avoidance motivation.

2. Physical vs. psychological manipulations of asymmetric frontal cortical activity

Physical manipulations of asymmetric frontal cortical activity are those that manipulate some aspect of the physical body tied to asymmetric frontal cortical activity. Some of these manipulations are more peripheral (i.e., manipulations of the hands and face) whereas others are more direct (e.g., neuromodulation). These techniques are contrasted with psychological manipulations that induce asymmetric patterns via some emotional or cognitive manipulation. Because physical manipulations generally circumvent affect and cognition, they can allow researchers to make more precise statements about the relationship motivational orientation and asymmetrical frontal cortical activity than psychological manipulations. Thus, the purpose of this paper is to review the literature employing physical manipulations of frontal asymmetry. The techniques reviewed include: a) neurofeedback training, b) muscular contractions, c) transcranial direct current stimulation (tDCS), and d) transcranial magnetic stimulation (TMS).

3. Neurofeedback training and asymmetric frontal cortical activity

Early studies manipulating asymmetric frontal cortical activity used neurofeedback. EEG neurofeedback training typically pairs a visual or auditory cue with the online movement in frontal EEG asymmetry either leftward or rightward. Participants view or hear a cue indicating reward when frontal asymmetry shifts in the desired direction; in other words, operant conditioning is used to alter asymmetric frontal cortical activity. Neurofeedback training has successfully altered EEG asymmetry in non-clinical and clinical contexts. Rosenfeld et al. (1995) used a tonal neurofeedback paradigm with operant conditioning where participants were rewarded when their frontal alpha asymmetry shifted in the desired direction (toward relative left frontal activity). Hardman et al. (1997) used neurofeedback training and the presence versus absence of affective instructions to guide neurofeedback training. To alter frontal asymmetry via neurofeedback, participants viewed a computer screen with a centrally located rocket ship, which rose to indicate an increase in relative left frontal activity and fell to indicate an increase in relative right frontal activity. Regardless of the instructions given, participants shifted asymmetric frontal cortical activity in the desired direction.

In clinical contexts, neurofeedback training has been utilized in conjunction with therapy for both depression and anxiety. For example, Baehr et al. (1997) found that neurofeedback training to reduce relative right frontal activity reduced depressive symptoms in individuals previously diagnosed with unipolar depression. More recently, these effects have been replicated in a randomized clinical trial of depressed individuals (Choi et al., 2010). Similar results were obtained in a neurofeedback study that aimed to reduce relative right frontal activity in clinically anxious individuals (Kerson et al., 2009).

The evidence just reviewed suggests that changes in resting frontal asymmetry covary with changes in mood state in patients undergoing neurofeedback treatment for some affective disorders. However, this evidence is limited, as these clinical case studies often involved participants receiving treatments in addition to neurofeedback and no control groups. Moreover, most of the studies described above trained participants in only the direction hypothesized to be therapeutic (i.e., increasing relative left frontal activity) but never in the opposite direction; this leaves open the possibility that nonspecific aspects of the neurofeedback training protocol, and not its specific effects on cortical activation, were therapeutic.

Allen et al. (2001) sought to determine whether manipulation of frontal asymmetry was causally related to emotional responding. Specifically, they sought to determine whether EEG changes could be obtained in both directions: increasing right-versus-left alpha power, and decreasing right-versus-left alpha power. To determine whether alteration of frontal EEG asymmetry could change subsequent emotional responses, participants viewed emotionally evocative film clips after the conclusion of training and reported their affective responses to the films. In addition to measuring self-reported affective responses to films, the researchers recorded facial electromyographic (EMG) responses over the corrugator supercilii and zygomatic major muscle regions; these muscle regions are activated during frowning and smiling respectively (Larsen et al., 2003). Following past research (e.g., Rosenfeld et al., 1995), Allen and colleagues utilized a 5-day tonal neurofeedback protocol. Emotionally evocative film clips were viewed on the first and last day while EMG and EEG were recorded. Indeed, shifts in asymmetric frontal cortical activity were observed because of neurofeedback training. Moreover, neurofeedback training to increase relative left frontal activity caused participants to rate positive and neutral films as more positive. Additionally, neurofeedback training to increase relative right frontal activity caused less zygomatic muscular activity after training, whereas neurofeedback training to increase relative left frontal activity caused less corrugator activity. Thus, neurofeedback training that increased relative right frontal activity decreased zygomatic muscle region activity, which is often associated with positive affect; whereas neurofeedback training that increased relative left frontal activity decreased corrugator muscle activity, which is often associated with negative affect.

3.1. Interim summary: neurofeedback

The results of Allen et al.'s study combined with work on neurofeedback training for affective disorders suggests that neurofeedback training can be used to cause both left and right lateralized shifts in frontal EEG asymmetry. These shifts can cause changes in self-reported emotional states as well as modulate indices of emotional expressions. However, many of the early neurofeedback studies suffered from low sample sizes. For example, the studies by Rosenfeld et al. (1995) had eight participants in one experiment and five participants in a second experiment. An additional study by Baehr et al. (1997) offered two clinical case studies. However, subsequent studies found similar results using samples of 18 to 28 participants. Moreover, operant conditioning paradigms like neurofeedback exert large effects on animal behavior and 18 to 28 participants is sufficient to detect moderate effects.

4. Unilateral muscular contractions and asymmetric frontal cortical activity

Another body of research has used contractions of muscles on one side of the body to influence emotional and motivational outcomes. These changes in emotive outcomes via unilateral muscle contractions may occur because of activation of the contralateral hemisphere. That is, innervation of the hand and face is associated with contralateral cerebral hemispheric activation (Hellige, 1993; Rinn, 1984). The emotional and motivational outcomes produced by the contractions may result from the spread of activation to, or recruitment of, contralateral frontal areas (Schiff and Lamon, 1989, 1994). Research on mu rhythm, an EEG oscillation with dominant frequencies in the 8–13-Hz band, suggests that contraction of unilateral muscles is associated with activation of the contralateral motor cortex (Andrew and Pfurtscheller, 1997; Pineda, 2005). This motor cortex activation might spread to frontal areas, via cortico-cortical connections between the motor cortex and dorsolateral prefrontal cortex, and cause approach or avoidance motivations, depending on which hemisphere is activated by the unilateral movements. The experiments below had individuals unilaterally contract their faces or hands and assessed effects of these contractions on outcomes related to approach/avoidance motivation.

4.1. Unilateral facial muscular contractions

Schiff and Lamon (1989) developed a paradigm for assessing the influence of contralateral facial muscular contractions on the experience of emotion. In their work, participants were asked to pull back and lift one corner of their mouth and hold it until the experimenter told them to relax. This procedure lasted approximately 1 min (see Fig. 1). Participants were asked to pay attention to the emotional experiences that came across their mind during the facial contraction task, allow them to occur naturally, and then report those felt emotions after the facial contraction exercise. Then, they were asked to contract the other corner of their mouth and report on their emotional experience a second time. Results indicated that following contractions of the left side of the face, participants reported feeling sad or depressed and had a sad facial expression. In contrast, following contractions of the right side of the face, no participants reported feeling sad but did report feeling sarcastic, cocky, up, good, and smug. Additionally, when the right side contractions were conducted *after* left side contractions, participants reported the alleviation of sadness. In a second experiment, Schiff and Lamon (1989) asked independent judges to read transcripts of participants reporting on their emotional experience after completing the facial contraction task. All judges had previous experience completing the facial contraction task. They found that after reading a transcript, judges were able to accurately predict which type of facial contraction preceded that report. This suggests that in addition to influencing immediate self-reports of emotional experience, the effects of the manipulation appear to sensitive enough to be detected by outside observers. However, the results of Experiment 2 should be looked at with some skepticism because the judges had previous experience with the methodology and were not naïve observers. A third experiment conceptually replicated the results of Experiment 1. In it, participants were asked to write stories about ambiguous stimuli after making left or right facial contractions. After contractions of the left

Fig. 1. Appearance of the face when subject performs the unilateral facial muscular contraction manipulation. The right side contraction is depicted in panel A and the left side contraction in panel B. This figure is based off the figure shown in Schiff and Lamon (1989).

side of the face, participant's stories were significantly more negative than those written by participants who contracted the right side of the face.

Schiff et al. (1992) used the same experimental procedure and found that contractions of the left side of the face were more likely to cause participants to express negative stereotypes about various ethnic groups relative to those who made contractions of the right side of the face. Taken together, the work by Schiff and Lamon (1989) and that of Schiff et al. (1992) suggests that contracting the muscles in the lower portion of the face causes changes in emotional experience consistent with the activation of the contralateral cerebral hemisphere.

4.2. Unilateral hand contractions

In addition to facial musculature, unilateral hand contractions are related to approach/avoidance motivation. In one experiment, Schiff and Lamon (1994) demonstrated that contractions of the right hand induced self-reported positive affect, assertiveness, and positively biased perceptions and judgments. In another series of experiments, Schiff and Truchon (1993) found that left-hand contractions reduced positive response bias in face perception. Moreover, right-hand contractions also caused increased behavior persistence on an insolvable puzzle task (Schiff et al., 1998). Recently, Harlé and Sanfey (2015) found that right-hand contractions promote reward-maximizing behavior in the Ultimatum Game (UG; Güth et al., 1982) and the Dictator Game (DG; Kahneman et al., 1986, see Engel, 2011 for a review).

Harmon-Jones (2006) had participants make unilateral hand contractions while EEG was recorded to directly test the hypothesis that unilateral hand contractions cause shifts in frontal asymmetry (see Fig. 2). Participants completed the hand contraction procedure while EEG was recorded. Next, participants listened to a radio broadcast of a student describing places to live and reported their emotional reactions to the radio broadcast. Self-report emotion questions tapped approach positive affect (e.g., determined), anger, sadness, guilt, and happiness. Results indicated that right-hand contractions produced greater relative left frontal activity, whereas left-hand contractions produced greater relative right frontal activity. Moreover, as compared to left-hand contractions, right-hand contractions caused greater self-reported approach positive affect to the radio editorial but did not influence other emotional states.

Conceptually replicating this finding, Peterson et al. (2008) found that right-hand contractions caused greater left frontal activation and behavioral aggression as compared to left-hand contractions. Within the right-hand contraction condition, greater relative left frontal activity was associated with greater aggression. Peterson et al. (2011) also found the effect of unilateral hand contractions on asymmetric frontal cortical activity and found that right-hand contractions caused more self-reported anger in response to being socially ostracized.

4.3. Interim summary: unilateral muscle contractions

We reviewed two methods for manipulating asymmetry via muscular contractions: unilateral facial muscular contractions and unilateral hand contractions. Although both methods modulate outcomes consistent with shifts in frontal asymmetry, the results appear weaker for unilateral facial muscular contracts as compared to unilateral hand contractions. Moreover, the unilateral hand contracts effects have been replicated in several independent laboratories and the effects of those contractions on approach/avoidance behaviors are mediated by shifts in frontal asymmetry.

5. Unilateral forced nostril breathing

The nasal cycle was first described in the late 19th century and refers to the observation that in any given individual, at any given point in the day, one nostril is taking in significantly more air that the other. These periods of nostril dominance are cyclical and typically about 2–3 h (Kayser, 1895; Keuning, 1968) and appear to be caused by the hypothalamus (Malcomson, 1959; Eccles and Lee, 1981). Shannahoff-Khalsa (2007) suggests that the nasal cycle is an example of a broader pattern of endogenous daily rhythms where one branch of the autonomic nervous system dominates one-half of an organ and the other branch dominates the other half of that organ. Thus, the nasal cycle appears to represent one example on the antagonistic relationship between the two branches of the autonomic nervous system – the parasympathetic and sympathetic nervous systems (Craig, 2005).

Werntz et al. (1987) observed a link between the nasal cycle and frontal cortical activity using EEG. They found that during period of greater activity in the left cerebral hemisphere, right nostril dominance occurred. Similarly, during periods of greater activity in the right cerebral hemisphere, left nostril dominance occurred. Thus, cerebral activity appears to be associated with the nasal cycle in a contralateral fashion.

Similarly, Quinn (1998) predicted that the nasal cycle would be associated with asymmetric frontal cortical activity in a contralateral

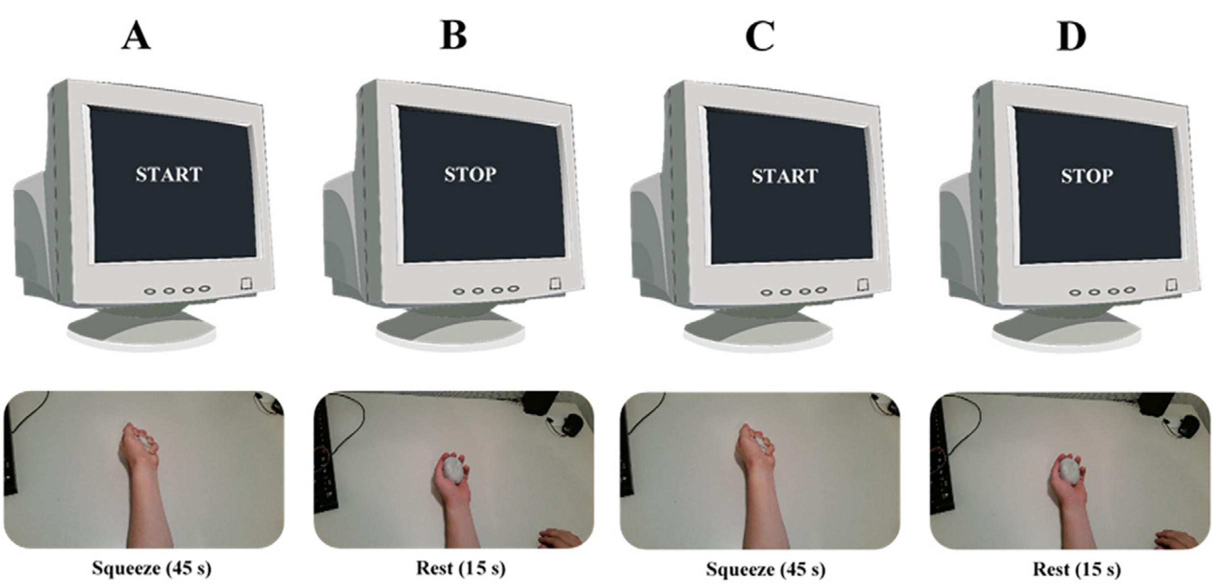

Fig. 2. Schematic diagram of unilateral hand contraction procedure used in Harmon-Jones (2006). Participants were asked to squeeze a ball as hard as they could for 45 s (A) then rest for 15 s (B), then another 45 s of squeezing (C) followed again by rest (D). A computer screen in front of the participant notified them when to start and stop squeezing the ball.

fashion. To test this hypothesis, Quinn first assessed nostril dominance by determining which nostril was exerting stronger airflow in participants. Next, he assessed asymmetric frontal cortical activity using EEG and asked participants to freely report their affective state. Results demonstrated the frontal asymmetry varied with the nasal cycle: participants with left nostril dominance showed reduced relative left frontal cortical activity and reduced positive affect, whereas those with right nostril dominance showed greater relative left frontal cortical activity and greater positive affect. Thus, nasal activity appears to be linked to EEG activity in a contralateral fashion.

Further support for links between nasal dominance and cortical activity comes from the study of uni-nostril yoga breathing. Singh et al. (2016) had experienced yoga practitioners' complete three different yoga-breathing exercises on three consecutive days: right nostril breathing, left nostril breathing, and breathe awareness, which served as a control condition. Participants inhaled for 6 s then exhaled for 9 s and repeated this pattern for 10 min. When participants were in the left nostril breathing condition, they were instructed to inhale and exhale exclusively out of their left nostril. Similarly, when they were in the right nostril breathing condition, they were instructed to inhale and exhale exclusively out of their right nostril. During the breath awareness condition, participants were instructed to breathe out of both nostrils and attend to the physical sensations of breathing. During each breathing condition, hemodynamic responses in the prefrontal cortex were recorded via functional near-infrared spectroscopy. Results indicated that right nostril breathing increased oxygenation and blood volume in the left prefrontal cortex, whereas left nostril breathing produced an opposite pattern.

Another manipulation of the nasal cycle, which does not require specialized training, is unilateral forced nostril breathing. This technique blocks airflow through one nostril and forces an individual to breathe through the other nostril. Werntz et al. (1987) demonstrated that unilateral forced nostril breathing is associated with increased contralateral EEG activity. Moreover, when forced breathing was changed to the other nostril, EEG activity shifted as well. As a result, unilateral forced nostril breathing can be used to assess the motivational consequences of frontal EEG asymmetry.

Schiff and Rump (1995) assessed the effects of a unilateral forced nostril-breathing paradigm on emotional responding. In order to induce nasal dominance, participants placed a moistened cottonball in one nostril, forcing them to breath exclusively out of the other nostril. Results revealed that when participants were forced to breathe through their left nostril (linked to right hemispheric dominance), they wrote significantly more negative propositions and reported more anxiety. When participants were forced to breathe through their right nostril (linked to left hemispheric dominance), participants reported feeling more positive, elated, calm, and happy. In summary, unilateral forced nostril breathing associated with relative right frontal activity caused more negative (avoidance-motivated) emotional reactions, whereas unilateral forced nostril breathing associated with relative left frontal activity caused more positive emotional reactions (some of which may be associated with approach motivation).

5.1. Interim summary: unilateral forced nostril breathing

Based on the observed links between cyclical variation in frontal brain activity and nasal dominance, research has suggested that manipulating the nasal cycle can cause corresponding shifts in approach-avoidance motivation and frontal asymmetry. Shifts in brain activity have been observed with EEG and functional near-infrared spectroscopy.

6. Transcranial direct current stimulation

Transcranial direct current stimulation (tDCS) is a noninvasive neuromodulation technique (Nitsche et al., 2008) that influences brain activity via a weak electrical current traveling between two electrodes fixed to the scalp causing subthreshold changes in membrane potentials, which in turn leads to bidirectional changes in cortical excitability (Nitsche and Paulus, 2000). The current in the brain flows from the positive, or anodal, electrode to the negative, or cathodal, electrode. Anodal stimulation increases cortical excitability and cathodal stimulation decreases cortical excitability (Nitsche and Paulus, 2000). By combining anodal and cathodal stimulation over the frontal cortex, tDCS is well suited for manipulating frontal asymmetry. With electrodes placed over the left and right prefrontal regions, tDCS can increase activation (i.e., anodal stimulation) in one hemisphere while decreasing activity (i.e., cathodal stimulation) in the other hemisphere. An increase in relative left frontal cortical activity is presumed to occur when the anodal electrode is placed over F3 (over the left dorsolateral prefrontal cortex) and the cathode electrode is placed over the F4 (over the right dorsolateral prefrontal cortex); an increase in relative right frontal cortical activity occurs when those parameters are reversed (cathode over F3/anode over F4). The experiments reported below utilized these stimulation parameters and assessed outcomes related to approach/avoidance motivation (See Fig. 3).

6.1. Anger and aggression

Anger and aggression are associated with the activation of the behavioral approach system (Harmon-Jones and Sigelman, 2001; Harmon-Jones, 2003). Using tDCS in laboratory aggression paradigms, several researchers have found additional support for a causal relationship between greater relative left frontal cortical activity and approach motivation. Hortensius et al. (2012) asked participants to write a short essay on a controversial topic (e.g., abortion) and then they received

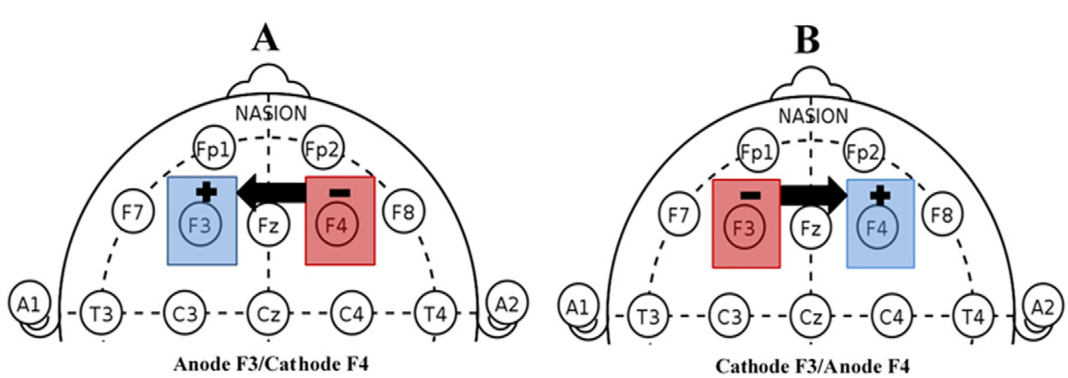

Fig. 3. Schematic diagram of transcranial direct current stimulation procedures used to manipulate frontal asymmetry. An increase in relative left frontal cortical activity is presumed to occur when the anodal electrode is placed over F3 and the cathode electrode is placed over the F4 prefrontal region (A). An increase in relative right frontal cortical activity occurs when cathode is placed over F3 and the anode is placed over F4 (B). The position of F3 and F4 is based on the 10-20 EEG system of measurement.

insulting feedback on their essay performance from another ostensibly real participant. After participants wrote the essay but before they received the insulting feedback, they received 15 min of tDCS in which they were randomly assigned to an increase in relative left frontal cortical excitability (anodal over F3/cathode over the F4), an increase in relative right frontal cortical excitability (cathode over F3/anode over F4), or sham stimulation. After tDCS, participants played a competitive reaction time game against the ostensible person who had insulted them. The game was based on the Taylor aggression paradigm (Taylor, 1967), which is a standard laboratory measure of aggression. Aggression was operationalized as the duration and intensity of a noxious noise blast given to the other participant. Participants also reported the level of felt anger pre- and post-insult. Results indicated that after receiving tDCS to increase relative left frontal cortical activity, individuals behaved more aggressively toward the other participant only when they were also high in insult-related anger. In other words, stimulation to increase relative left frontal activity strengthened the link between anger and aggression.

Dambacher et al. (2015) also used tDCS over the DLFPC with the Taylor Aggression Paradigm. They found that stimulation to increase relative right frontal activity reduced aggression. Taken together with the results of Hortensius et al. (2012), these results suggest that manipulating frontal asymmetry with tDCS can modulate aggressive behaviors in a manner consistent with previous correlational work linking aggression to frontal asymmetry. However, Dambacher and colleagues did not include a condition where relative left frontal activity was increased. Thus, they were unable to examine whether or not increased left frontal activity caused increased aggressive behavior, as was the case above, for angry individuals, in the study by Hortensius et al. (2012).

One important distinction between the studies of Dambacher and Hortensius is that the former found a main effect of tDCS on aggressive behavior whereas the latter did not. Rather the latter found a moderated pattern of results whereby anodal stimulation over the left DLPFC/cathodal stimulation over the right DLPFC caused increased aggression only for those high in insult-related anger. Dambacher's study included two experimental conditions whereas Hortensius study included three conditions. Moreover, another study (Dambacher et al., 2015b) did not find an effect of stimulation condition on aggressive behavior. Although this study did include all three stimulation conditions as in Hortensius et al. (2012) study, stimulation occurred over the F7/F8 prefrontal regions, whereas Hortensius et al. (2012) and Dambacher et al. (2015) stimulated over the F3/F4 prefrontal regions. Thus, methodological differences preclude a direct comparison of these studies. Despite modest support for the effect of asymmetrical frontal cortical activity on aggressive behavior, further high-powered research is needed.

Aggression is one possible response to anger-evoking situations. Another possible response to anger-evoking situations is rumination, an automatic cognitive process in which thoughts are repetitious and difficult to inhibit associated with a passive focus on the symptoms of distress (Nolen-Hoeksema, 1991, 2000; Wade et al., 2008). This rumination response may be more likely to occur when persons are unwilling or unable to aggress toward a target. Using the same stimulation parameters and writing task as Hortensius et al. (2012), Kelley et al. (2013) measured rumination after an interpersonal insult that lacked an expected opportunity for aggression. Results indicated that after receiving stimulation to increase relative right frontal cortical activity (cathode over F3/anode over F4), participants reported significantly more ruminative thoughts on a thought-listing procedure and scored higher on a self-report measure of state rumination. These studies suggest that a manipulated increase in relative left frontal cortical activity increases anger-driven aggression, whereas an increase in relative right frontal cortical activity decreases aggression and increases rumination.

6.2. Jealousy

In addition to anger, jealousy is another approach-motivated emotion that has been studied in the context of asymmetrical frontal cortical activity (Harmon-Jones et al., 2009). The emotions associated with and perhaps underlying jealousy are debated, though many emotion scientists posit that jealousy involves anger, fear, and sadness (Sharpsteen, 1991). The research that examined asymmetric frontal cortical activity and jealousy used a modified version of the Cyberball paradigm – a virtual ball-tossing game in which the participant tosses a virtual ball with two other ostensible individuals (Williams, 2007). In this modified version, participants first chose a partner from a group of images of eight opposite-sex individuals. The third Cyberball player was assigned by the experimenter and was always the same sex as the participant. Harmon-Jones et al. (2009) found that this paradigm evoked jealousy.[2] In a second experiment, they found that self-reported jealousy after being excluded by a desired partner correlated with relative left frontal cortical activity.

Kelley et al. (2015) extended this research by using tDCS to manipulate asymmetric frontal cortical activity. After participants chose a partner in the modified Cyberball paradigm and played a practice version of the game, participants received 15 min of tDCS in which they were randomly assigned to an increase in relative left frontal cortical activity (anodal over F3/cathode over the F4), and increase in relative right frontal cortical activity (cathode over F3/anode over F4) or sham stimulation. They found that stimulation to increase relative left frontal cortical activity increased self-reported jealousy. Because the direct manipulation of cortical excitability with tDCS produced the same outcome as the correlational finding of Harmon-Jones et al. (2009), this suggests that tDCS over the dorsolateral prefrontal cortex does indeed modulate emotive responses associated with asymmetric frontal cortical activity.

6.3. Risky decision-making

According to an asymmetric inhibition model of frontal asymmetry (Grimshaw and Carmel, 2014; Kinsbourne, 1974; Silberman and Weingartner, 1986), cortical activations for approach and avoidance motivation are antagonists. In addition to increasing approach motivation, increased relative left frontal activity inhibits avoidance motivation. Increased relative right frontal activity facilitates avoidance motivation while inhibiting approach motivation. Several experiments using tDCS have found evidence supporting half of this model – the inhibition of the approach motivational system via increased right frontal excitability.

For example, Fecteau et al. (2007) used tDCS to manipulate asymmetric frontal brain activity while individuals performed a risk task (Rogers et al., 1999). In the task, participants were presented with 100 trials, which occurred as follows: participants viewed 6 horizontal boxes; some boxes were blue and some were pink; and the ratio of blue to pink boxes varied from trial to trial. Participants were to indicate which color box contained a token. Participants were rewarded for selecting the correct color box and penalized for selecting the incorrect color box. Larger rewards were always paired with riskier decision-making (e.g., selecting a pink box when it only has a 1/6 chance of containing the token). Results indicated that tDCS that increased relative right frontal cortical activity (cathode over F3/anode over F4) caused participants to earn more points on this task. Results also indicated that the increase in relative right frontal activity caused a decrease in risk-taking on the task. Specifically, these participants were more likely to select safer, less risky choices suggesting that a manipulated increase in relative right frontal activity made participants less tempted by larger, less likely rewards.

6.4. Food craving and caloric ingestion

Another way in which tDCS has been used to study the motivational consequences of frontal asymmetry has been in regards to food craving

[2] Jealousy in Experiment 1 was positively associated with anger, negatively with feelings of inclusion, belonging, control, and meaningful existence. In Experiment 2, relative left frontal cortical activity was also associated with greater anger and lower feelings of inclusion.

and caloric ingestion. Fregni et al. (2008) manipulated frontal asymmetry with tDCS and included several measures of food craving. Self-report measures of food craving and craving in response to food in the laboratory were assessed before and after tDCS. Additionally, after tDCS, participants completed an image-viewing task in which their gaze patterns were recorded while they viewed an array of nature scenes and images of tempting foods (e.g., desserts). Finally, participants were given the opportunity to ingest foods and the number of calories ingested was recorded. Results indicated that a manipulated increase in relative right frontal cortical activity (cathode over F3/anode over F4) decreased food cravings, decreased visual attention toward tempting desserts, and decreased caloric consumption relative to a manipulated increase in relative left frontal cortical activity and sham stimulation.

Goldman et al. (2011) conduced a similar experiment in a group of healthy individuals with frequent food cravings. Participants viewed food images from the International Affective Picture System (IAPS; Lang et al., 2008) before and after tDCS. Additionally, after stimulation, participants were free to eat a variety of tempting foods: chips, cookies, chocolate, and donuts. Consistent with the work of Fregni et al. (2008), Goldman and colleagues found that a manipulated increase in relative right frontal activity (cathode over F3/anode over F4) decreased food cravings, notably for sweets. However, unlike Fregni et al., Goldman et al. did not find that the effects of tDCS on craving extended to actual consumption. Taken together, these studies suggest that manipulated increases in relative right frontal cortical activity reduces approach motivation.

6.5. Fear memory

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) used 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 enhances the consolidation of fear memories, which lends support to the hypothesis that right frontal cortical activity increases avoidance motivation. However, this study did not use stimulation procedures that would produce an asymmetric pattern of activity (i.e., it did not simultaneously provide anodal stimulation to the right dorsolateral prefrontal cortex and cathodal stimulation to the left dorsolateral prefrontal cortex).

6.6. Interim summary: transcranial direct current stimulation

The results of the tDCS experiments reported above provide modest support for the role of lateralized patterns of frontal brain activity in approach/avoidance responses. These experiments suggest that a manipulated increase in relative left frontal cortical activity increases approach-motivated responses (e.g., aggression, jealousy), whereas a manipulated increase in relative right frontal cortical activity decreases approach-motivated responding and increases avoidance motivated responding. One weakness of these tDCS studies is that they did not measure concurrent brain function. Thus it is unknown whether certainty that asymmetric patterns were induced. Future tDCS studies that measure brain functioning are a critical direction for future research.

7. Transcranial magnetic stimulation

Transcranial magnetic stimulation (TMS) is another neuromodulatory technique that has been used to gain insight into the casual role of asymmetric frontal cortical activity on approach and avoidance motivation. TMS is a noninvasive technique that is capable manipulating cortical activity by applying magnetic pulses to the scalp (Hallett, 2000). When electrical pulses are slowly and repetitively applied unilaterally to one hemisphere, TMS is thought to induce some neuromodulatory effect in the contralateral hemisphere (Wagner et al., 2007; Fecteau et al., 2007; for a review, see Schutter et al., 2004). When pulses are applied over the right prefrontal cortex, shifts toward left frontal activity and corresponding increases in approach-motivated behavior are thought to occur. Likewise, when pulses are applied over the left prefrontal cortex, shifts toward right frontal activity and corresponding increases in avoidance motivation are thought to occur (e.g., Veniero et al., 2011). Thus, rTMS applied to the one hemisphere of the dorsolateral prefrontal cortex may also induce asymmetric patters of frontal cortical activity.

In support of this viewpoint, and in accord with the tDCS work reviewed above, dampening activity the right dorsolateral prefrontal cortex (viz. increasing left frontal activity) increases approach motivation, whereas disruption of the left dorsolateral prefrontal cortex (viz. increasing right frontal activity) reduces approach motivation and in some cases increases avoidance motivation. For example, George et al. (1996) found that positive affect was increased by TMS over the right prefrontal cortex, whereas sadness was increased by TMS over the left prefrontal cortex. These results provide initial support for the idea that TMS to inhibit the right prefrontal cortex increases approach motivation, whereas TMS to inhibit the left prefrontal cortex increases avoidance motivation.

Several additional TMS studies have found support for the frontal asymmetry model of motivational orientation by demonstrating shifts to more approach motivation or away from avoidance-related behavior after applying slow inhibitory repetitive TMS over the right frontal cortex. For example, Schutter et al. (2001) found evidence of leftward shifts in frontal asymmetry and reduced anxiety after TMS to the right prefrontal cortex. Further support for the hypothesis that TMS over the right prefrontal cortex reduces avoidance motivation comes from a study of motivated attention (van Honk et al., 2002). In this study, TMS occurred over the right prefrontal cortex, and participants completed an emotional Stroop task in which they vocalized the color of emotional faces while ignoring the emotional content of the faces. The critical dependent measure was attentional bias toward fearful faces (i.e., the mean individual color-naming latencies of fearful faces minus the individual mean color-naming latencies on neutral faces). Results indicated that participants who received TMS over the right prefrontal cortex has reduced attentional bias toward fearful faces, consistent with the interpretation of relative left frontal activity being associated with increased approach motivation or decreased avoidance motivation.

Additional research supporting this viewpoint comes from TMS research on anger. Anger is most often associated with approach motivation (Carver and Harmon-Jones, 2009a,b). Using a similar TMS and Stroop paradigm, increased selective attention angry faces was found after TMS to disrupt right prefrontal cortical activity, whereas TMS to disrupt the left prefrontal cortex caused a decreased attentional bias toward angry faces (d'Alfonso et al., 2000).

Consistent with the tDCS studies on risk taking reported above, rTMS to modulate frontal asymmetry causes similar shifts in risk taking behavior. For example, Knoch et al. (2006a) used rTMS over the dorsolateral prefrontal cortex with the same risk task reported above (Rogers et al., 1999). There results were complementary, such that individuals displayed significantly riskier decision-making after disruption of the right dorsolateral prefrontal cortex (inducing relative left frontal activity), but not disruption of the left dorsolateral prefrontal cortex (inducing relative right frontal activity).

Similar disruptions of the right dorsolateral prefrontal cortex also promote reward-maximizing behavior in an ultimatum game (Knoch et al., 2006b). This result is also consistent with work finding that hand contraction to increase relative left frontal activity produce similar results on the ultimatum game (e.g., Harlé and Sanfey, 2015). Moreover, rTMS to right but not left dorsolateral prefrontal cortex reduced cocaine cravings in a sample of cocaine addicts (Camprodon et al., 2007).

In sum, targeted manipulations of the prefrontal cortex with TMS influence approach and avoidance orientation where disruptions of the right dorsolateral prefrontal cortex cause greater activation of the approach system and disruptions of the left dorsolateral prefrontal cortex cause reduced activation of the approach system. These TMS studies modulate motivation and asymmetry in a manner consistent with the tDCS studies reported previously.

8. The treatment of major depressive disorder with non-invasive brain stimulation

According to the Diagnostic and Statistical Manual of Mental Disorders (4th ed.; DSM–IV; American Psychiatric Association, 2000), depressive disorder is a mood disorder characterized by a loss of interest or pleasure in daily activities for more than two weeks. The specific symptoms associated with depressive disorder include lack of initiative, rumination, loss of energy, anxiety, feelings of guilt and worthlessness. These symptoms can be partially explained by reduced reward and increased punishment sensitivity. This translates to diminished approach and elevated avoidance orientation. In agreement with asymmetric frontal cortical activity, meta-analyses of randomized controlled trials have demonstrated that 'boosting' excitability of the left frontal cortex with either high frequency rTMS or anodal tDCS improves depressive symptoms (Schutter, 2009; Brunoni et al., 2016). Also, dampening of excitability of the right frontal cortex with rTMS decreases depressive severity in patients (Schutter, 2010).

These results are in line with the frontal cortical conceptualization of approach and avoidance orientation. Taken together, clinical studies on transcranial brain stimulation and depression support the frontal cortical lateralization of approach and avoidance orientation.

9. Remaining issues and future research directions

In this last section, we consider some remaining conceptual and methodological issues. We also discuss some possible future research directions.

9.1. What are the underlying mechanisms driving the relationship between asymmetric frontal cortical activity and approach/avoidance motivation?

One 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 thus crucial for interhemispheric communication. Researchers have suggested that the corpus callosum may play a role in the lateralization of motivational orientation in the prefrontal cortex (Schutter and Harmon-Jones, 2013). For example, Hofman and Schutter (2009) used a callosal brain stimulation paradigm and measured visual attention toward angry faces, which is associated with relative left frontal cortical activity. They found that higher levels of interhemispheric signal transmission from the right to the left side of the brain correlates with increased attention toward angry faces. Based on this evidence, approach-avoidance patterns of responding may be driven by an increase in interhemispheric signal transmission toward the right side (in the case of avoidance motivation) or toward the left (in the case of approach motivation). Future work using tDCS with neuroimaging techniques should test this possibility.

9.2. Functional neuroimaging and asymmetric frontal cortical activity

Functional MRI studies do not offer particularly strong support for the link between approach-avoidance motivation and asymmetric frontal cortical activity (Tomarken and Zald, 2009). One potential reason for this is the difference in body posture. While EEG experiments are typically conducted with participants sitting upright, fMRI experiments are typically conducted with participants lying in a supine position. This is important because several experiments have demonstrated that manipulations of body positions influence asymmetric frontal cortical activity such that being in a supine posture reduces approach motivation and decreases relative left frontal cortical asymmetry (Harmon-Jones and Peterson, 2009; Price and Harmon-Jones, 2010; Harmon-Jones et al., 2011; Price et al., 2012). Magnetoencephalography (MEG) is a neuroimaging technique that has good spatial and temporal resolution and like EEG uses an upright position. One MEG experiment found an association between left frontal asymmetry and trait approach motivation (Hwang et al., 2008) which suggests that the lack of asymmetry effects in fMRI research may be due in part to the supine body position.

Another reason fMRI studies may not find results consistent with the EEG literature is that fMRI may be measuring different neuronal activity than that targeted by electrical measures and manipulations. For example, the EEG signal is largely independent of action potentials in the underlying cortex whereas the hemodynamic response measured by MRI is heavily dependent on action potentials in the underlying cortex. In addition, cortical stellate cells are effectively undetected by the EEG signal but significantly contribute to metabolic activity in the cortex and thus to the hemodynamic response (for a review, see Carver and Harmon-Jones, 2009a,b).

9.3. Sample size and reproducibility

Some readers might be concerned about some of the studies reviewed because they had small sample sizes and small effects (e.g., Schiff and Lamon, 1989). We agree that concerns with sample sizes and effect sizes are important factors contributing to the replicability of effects. It is important to note that many of the early studies provided inspiration for later studies that did conceptually replicate the effects and extended them by providing evidence of an underlying mechanism. For instance, some of the Schiff and colleagues' studies that utilized unilateral body contractions were conceptually replicated in other research that revealed that asymmetric frontal cortical activity contributed to the effects of unilateral body contractions on emotive outcomes (e.g., Harmon-Jones, 2006; Peterson et al., 2008). Conceptual replications such as these provide strong evidence in support of a phenomenon (Murayama et al., 2014).

However, some published research has failed to replicate the early Schiff results (e.g., Kop et al., 1991). Before concluding that the effects obtained in these studies by Schiff and colleagues as well as other studies are not "real," it is important to consider a few things. Consider the data simulation by Geoff Cumming on the dance of the p values (https://www.youtube.com/watch?v=5OL1RqHrZQ8). In this simulation, he begins with a large dataset he created that has two (normally distributed) experimental conditions that differ from each other with an effect size d of 0.50. Then, he randomly selects 32 cases from each condition in this data set and performs a simple t-test comparison of the two conditions. He finds over repeated tests of this random selection from the larger dataset and t-test comparisons that the difference is clearly not significant by conventional standards ($p > 0.10$) over 35% of the time. In other words, even with a moderately strong effect size in the population, individual experiments may fail to demonstrate or replicate a difference between two conditions one out of three times. This situation is much more complex for experiments with many more conditions.

In addition, methods such as unilateral body contractions and facial contractions use subtle and relatively weak manipulations to test important theoretical principles. Because of the subtly and weakness of the manipulations, any number of other uncontrolled variables in the situation could cause a failure to replicate. Compare this situation to a biology lab trying to grow a particular type of mushrooms. Mushrooms of this type have been found to grow before. The original lab had perfect temperature, relative humidity, light, growth medium, and air flow for growing this type of mushroom (different varieties of mushrooms require different conditions; Miles and Chang, 2004). Moreover, the lab environment was controlled so that airborne microorganisms could not contaminate the mushrooms. If any of these delicate conditions were not present in subsequent replications, the lab would likely fail to produce mushrooms. In fact, often the mushrooms will not grow at all if the incorrect conditions are present (e.g., microorganisms can overwhelm the environment and prevent mushrooms from growing). The same considerations should be given to psychological experiments. Humans are more complex than mushrooms and subtle manipulations such as unilateral body contractions and facial contractions are perhaps even more likely to be overwhelmed by extraneous variables or contaminates. Achieving such sterile conditions in a human psychological lab may be quite difficult. Participants and experimenters come to the lab in a variety of affective and cognitive states. If, for example, a participant is worried about an upcoming exam, it seems unlikely that the subtle affective manipulation would override the participant's concerns about the exam and influence the dependent variable. Likewise, an experimenter worried about a similar exam may induce anxiety in the participants, which would override the subtle affective manipulations. Thus, the wildering array of possible contaminates may exert non-systematic influences and indeed overwhelm any affective outcomes of a subtle emotion manipulation in the lab.

Nevertheless, issues with reproducibility exist in science and are not historical artifacts. Researchers can find support for their hypotheses in many ways including (but not limited to) post-hoc exclusion criteria, changing one's hypotheses after examining the data, and computing dependent variables in multiple ways. For these reasons, we believe that both direct and conceptual replications are important and have evidentiary value. Moving forward researchers using manipulations of asymmetry should employ both high-powered direct replications and conceptual replications/extensions while taking care to create “sterile” environments in which to test the subtle effects. We would also encourage researchers to pre-register their hypotheses and data analysis plan in a manner that encourages open and reproducible science.

10. Implications for the asymmetric inhibition model of frontal asymmetry

In next section we evaluate how well each of the physical manipulations of asymmetric frontal cortical activity tests and supports the asymmetric inhibition model of frontal asymmetry. According to an asymmetric inhibition model of frontal asymmetry (Grimshaw and Carmel, 2014; see also Kinsbourne, 1974; Schutter and Harmon-Jones, 2013; Silberman and Weingartner, 1986), cortical systems for approach and avoidance motivation are antagonists. In to this model, increased relative left frontal activity increases approach motivation and inhibits avoidance motivation. In contrast, increased relative right frontal activity increases avoidance motivation and inhibits approach motivation. The evidence reviewed above supports this model.

Neurofeedback studies to boost left frontal asymmetry increase positive affective reactions to films, whereas reducing right frontal asymmetry decreases depression and anxiety in clinical populations. These studies demonstrate support for two parts of the asymmetric inhibition model: an increase in approach motivation and a decrease in avoidance motivation via an increase in left frontal asymmetry. However, the neurofeedback studies have not tested the effects of an increase in right frontal asymmetry on elevated avoidance motivation.

Unilateral facial muscular contraction studies provide weaker support for the asymmetric inhibition model of frontal asymmetry. Schiff and Lamon (1989) found that following contractions of the left side of the face (corresponding to increased right frontal asymmetry), participants reported feeling sad or depressed and were observed to have sad facial expressions. Moreover, when asked to write stories about ambiguous stimuli, their stories were significantly more negative. In contrast, following contractions of the right side of the face, participants reported feeling sarcastic, cocky, up, good, and smug. Schiff et al. (1992) found that contractions of the left side of the face caused participants to express stereotypes that are more negative about various ethnic groups relative to those who made contractions of the right side of the face. These results modest support increased right frontal asymmetry increasing avoidance motivation but provide weak support or do not test the other parts of the model.

Unilateral hand contraction studies demonstrate stronger support for part of the asymmetric inhibition model: increased left frontal asymmetry increases approach motivation. Results indicated that right-hand contractions produced greater relative left frontal activity and greater self-reported high approach positive affect (Harmon-Jones, 2006), anger (Peterson et al., 2011), and behavioral aggression (Peterson et al., 2008). Other studies found that right-hand contractions increased positive affect and assertiveness (Schiff and Lamon, 1994), behavioral persistence (Schiff et al., 1998), and reward maximizing behavior (Harlé and Sanfey, 2015). In addition, Schiff and Truchon (1993) found that left-hand contractions reduced positive response bias in face perception. Taken together these studies provide strong support for increased left frontal asymmetry increasing approach motivation but did not attempt to test the other parts of the asymmetric inhibition model.

Experiments using tDCS and TMS have demonstrated the strongest support for the asymmetric inhibition model. First, these neuromodulation studies support the activation of the approach motivational system via increased left frontal excitability. Increased anger, jealousy, and aggression support this viewpoint insofar as anger, jealousy, and aggression are approach motivated. Other experiments using tDCS and TMS demonstrated evidence-supporting inhibition of approach motivation system via increased right frontal excitability. In support, increased right frontal excitability decreases food cravings, caloric ingestion, and risky decision-making. In support of the activation of avoidance motivation via increased right frontal excitability, increased fear memory consolidation and rumination have been observed. The results of the neuromodulation studies show support 3 of the 4 components of the asymmetric inhibition model - activation of approach via increased left frontal excitability, inhibition of approach via increased right frontal excitability, activation of avoidance via increased right frontal excitability. These studies did not attempt to test inhibition of avoidance via increased left frontal excitability.

11. Implications for the behavioral activation-behavioral inhibition model of frontal asymmetry

In contrast to the asymmetric inhibition model (otherwise known as the motivational direction model), the behavioral activation-behavioral inhibition model of frontal asymmetry (BBMAA; Wacker et al., 2003; Wacker et al., 2008) makes a different set of predictions regarding the relationship between motivation and frontal EEG asymmetry. Inspired by the revised reinforcement sensitivity theory (Gray and McNaughton, 2000), the BBMAA argues, like the motivational direction model, that left frontal asymmetry is associated with behavioral activation. Unlike the motivational direction model, this alternative model argues that this goal-directed, behavioral activation can be the inspired by either approach or avoidance motivated. This could be due to avoidance being transformed into approach. For example, when running from a predator avoidance motivation may transform into approach toward sources of safety. Further, the behavioral activation-behavioral inhibition model links right frontal asymmetry to goal conflict or inhibition whereas the motivational direction model links right frontal asymmetry to withdrawal motivation.

In support of the motivational direction model but not the behavioral activation-behavioral inhibition model, right frontal asymmetry at rest has been linked to fear behaviors in rhesus monkeys (Kalin et al., 1998), crying in response to maternal separation in human infants (e.g., Davidson and Fox, 1989), and disgust in human adults (e.g., Davidson et al., 1990). Consistent with these results and as reviewed previously, Mungee et al. (2014) found evidence of greater fear memory consolidation following stimulation of the right DLPFC. Taken together these studies lend support to the motivational direction model and are difficult to interpret through the lens of the BBMAA.

Despite this, correlational studies support the behavioral activation-behavioral inhibition model of frontal asymmetry. Wacker et al. (2003) asked soccer players to read about an anger inducing or fear inducing situation. Critically, for the anger prompts, the protagonist either confronted a coach who insulted him (anger-approach) or left the room post-provocation (anger-withdrawal). Likewise, fear prompts describe a situation where the protagonist is afraid of missing a scoring opportunity and attempts to score the goal (fear-approach) or passes the ball to another player (fear-withdrawal). Thus, this experiment crossed emotion with motivation and allows for the test the motivational direction and BBMAA models. They found that anger was associated with left frontal asymmetry regardless of motivational direction, consistent with both models. Additionally, greater negative valence ratings were associated with greater left frontal asymmetry for the fear-withdrawal and with right frontal asymmetry for fear-approach. Wacker et al. (2010) found that shifts toward right frontal asymmetry were associated with behavioral inhibition sensitivity during the No-Go trials on Go/No-Go task. Ravaja et al. (2016) found evidence of elevated right frontal asymmetry in approach-approach goal conflicts. Taken together these studies provide modest support for the BBMAA model.

However, inconclusive support for either model comes from studies linking frontal asymmetry to individual differences in anger expression. Hewig et al. (2004) found that left frontal asymmetry was associated with elevated anger-out, an index of approach motivation, but not anger-in, an index of avoidance motivation. In contrast, Stewart et al. (2008) found that trait anger was associated with left frontal asymmetry regardless of the motivational underpinnings of that anger (i.e., collapsed across anger-in [withdrawal] and anger-out [approach]). As Wacker et al. (2008) note, many findings in the frontal asymmetry literature would be predicted by both models. Indeed, many results discussed in this review can be accounted for by both models. For example, an increase in approach motivation after a manipulated increase in left frontal asymmetry can be accounted for by both models as can a decrease in approach motivation after a manipulated increase in right frontal asymmetry.

While evidence supports both models and many results can be accounted for by both models, a few experiments have attempted to test these two theoretical models against one another. In one experiment, Kelley and Schmeichel (2016) tested whether a manipulated increase in right frontal asymmetry reflects increased inhibition or avoidance motivation. To do this, they administered tDCS over the DLPFC and then used a joystick task in which participants either pushed away appetitive images or pulled aversive images toward themselves. If right frontal asymmetry underlies avoidance motivation, then in Kelley and Schmeichel's experiment the manipulation to increase right frontal asymmetry would have strengthened the impulse to move away from aversive stimuli and caused participants to be slower to enact the motive-incongruent response. If right frontal asymmetry underlies inhibition, then the manipulation would have caused participants to be faster to enact the motive-incongruent responses. Results were consistent with the behavioral activation-behavioral inhibition model, as stimulation to increase right frontal asymmetry caused participants to move toward aversive images more quickly. In further support of the view that right frontal asymmetry enables inhibition, results also indicated that tDCS to increase right frontal asymmetry facilitated responses that were incongruent with approach-motivated impulses. Although this evidence is more consistent with the BBMAA model, this experiment offered an incomplete test because it did not include a condition in which participants were asked to push aversive stimuli away from their bodies. It is also important to note that the right frontal cortical region may be involved in both inhibition and withdrawal motivation, and that specific sub-regions are involved in these discrete psychological processes.

12. Conclusion

Frontal cortical asymmetry has served as a proxy for approach and avoidance motivation. The role of frontal cortical asymmetry has been investigated at the crossroads of neuroscience, clinical psychology, and experimental psychology for the better part of three decades. Much of this work has been correlational in nature. As reviewed above, the means to manipulate frontal asymmetry exist including manipulations of the body and breathing patterns as well as direct manipulations of the cortex using tDCS and rTMS. This body of work allows us to make stronger causal inferences regarding the role of asymmetric frontal cortical activity in approach and avoidance motivation.

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