Transcranial Direct Current Stimulation of the Motor Cortex Biases Action Choice in a Perceptual Decision Task

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Abstract

■ One of the multiple interacting systems involved in the selection and execution of voluntary actions is the primary motor cortex (PMC). We aimed to investigate whether the transcranial direct current stimulation (tDCS) of this area can modulate hand choice. A perceptual decision-making task was administered. Participants were asked to classify rectangles with different height-to-width ratios into horizontal and vertical rectangles using their right and left index fingers while their PMC was stimulated either bilaterally or unilaterally. Two experiments were conducted with different stimulation conditions: the first experiment ($n = 12$) had only one stimulation condition (bilateral stimulation), and the second experiment ($n = 45$) had three stimulation conditions (bilateral, anodal unilateral, and cathodal unilateral stimulations). The second experiment was designed to confirm the results of the first experiment and to further investigate the effects of anodal and cathodal stimulations alone in the observed effects. Each participant took part in two sessions. The laterality of stimulation was reversed over the two sessions. Our results showed that anodal stimulation of the PMC biases participants' responses toward using the contralateral hand whereas cathodal stimulation biases responses toward the ipsilateral hand. Brain stimulation also modulated the RT of the left hand in all stimulation conditions: Responses were faster when the response bias was in favor of the left hand and slower when the response bias was against it. We propose two possible explanations for these findings: the perceptual bias account (bottom–up effects of stimulation on perception) and the motor-choice bias account (top–down modulation of the decision-making system by facilitation of response in one hand over the other). We conclude that motor responses and the choice of hand can be modulated using tDCS. ■

INTRODUCTION

It is well known that the primary motor cortex (PMC) is involved in the execution of motor actions. Single cell recording and intracranial stimulation studies have demonstrated how neuronal activity and changes in regional firing rates within the motor cortices can create simple or complex movements that involve groups of muscles or individual muscles in isolation. Kakei, Hoffman, and Strick (1999) recorded the activity of neurons in the PMC of monkeys. Their results revealed two subsets of neurons coding for muscles and movements, respectively. In another study, Graziano, Taylor, and Moore (2002) showed that microstimulation of the primate PMC and premotor areas evoked complex movements that involved many muscles. The activity of single neurons in the motor cortex of freely moving monkeys was investigated by Aflalo and Graziano (2007). Using a computational modeling approach, they showed that the final multijoint posture of the animal's arm could be explained by a third of the recorded cortical activity. Using electrical microstimulation, Overduin, d'Avella, Carmena, and Bizzi (2012) stimulated motor cortical areas of rhesus macaques to evoke hand movements. Their results showed that induced movements tend to converge toward particular postures. These studies demonstrate that stimulation of parts of the motor cortex not only activates individual muscles in isolation but can also activate sets of muscles for specific behaviors or a final posture.

Although the PMC is mostly associated with its role in signal generation for the control of movement execution or muscle control, other studies have revealed its possible involvement in cognitive processes such as motor learning and memory storage for motor actions (Sanes & Donoghue, 2000), and perceptual decision-making (Romo & de Lafuente, 2013). Salinas and Romo (1998) recorded the activity of primary motor neurons in monkeys. Monkeys were required to categorize the speed of tactile stimuli as either low or high and respond using their left or right hand. Extracellular recordings revealed that a proportion of the neurons responded to the speed of the stimuli and that their response was specific to the vibrotactile sensory input in a flutter discrimination task (Romo & Salinas, 2003). Similar results have also been shown for visual stimuli. Merchant, Battaglia-Mayer, and Georgopoulos (2001) showed eight different kinds of moving visual stimuli to monkeys while recording from the arm area of their motor cortex and area 7a (an area

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in the posterior parietal lobe). Their results showed that activity of the neurons was significantly modulated by the visual stimuli. Additionally, these two areas responded differently to the location and motion of the stimuli. Although area 7a was mostly modulated by the location of the stimuli, the motor cortex was mostly modulated by the motion (Mendoza & Merchant, 2014).

Although single cell recordings and intracranial stimulation of the motor cortex in primates provides a rich understanding of its function, the results from brain stimulation studies in humans are scarce. Only a handful of brain stimulation studies have investigated the contribution of the PMC to motor behaviors in humans. Ammon and Gandevia (1990) were the first to show that TMS can affect higher level motor planning. Their participants were required to extend either the left or right index finger in a forced-choice paradigm after hearing a click. They found that single pulse TMS could influence participants' responses toward or away from the laterality of the stimulation depending on the stimulation protocol. In a similar vein, Brasil-Neto, Pascual-Leone, Valls-Sole, Cohen, and Hallett (1992) reported that participants' hand response preferences were biased toward the hand contralateral to the site of stimulation of motor cortices. Sohn, Kaelin-Lang, and Hallett (2003) argued that previous studies were biased because participants could anticipate the site of stimulation. Therefore, they ran a study in which they stimulated both left and right lateralities with two separate coils. Contrary to the previous findings, their results showed no bias in the response. In a more recent study, Oliveira, Diedrichsen, Verstynen, Duque, and Ivry (2010) showed that stimulation of the left posterior parietal cortex (PPC) biases the choice of hand used for reaching toward the left hand. Stimulation of the right PPC, however, did not alter responses. In addition to further control for anticipation of effect, they stimulated left or right anterior parietal cortex. Stimulation of these sites showed no significant modulation of response bias.

In the current study, we aimed to produce a bias by stimulating the motor cortex using transcranial direct current stimulation (tDCS; Nitsche & Paulus, 2000). It has been shown that anodal and cathodal stimulation of the motor cortex can lead to excitation and inhibition of neurons, respectively (Nitsche & Paulus, 2001). This method has been demonstrated to modulate a range of behaviors, including perception, cognition, motor function, and learning (Bestmann, de Berker, & Bonaiuto, 2015; Miniussi, Ambrus, Pellicciari, Walsh, & Antal, 2012). We hypothesized that anodal stimulation of the PMC would result in the preferential use of the contralateral hand and that cathodal stimulation of the PMC would bias the responses toward the ipsilateral hand.

To minimize participants' awareness of the goal of the current study while biasing their responses with external stimuli, we used a perceptual decision task in which perceptual reports were arbitrarily coupled with the left or right hand. Specifically, participants were asked to report whether a briefly presented rectangle was longer in the vertical or horizontal dimension using their left and right index fingers.

Two separate experiments were conducted with different stimulus presentation times and electrode montages. The aim of the first experiment was to determine whether there is any effect of tDCS over the PMC on the perceptual decision-making task using a bilateral stimulation montage. We expected that this montage would be most effective, as the anode side would excite the PMC on one hemisphere and the cathode would suppress the activation in the contralateral hemisphere. Once the effect of tDCS over the PMC has been established, the second experiment will tease apart the effect of anodal and cathodal tDCS using unilateral stimulation of the left or right PMC. The second electrode was placed over the contralateral upper arm. This montage has been used before and is shown to be effective in stimulation of the motor cortex (Nasseri, Nitsche, & Ekhtiari, 2015; Reis & Fritsch, 2011). Additionally, in the second experiment, we changed the duration of the mask presentation following presentation of the target stimulus—from 400 to 100 msec. This was done to achieve increased accuracy for measurement of RTs.

METHODS

Participants

Twelve participants (six women, mean age = 21.67 years, range = 18–26 years) took part in the first experiment with one stimulation group and 45 participants (26 women, mean age = 21.89, range = 18–25 years) took part in the second experiment with three stimulation groups ($n = 15$ per group). Participants attended two sessions with different stimulation conditions that were separated by at least 2 days (see Transcranial Direct Current Stimulation section). The order of sessions was randomly chosen and fully counterbalanced. All participants were right-handed and had normal or corrected-to-normal vision. Participants were naive to the purpose of the study. Informed consent in accordance with the Declaration of Helsinki and the guidelines approved by the ethics committee of University College London was obtained from all participants. At the end of the study, participants were monetarily reimbursed.

Apparatus

The experiment was run on a Windows computer with a 17-in. CRT monitor, 100-Hz refresh rate, and a resolution of 1024 × 768 pixels. Stimulus presentation and the recording of responses were achieved using MATLAB (v7.5; The MathWorks, Natick, MA) and the Psychophysics Toolbox (v3; Brainard, 1997; Pelli, 1997). Data analyses were conducted with SPSS (v20; IBM Corp., Armonk, NY).

Procedure

Sessions began with the placement of electrodes. Each session consisted of two phases: (1) without and (2) with stimulation. Figure 1A depicts the procedure of sessions. Each phase consisted of four blocks of 81 trials (nine repetitions per stimulus type). Each phase lasted approximately 10 min.

Rectangles with nine different height-to-width ratios were used as target stimuli ($k = [4, -3, -2, -1, 0, +1, +2, +3, +4]$). In addition to changes of height-to-width ratios, the rectangles were scaled to ratios of 1, 1.4, and 1.8 to achieve three different group sizes. Figure 1B shows the set of target stimuli.

Participants were instructed to use their left and right index fingers to respond to the orientation of a briefly presented rectangle. In the first experiment, they were instructed to respond as soon as they saw the question mark on the screen. By contrast, in the second experiment, they were instructed to respond as soon as they saw the target rectangle. The target rectangle appeared at a random location within a virtual frame (10.94×8.22 visual degrees). Figure 1C shows the procedure of a trial.

The order of the keys was counterbalanced between participants; that is, half of them responded to horizontal rectangles using their right index finger and half using their left index finger. Participants' heads were fixed using a chin rest, positioned 53 cm away from the monitor with their eye level adjusted to the center of the monitor. They were instructed to fixate their gazing point at the center of the monitor. Participants were asked to verbally report whenever they made a mistake in their response due to rushing.

Transcranial Direct Current Stimulation

Direct electrical current was delivered with a neuroConn DC Brain Stimulator Plus unit (Rogue Resolutions, Wales, UK). Multiple montages were used in the two experiments. Electrodes were placed according to the 10–20 international system for electrode placement over C3 and C4 for stimulation of the left and right PMC, respectively. Table 1 summarizes the different montages. Each session began with a no-stimulation condition in which no stimulation was administered. Performance in this phase was considered as the baseline.

Stimulation was administered via a pair of surface sponge electrodes soaked in saline solution. A direct current of 1.5 mA with a fade-in and fade-out time of 10 sec was delivered for 10 min after the first phase and continued for another 5 min during the second phase (Figure 1A). Sponge electrodes of similar size were used (35×35 mm^2). This stimulation protocol has been shown to be safe for use on human participants (Poreisz, Boros, Antal, & Paulus, 2007; Iyer et al., 2005).

Statistical Analysis

Choice

The percentage of responses using the left index finger was considered as the measure of response percentage. The difference between the two phases (ΔLeft-hand Response; Figure 1A) in one session was considered for further analysis. For the first experiment, a one-way repeated-measures ANOVA was run with Stimulation condition (lA-rC/rA-lC) as the within-subject factor. For the second experiment, a two-way mixed-factor ANOVA was run with Stimulation group (bilateral/unilateral-anodal/unilateral-cathodal) as the between-subject factor and Stimulation condition (Table 1) as the within-subject factor. Subsequently, post hoc paired-sample t tests were run to compare ΔLeft-hand Response for the two sessions. These values were also subjected to one independent sample t tests to compare with zero to investigate whether there was any change from baseline (first phase).

Figure 1. (A) Procedure of sessions. (B) Stimuli used with nine different ratios of width and height (k). The numbers represent the index of each stimulus with $k = 0$, $k = -4$ and $k = +4$ representing a square, a vertical rectangle, and a horizontal rectangle, respectively. (C) Procedure of a trial. A target rectangle was presented briefly after a fixation cross. This was followed by a mask screen composed of 50 random rectangles to mask the after-image of the target rectangle. Finally, a screen with a question mark was presented, prompting the participants to respond to the orientation of the target rectangle using the left and right "ctrl" keys using their left and right index fingers, respectively. 2-AFC stands for two alternative forced choice. *Mask was presented for 400 msec in the first experiment and 100 msec in the second experiment.
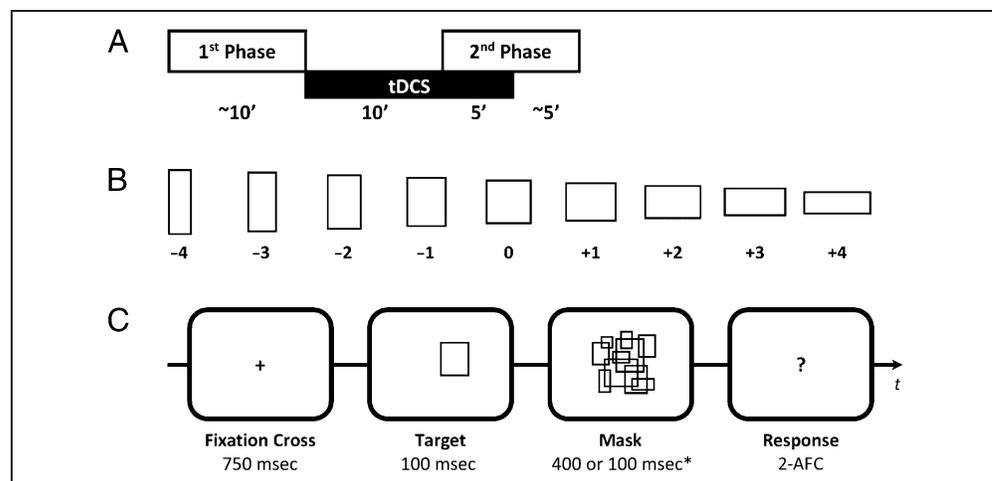
Table 1. Summary of the Montages Used in the Two Experiments

| Stimulation Group | First Experiment | | | Second Experiment | |
	Stimulation Condition	Label		Stimulation Condition	Label
Bilateral	Left anodal and right cathodal	lA-rC		Left anodal and right cathodal	lA-rC
	Right anodal and left cathodal	rA-lC		Right anodal and left cathodal	rA-lC
Unilateral-anodal				Left anodal and right upper arm	lA
				Right anodal and left upper arm	rA
Unilateral-cathodal				Left cathodal and right upper arm	lC
				Right cathodal and left upper arm	rC

Each participant participated in two sessions. Left and right refer to the left and right PMC (C3 and C4 according to the 10–20 international system for electrode placement), respectively. The laterality of the stimulation swapped over the two sessions; that is, they participated in both left anodal–right cathodal (lA-rC) and right anodal–left cathodal (rA-lC), or lA and rA, or lC and rC.

RT

RTs for left and right index fingers were analyzed. The median RT for each phase was considered for further analysis. We calculated the RT difference between the two phases for the analysis. For the first experiment, a 2×2 repeated-measures ANOVA was run on the RT differences with Hand (left/right hand) and Stimulation condition as within-subject factors. For the second experiment, a $3 \times 2 \times 2$ mixed-factor ANOVA was run with Stimulation group as the between-subject factor and Hand and Stimulation condition as within-subject factors. To further analyze RTs, we ran similar analyses on RTs for correct responses, excluding the $k = 0$ (square) conditions. Similar to Choice, these values were also subjected to one independent sample t tests.

RESULTS

Choice

First Experiment

The repeated-measures ANOVA showed a significant main effect of Stimulation condition ($F(1, 11) = 5.096$, $p = .045$, $\eta_p^2 = 0.317$). One-sample t tests showed a trend for rA-lC condition ($t(11) = 2.151$, $p = .055$) and a non-

significant difference for lA-rC condition ($t(11) = 0.140$, $p = .891$; Figure 2A).

Second Experiment

The mixed-factor ANOVA showed a nonsignificant main effect of Stimulation group ($F(2, 42) = 0.983$, $p = .383$, $\eta_p^2 = 0.045$), a nonsignificant main effect of Stimulation condition ($F(1, 42) = 0.954$, $p = .334$, $\eta_p^2 = 0.022$), but a significant interaction of the two factors ($F(2, 42) = 10.101$, $p < .001$, $\eta_p^2 = 0.325$). Post hoc paired-sample t tests showed significant differences for all stimulation groups (bilateral $t(14) = 3.446$, $p = .004$, unilateral-anodal $t(14) = 2.953$, $p = .010$, unilateral-cathodal $t(14) = 2.281$, $p = .039$). One-sample t tests showed a significant difference for rA-lC ($t(14) = 3.353$, $p = .005$) and rC ($t(14) = 2.301$, $p = .037$) and nonsignificant differences for the rest of the conditions ($p > .112$; Figure 2B).

RT

Figure 3 shows a histogram of the distribution of RTs for the two experiments. RTs for the first experiment was significantly shorter than the RTs for the second experiment (Mann–Whitney U test $p < .001$).

Figure 2. Difference in percentage of response with left hand between first and second phases for (A) the first experiment and (B) the second experiment. Higher values show more responses with the left hand. lA and rA stand for left and right anodal, respectively. lC and rC stand for left and right cathodal, respectively. $*p < .05$. $**p < .01$. $^\dagger p < .10$. Error bars indicate one standard error of mean.
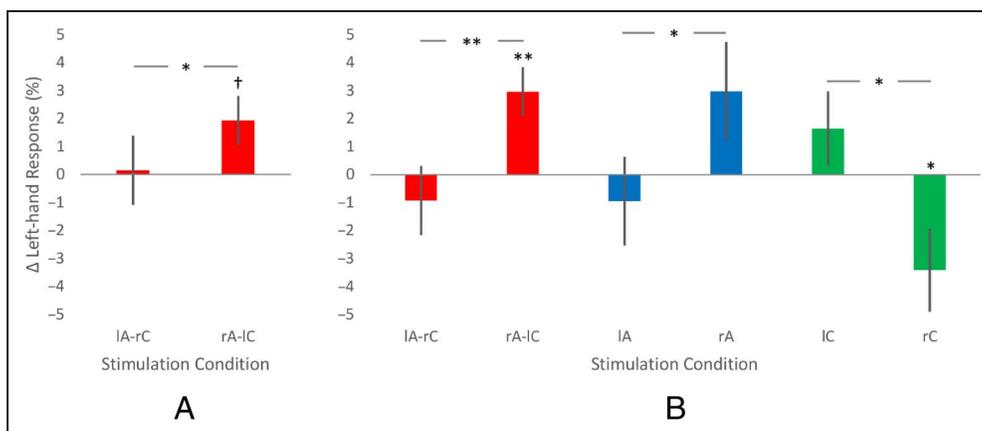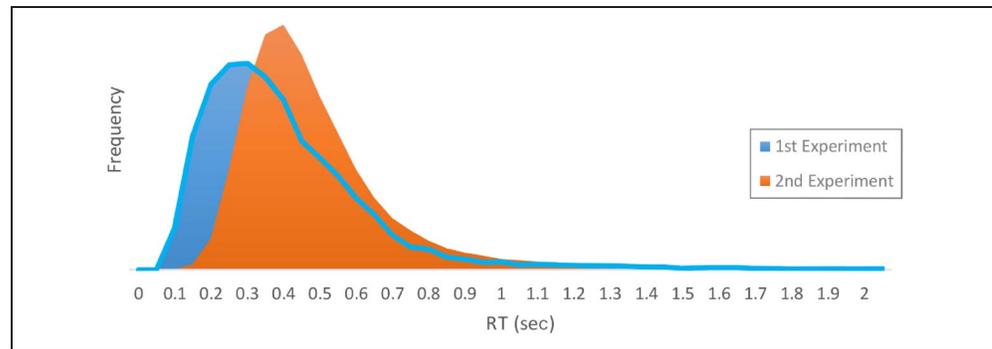
Figure 3. Histogram of the distribution of RTs for the two experiments. As expected responses for the second experiment happened later than the first experiment, most likely because of the longer presentation of mask—400 msec for the first experiment versus 100 msec for the second experiment.

Analyzing the RTs all together revealed no significant difference in any of the comparisons. Analyzing the RTs for only correct trials, however, showed significant differences between conditions. Table 2 summarizes the ANOVAs run for the two experiments.

First Experiment

Post hoc paired-sample t tests on left and right hands for different stimulation conditions showed a significant difference for the left hand ($t(11) = 10.073, p < .001$) and a nonsignificant difference for the right hand ($t(11) = 1.104, p = .293$; Figure 4A).

Second Experiment

Post hoc paired-sample t tests on the left hand showed a significant difference for all stimulation groups (Bilateral $t(14) = 4.355, p = .001$, Unilateral-anodal $t(14) = 2.832, p = .013$, Unilateral-cathodal $t(14) = 2.417, p = .030$). Post hoc paired-sample t tests on the right hand, however, showed significant difference only for the bilateral group

($t(14) = 2.896, p = .012$, unilateral-anodal $t(14) = 0.681, p = .507$, unilateral-cathodal $t(14) = 0.406, p = .691$; Figure 4B).

To further analyze the changes in RTs, we ran one independent sample t tests for each hand in each stimulation condition. Table 3 summarizes results of these tests.

DISCUSSION

We investigated whether tDCS of the PMCs would bias responses toward one hand or another. The results of the first experiment revealed a significant difference between the laterality of bilateral stimulation of PMCs: Anodal stimulation of the right PMC and cathodal stimulation of the left PMC (rA-lC stimulation condition) led to significantly more responses using the left hand than anodal stimulation of the left PMC and cathodal stimulation of the right PMC (lA-rC stimulation condition). Because of the bilateral positioning of the electrodes, it remained unclear whether these results were driven by cathodal or anodal stimulation, or a combination of both. Thus, a follow-up experiment incorporated additional

Table 2. Summary of ANOVAs Run on RT Differences for the Two Experiments

Experiment	Effect	F	p	η_p^2
First	Main effect of Hand	$F(1, 11) = 1.951$	.190	0.151
	Main effect of Stimulation condition[a]	$F(1, 11) = 226.533$	<.001	0.954
	Interaction of Hand and Stimulation condition[a]	$F(1, 11) = 31.230$	<.001	0.740
Second	Main effect of Hand	$F(1, 42) = 0.463$	.500	0.011
	Main effect of Stimulation group	$F(2, 42) = 2.156$	.128	0.093
	Main effect of Stimulation condition	$F(1, 42) = 3.584$	.065	0.079
	Interaction of Hand and Stimulation group	$F(2, 42) = 0.483$	.620	0.022
	Interaction of Stimulation condition and group[a]	$F(2, 42) = 5.273$	.009	0.201
	Interaction of Hand and Stimulation type[a]	$F(1, 42) = 5.188$	.028	0.110
	Interaction of the three factors[a]	$F(2, 42) = 11.291$	<.001	0.350

A 2 × 2 repeated-measures ANOVA was run for the first experiment with Hand (left/right hand) and Stimulation condition as within-subject factors. A 3 × 2 × 2 mixed-factor ANOVA was run for the second experiment with Stimulation group as a between-subject factor and Hand and Stimulation condition as within-subject factors.

[a] Significant effect.

Figure 4. Difference in RTs between first and second phases for left and right hands for (A) the first experiment and (B) the second experiment. Higher values show slowing for the second phase. lA and rA stand for left and right anodal, respectively. lC and rC stand for left and right cathodal, respectively. *p < .05. **p < .01. †p < .10. Error bars indicate one standard error of mean.

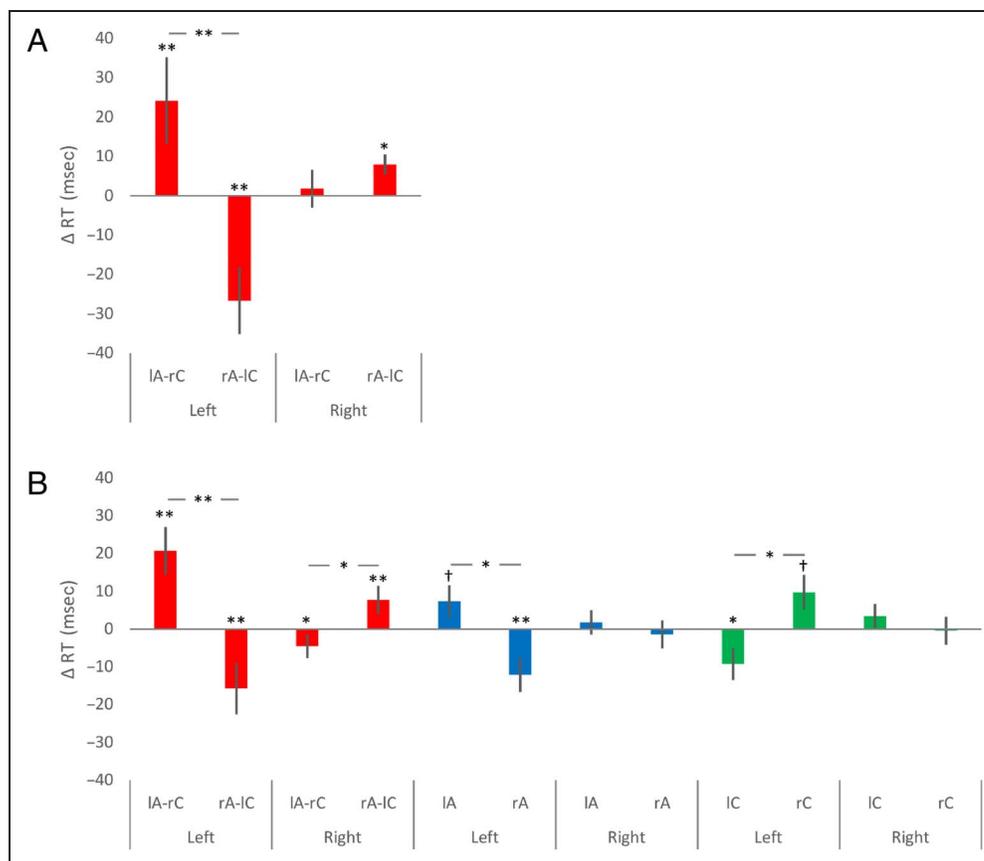**Table 3.** Summary of the One-sample *t* Tests Run on ΔRTs to Compare the Difference between RTs in the First and Second Phases with Zero

Experiment	Stimulation Group	Hand	Stimulation Condition	t	p
First	Bilateral	Left	lA-rC	t(11) = 6.423	<.001
			rA-lC	t(11) = 10.181	<.001
		Right	lA-rC	t(11) = 0.370	.719
			rA-lC	t(11) = 3.054	.011
Second	Bilateral	Left	lA-rC	t(14) = 4.669	<.001
			rA-lC	t(14) = 3.293	.005
		Right	lA-rC	t(14) = 2.231	.043
			rA-lC	t(14) = 3.046	.009
	Unilateral-anodal	Left	lA	t(14) = 1.811	.092
			rA	t(14) = 3.412	.004
		Right	lA	t(14) = 0.837	.417
			rA	t(14) = 0.531	.604
	Unilateral-cathodal	Left	lC	t(14) = 2.220	.043
			rC	t(14) = 1.873	.082
		Right	lC	t(14) = 0.735	.475
			rC	t(14) = 0.085	.933

lA and rA stand for left and right anodal, respectively. lC and rC stand for left and right cathodal, respectively.

conditions with bilateral and unilateral configurations to further investigate the different polarity and hemispheric contributions. The results from the second experiment replicated the results of the first experiment. Furthermore, they indicate that unilateral stimulation of the left and right PMC modulates the responses differently. Anodal stimulation of the right PMC (rA stimulation condition) led to significantly more responses using the left hand than anodal stimulation of the left PMC (lA stimulation condition). In contrast, cathodal stimulation of the right PMC (rC stimulation condition) led to significantly fewer responses using the left hand than cathodal stimulation of the left PMC (lC stimulation condition). Shift of response toward the left hand was accompanied by faster RTs and vice versa; shift of response away from the left hand was accompanied by slower RTs. This is a remarkable finding, as tDCS, unlike intracranial electrical stimulation and TMS, does not induce muscle movement per se. Therefore, the shift in response must have been initiated via the modulation of intention to respond using one hand or another.

From a behavioral perspective, our results appear to reflect a change in perceptual decision-making, in which tDCS changed what participants reported to be a horizontal or vertical rectangle. Intuitively, however, it is unlikely that stimulation over the motor cortex changed the subjective visual experience. Instead, one may find it more parsimonious to consider that tDCS induced a bias in hand choices. In what follows, we consider these two possible accounts: (a) Perceptual bias account: for the rectangles with width-to-height ratio close to 1 (i.e., square), tDCS biased participants to perceive the stimulus as slightly elongated or broadened, and (b) Motor-choice bias account: when participants had no idea about the correct answer, they picked one of the responses randomly (or freely) and this process was biased, possibly because of facilitation of responding using one hand over another.

Perceptual Bias Account

As mentioned earlier, increasing evidence shows that the PMC, in contrast with its traditional role as the center for execution of movements, is also engaged in the integration of sensory input and perceptual decision-making (Mendoza & Merchant, 2014; Romo & de Lafuente, 2013; Heekeren, Marrett, & Ungerleider, 2008). In addition to the PMC, other surrounding brain areas might have also played a role in this process. Although the majority of our stimulation was focused on PMC, it has been shown that tDCS of this area does not only affect the underlying brain area but also surrounding areas including some parts of the frontal and parietal cortex (Bikson, 2013; Bikson, Rahman, & Datta, 2012; Lang et al., 2005). Therefore, the observed effects could emerge as a result of the modulation of activity in PMC or any other surrounding areas or a combination of those.

There is evidence that some parts of the frontal lobe (e.g., ventral premotor cortex [PMv]), are involved in multimodal sensory integration, perception, and decision-making. Schieber (2000) inactivated the PMv in rhesus monkeys unilaterally using intracortical injection of muscimol. This inactivation did not produce any visible changes in the monkeys' behavior in reaching out and grasping food with either hand. It did, however, change the monkeys' preferred laterality of motoric choices. When two options were presented simultaneously on both sides, the monkey made fewer motoric responses contralateral to the inactivated PMv. This result demonstrates the contribution of the PMv in choosing the side of motoric response. Romo, Hernández, and Zainos (2004) applied a vibrating stimulus to the fingertips of monkeys and trained them to make a decision based on a comparison of the frequency of vibrations while recording the responses of PMv neurons. They found that the activity of PMv neurons code for current sensory input as well as remembering it and comparing them. More importantly, their results showed involvement of the PMv in expressing motor commands. Dorsal premotor cortex (PMd) also has been shown to be involved in the decision-making process. Cisek and Kalaska (2005) recorded from PMd while monkeys were performing an instructed-delay reaching task. Two dots in opposite directions from the center of a circle were presented and monkeys were required to select one dot based on a nonspatial cue. Almost half of the PMd neurons fired if one of the dots was near their preferred direction. The results showed that subsequent to the appearance of the nonspatial cue, before the monkey's response, PMd neurons corresponding to the target dot increased firing and other PMd neurons' firing was suppressed. Therefore, PMd neurons reliably predicted the monkey's response choice.

In addition to the modulation of activity of neurons in the frontal area, the modulation of neuronal activity in the parietal cortex can also explain our results. The lateral intraparietal area (LIP) has been implicated as the interface between motor, cognitive, and perceptual information (Gold & Shadlen, 2007). This hypothesis is consistent with the idea that the parietal cortex is responsible for accumulating perceptual information from our environment to derive a motor decision. Shadlen and Newsome (2001) recorded the activity of single neurons in the LIP of rhesus monkeys while they categorized the direction of motion of a set of dots presented on either side of the screen using saccadic eye movements. Their results showed that the activity of neurons in the LIP could predict monkeys' saccadic eye movements in response to the stimuli. Roitman and Shadlen (2002) used a similar task and recorded from the same area in rhesus monkeys. Further to confirming previous findings, they showed that there exists a threshold level of neuronal activity in the LIP that marks the completion of the decision process (see also Huk & Shadlen, 2005). These results provide evidence that the parietal cortex is a site of perceptual, sensory, and motor processing.

In a more recent study, however, Filimon, Philiastides, Nelson, Kloosterman, and Heekeren (2013), using event-related fMRI and effective connectivity analysis, showed that involvement of sensorimotor regions such as the LIP in accumulating sensory evidence is reduced when hand motor preparation is disentangled from perceptual decision-making. This suggests that the LIP area's role in perceptual decision-making is modulated by the task and is more involved in the context of hand motor preparation.

There is the possibility that tDCS modulated the interaction of frontal-parietal circuitry. Functionally, there is evidence of a strong coupling between connections of the PPC areas during the planning of actions. These areas include the PPC, LIP, parietal reach region, and frontal lobe areas, such as PMd (Andersen & Cui, 2009). Pesaran, Nelson, and Andersen (2008) simultaneously recorded from the PMd and the parietal reach region in monkeys. Monkeys were either freely making choices or were following instructions. Their results showed that a subpopulation of cells in the frontal and parietal cortex exchange information to coordinate the decision process. Hernández et al. (2010) showed a concurrent interaction between frontal-parietal lobes in a perceptual decision-making task. They incorporated multisite recording and showed that frontal lobe circuitry, medial/ventral/dorsal premotor cortices, prefrontal cortex, and PMC, are involved in the comparison of sensory inputs rather than simply engaged in motor responses.

Our situation may be akin to the experiment reported by Hanks, Ditterich, and Shadlen (2006), in which monkeys were trained on a motion direction discrimination task by indicating their decision of direction with a saccade. They found that directly stimulating the LIP in a macaque influenced its choices toward the stimulated response field faster, without ever directly evoking a saccade. Although it is unclear whether perception is altered by microstimulation to the decision-making area, which links sensory to motor regions, our experiment is similar to the latter experiment in that perceptual decision-making was biased by modulation of a motor-related region. Although anodal tDCS does not induce neuronal firing, it modulates neuronal activity, which can subsequently lead to bias in decision-making in a similar manner. Combined with previous findings of overlapping areas responsible for perceptual and motor decisions (Romo & de Lafuente, 2013; Andersen & Cui, 2009; Gold & Shadlen, 2007), it is possible that stimulation of the PMC and surrounding area simultaneously influenced perceptual decisions.

The evidence from this study, however, is mostly an examination of motor behavioral responses and thus an investigation limited to the decisions that were made, not regarding any perceptual biases or processes that might have led to these actions. Moreover, if motor stimulation modulated participants' perception of stimulus shape, it is uncertain as to why the effect would be observed only for certain response hand, especially when instructions for which hand to respond with for more vertical or hori-zontal shaped stimuli were counterbalanced both within and across participants. Future studies ought to seek replicating the response hand mapping effect with stimulation of PMC, though include additional controls to help eliminate other hypotheses to arrive to a stronger conclusion.

Motor-choice Bias Account

Alternatively, our findings can be explained as a result of a choice bias. Weak electrical current may have changed the excitability of the motor cortex and possibly surrounding regions, which subconsciously affected participants' motor-choice decisions. On the basis of a study by Desmurget et al. (2009) and other evidence (Sirigu et al., 2004; Wise & Murray, 2000), Haggard (2009) argued that the premotor cortex and the pre-SMA are both involved in volition: The former prepares the action, and the latter generates the intention. Subsequently, this action is executed by PMC. Copies of prepared motor commands are also projected to different parts of parietal cortex for prediction of sensory consequences of movement (Haggard, 2008). Using an fMRI, Gallivan, McLean, Valyear, Pettypiece, and Culham (2011) confirmed this proposition. They showed that patterns of activity in multiple premotor and parietal brain areas could accurately predict upcoming intentions.

Transcranial electrical stimulation in humans also provides evidence for the contribution of premotor cortex and PPC in body movement and forming intentions. Using electrical stimulation of patients undergoing awake brain surgery, Desmurget et al. (2009) showed that the premotor cortex and PPC are highly responsible for motor responses and awareness of intentions. Unknown to participants, stimulation of premotor regions induced mouth and contralateral limb movements. In contrast, stimulation of parietal regions provoked the intention to move based on participants' reports. Higher amplitudes of stimulation in these regions gave participants the belief that they had really performed these movements (see also Desmurget & Sirigu, 2009).

With the evidence provided thus far, the motor-choice bias account appears to be the more plausible account. Cisek (2006) argued that decision-making and action planning happen concurrently while several potential actions are processed simultaneously, rather than in a serial manner. On the basis of this argument, they suggested the affordance competition hypothesis (Cisek, 2007). This hypothesis explains how potential actions compete against each other while further information is gathered. This process continues until the gathered information biases this competition. Ultimately, this bias leads to the selection of a single response (Cisek & Kalaska, 2010). To validate this model, Thura and Cisek (2014) recorded from the PMd and PMC of monkeys who were trained to perform a two-choice reaching task. The task was specially designed such that the evidence available varied over the course of each trial. This is in contrast

to previous studies in which constant sensory evidence was presented throughout each trial. This allowed monkeys to make decisions at any time. They found that, during deliberation, information continuously influences activity in the two areas. During this time, a nonspecific urgency signal gradually biases the response toward one of the options. This process continues until one of the options becomes strong enough to suppress the other. At this point, the competition between actions is resolved, and the action is initiated. This resolution happens approximately a quarter of a second before movement onset. More importantly, they showed that, at this moment, the activity of the PMd and PMC could reliably define the target. Specifically, the activity of PMd neurons tuned to the selected target reached a peak, whereas the activity of PMC neurons tuned to the unselected target were suppressed.

Similar processes have been shown in humans. Cisek, Puskas, and El-Murr (2009) used a task similar to Thura and Cisek (2014) for human participants. On the basis of trade-offs between the speed and accuracy of decisions, they argued that their results are more inline with the urgency gating model. This model claims that the build-up of neural activity in response to increasing evidence represents the urgency to respond, rather than the temporal integration of sequential samples of sensory input. Thura, Beauregard-Racine, Fradet, and Cisek (2012) gave further evidence in favor of the urgency gating model. They tested human participants on a modified random-dot coherent motion task with variable coherency during each trial. Therefore participants had to estimate evidence by accumulating only novel information. They argued that the urgency gating model can explain results of all of the previous studies. This is in favor of integration models as they are equivalent in the conditions tested—evidence did not change throughout each trial.

The threshold in the urgency gating model is similar to the bound in accumulation-to-bound models. These models give two possible explanations for the effects: prior knowledge, which biases the starting point of the accumulation, and the rate of evidence accumulation, which changes the slope. Mulder, Wagenmakers, Ratcliff, Boekel, and Forstmann (2012) used a drift diffusion model (Voss, Nagler, & Lerche, 2013; Wagenmakers, 2009; Ratcliff & McKoon, 2008) to investigate bias in human participants (see also Forstmann, Brown, Dutilh, Neumann, & Wagenmakers, 2010). They used two versions of a random-dot motion paradigm in which they manipulated bias by changing the prior probability and potential payoff for the two alternatives. Their behavioral results showed that the observed bias in participants' behavior was mostly due to changes in the starting point of the accumulation process, rather than the rate of accumulation. Their fMRI imaging data showed that the regions of the frontoparietal network are involved in this bias.

Our findings can be explained using aforementioned models: Electrical stimulation biased the decision toward one of the responses by changing the starting or ending point or by changing the accumulation rate.

Asymmetry of Hands and RTs

Although comparison between lateralities showed a clear difference, changes in hand responses did not always lead to a significant difference from baseline (performance during the first phase; Figure 2). From all the comparisons, only rA-lC and rC stimulation conditions in the second experiment led to a significant difference with rA-lC stimulation condition in the first experiment showing a trend toward difference. Asymmetry of lateralities has been repeatedly shown in the literature.

On the basis of physiological evidence, there is hemispheric asymmetry related to interhemispheric inhibition between the left and right PMC. This is characterized by an increased robustness of the dominant motor cortex's inhibitory projections. Interhemispheric inhibition refers to the inhibition of one brain hemisphere by the opposing hemisphere via neurophysiological mechanisms (Ni et al., 2009; Daskalakis, Christensen, Fitzgerald, Roshan, & Chen, 2002). Additionally, given that there are structural differences between the two PMC hemispheres based on handedness, this could explain why neuromodulatory studies that recruit participants with the same handedness have observed stronger hand responses when stimulation is applied over one PMC hemisphere, as opposed to the other. Vines, Nair, and Schlaug (2008) investigated this hemispheric asymmetry using a finger sequence coordination task. Participants were asked to respond with each hand before and after stimulation (tDCS). Their results showed that the modulatory effects of tDCS depend on which hemisphere is stimulated: Cathodal stimulation of the right hemisphere did not significantly change performance for the right hand. In contrast, anodal stimulation of the right hemisphere did significantly change performance for the left hand (see also Schade, Moliadze, Paulus, & Antal, 2012).

Recently a TMS study by Oliveira et al. (2010) revealed that PPC involvement for voluntary hand choices in a decision-making motor task displayed this asymmetry. On the basis of bounded accumulation model theory, authors suggest that there is parallel competition between right- and left-hand action plans for motor decisions. Specifically, longer RTs reflected increased competition as a result of increased ambiguity in these motor decisions. In this study, TMS applied over left PPC reduced competition for right-hand action plans and thus increased hand choice for the ipsilateral hand; however, there were no such effects with right PPC stimulation. The authors point to neuroimaging evidence, which has shown that there is smaller activation in the right PPC compared to left PPC regarding hand reaches. It is therefore suggested that consequently it is more difficult to target this smaller region of the PPC involved in decision-making for hand reaches. A second possibility the authors reported is that

right-hand dominance might have created a higher baseline, resulting in a decreased observable bias after TMS was applied to the right PPC. This asymmetry was also present in our study, in which the left hand was more affected by the stimulation of the right PMC compared to the right hand by the stimulation of the left PMC; for example, the rC stimulation condition led to a significant difference in the number of responses using the left hand but lC stimulation did not for the right hand.

The results of our study also show that tDCS has a modulatory effect on RTs. There was a significant difference for left-hand responses between different lateralities for all stimulation conditions (see Figure 4). The modulation of right-hand responses, however, was less consistent—only bilateral stimulation in the second experiment showed a significant difference for the RTs of the right hand between lA-rC and rA-lC. In a study, Nitsche et al. (2005) utilized single-pulse TMS during and after electrical stimulation of the PMC to examine changes in corticospinal excitability. Paired-pulse TMS was also used to examine changes in short-interval intracortical inhibition. They showed that anodal stimulation of the PMC enhanced facilitation, reduced intracortical inhibition, and caused a lasting reduction in short-interval intracortical inhibition. On the other hand, cathodal stimulation of the PMC showed the opposite effects (Di Lazzaro, Ziemann, & Lemon, 2008). Confirming these results, Hummel et al. (2006) showed that anodal stimulation of the PMC leads to shorter RTs and improvement of pinch force (see also Tanaka, Hanakawa, Honda, & Watanabe, 2009). In addition to the possible contribution of factors explained by the previously mentioned models, changes in RT could be the result of changes in corticospinal and intracortical facilitation and inhibition.

Conclusion

In two experiments, we aimed to investigate whether tDCS of the PMCs can modulate hand choice. Although the results of this study showed modulatory effect of tDCS on hand choice, no firm conclusions about the mechanisms of the observed hand preference can be drawn from them. Both lower level perceptual tasks in humans and monkeys as well as those involving more advanced aspects of cognition are successfully modulated by intracranial and transcranial current stimulation. It seems possible that both bottom–up feedback from the muscles and peripheral nervous system to the PMC and higher areas, as well as top–down control, contribute to the observed pattern of findings. The results of this study indicate that tDCS successfully modulates motor responses in visual categorisation tasks by increasing the participants' preference for using the hand contralateral to the site of anodal stimulation. Future studies should aim to distinguish whether tDCS modulates motor-choice behavior alone or perceptual decision-making.

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