

# Transcranial direct current stimulation (tDCS) of the inferior frontal gyrus disrupts interpersonal motor resonance

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## ABSTRACT

Interpersonal motor resonance (IMR) is presumed to result from activity within the human mirror neuron system, which itself is thought to comprise the inferior parietal lobule (IPL) and inferior frontal gyrus (IFG). Twenty healthy adults underwent anodal, cathodal, and sham transcranial direct current stimulation (tDCS) to either IPL or IFG immediately before the assessment of IMR (using transcranial magnetic stimulation). IMR (i.e., motor-evoked potential amplitude during transitive action observation relative to static observation) was significantly reduced following both anodal and cathodal stimulation of IFG (relative to sham), but there was no effect of stimulation for IPL. These data support the role of IFG, a presumed mirror neuron region, in IMR.

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## 1. Introduction

Interpersonal motor resonance (IMR) describes the activation of an individual's motor system during the observation of another's behaviour (Uithol, van Rooij, Bekkering, & Haselager, 2011), that is, during the observation of an action by another the visual representation of action is presumed to be 'mapped' onto the motor representation of that particular action (Rizzolatti & Craighero, 2004). IMR has been assessed using a variety of methods. When using transcranial magnetic stimulation (TMS), IMR is reflected in enhanced motor corticospinal excitability (CSE) during the observation of behaviour involving the stimulated muscle (Fadiga, Craighero, & Olivier, 2005). IMR is also measured behaviourally (e.g., spontaneous mimicry when observing another's facial expression) (Oberman, Winkelman, & Ramachandran, 2007; Sato & Yoshikawa, 2007).

IMR is thought to be underpinned by the mirror neuron system (MNS). Initially discovered in macaque monkeys (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992), mirror neurons are cortical brain cells that fire during the performance and observation of behaviour. An analogous system has since been established in humans (Rizzolatti & Craighero, 2004). While the human MNS involves a broad neural network comprising temporal, parietal, and

frontal cortices, mirror neurons themselves are thought to reside in two cortical regions: inferior parietal lobule (IPL) and inferior frontal gyrus (IFG) (Iacoboni & Dapretto, 2006) (although other regions have also been implicated; Molenberghs, Cunnington, & Mattingley, 2012; Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010). With respect to TMS, action observation is thought to promote mirror neuron activity in IPL and IFG, which then inputs to M1 and increases motor CSE (Fadiga et al., 2005). Thus, any subsequent increase in CSE during action observation (relative to the observation of an appropriate static or control display) is typically interpreted as reflecting mirror neuron activity (Enticott, Kennedy, Bradshaw, Rinehart, & Fitzgerald, 2010; Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Gangitano, Mottaghy, & Pascual-Leone, 2001; Gangitano, Mottaghy, & Pascual-Leone, 2004; Maeda, Kleiner-Fisman, & Pascual-Leone, 2002; Theoret et al., 2005).

The extent to which IFG and IPL are involved in IMR, however, is not established, and any causal link might be best explored via brain stimulation. This includes transcranial direct current stimulation (tDCS), which is a non-invasive brain stimulation technique that involves the application of mild electrical stimulation to the scalp in order to modulate cortical excitability. Typically, anodal stimulation is associated with an increase in cortical excitability, while cathodal stimulation yields a decrease in excitability (Stagg & Nitsche, 2011). Brain stimulation support for MNS regions in measures linked to IMR comes from TMS studies. Using bilateral paired-pulse TMS, Catmur, Mars, Rushworth, & Heyes (2011) found that a conditioning pulse delivered to either dorsal or ventral premotor cortex (often included with IFG as a broader MNS region) enhanced a TMS measure of IMR. Although not directly

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assessing motor resonance, repetitive TMS to IFG in both hemispheres has also been found to disrupt motor imitation (Heiser, Iacoboni, Maeda, Marcus, & Mazziotta, 2003), while theta burst TMS to IFG (but not posterior parietal cortex) appears to disrupt automatic motor imitation (Catmur, Walsh, & Heyes, 2009). TMS to IFG has also been shown to disrupt weight-judgments of items lifted by a human hand, which was interpreted as reflecting action understanding (Pobric & Hamilton, 2006). Thus, while there has been some research looking at the effect of brain stimulation on abilities thought to arise from the MNS, there has been very little research looking at the effect of these regions on measures of putative mirror neuron activity, and none looking at the influence of IPL or tDCS.

The current study investigated the effect of tDCS to IFG and IPL on subsequent IMR (measured via TMS, with enhanced IMR indicated by greater cortical excitability during the observation of a transitive hand action relative to the observation of a static hand). It was hypothesised that anodal stimulation would enhance IMR during action observation, and that cathodal stimulation would decrease this response, thus supporting the roles of both IFG and IPL in IMR.

## 2. Methods

### 2.1. Participants

Participants were 24 healthy adults (15 females, 23 right-handed; mean age: 22.58 [SD = 5.87] [IFG group], 28.58 [SD = 8.71] [IPL group]) recruited from advertisements placed within Monash University and The Alfred hospital. Participants were screened to ensure that they met the safety requirements of TMS. All participants provided signed informed consent and were reimbursed AU\$30 for each of the three sessions attended. This project was approved by the human research ethics committees of Monash University and The Alfred.

### 2.2. Procedure

Each participant attended three separate sessions, during which they received anodal, cathodal, or sham tDCS prior to an assessment of IMR using TMS. There were at least seven days between each session for each participant. For 10 participants, the site of stimulation was the left IPL, while for the other 10 participants the site of stimulation was the left IFG. The order of sessions was randomised, and both participants and experimenters were blind to tDCS condition (i.e., active or sham), but experimenters were not blind to polarity. This was achieved by experimenters being provided with a code to input to the stimulator (yielding either active or sham stimulation) and an instruction for either anodal or cathodal stimulation. Off-line processing of EMG signals was also blinded. tDCS and TMS procedures are described below.

#### 2.2.1. Transcranial direct current stimulation

Twenty minutes of 2 mA tDCS was provided using a pair of saline-soaked surface sponge electrodes (35 cm<sup>2</sup>) and a battery-driven, constant current DC-Stimulator (neuroConn). The two active conditions (anodal and cathodal) involved a fade-in over 120 s, 20 min of 2 mA stimulation, and a fade-out over 15 s. The sham condition involved a fade-in over 120 s, 30 s of 2 mA stimulation, and then a fade-out of 15 s (followed by 19 min 30 s of no stimulation).

Stimulation sites were determined according to the international 10–20 system for electrode placement sites that are presumed to lie above the relevant cortical regions. For left IPL this corresponded to position P3, and for left IFG this corresponded to one-third of the distance from F7 to C5 (Kim et al., 2007; Loui, Hohmann, & Schlaug, 2010). Anodal stimulation involved placing the anodal electrode over the IPL/IFG, while cathodal stimulation involved placing the cathodal electrode over the IPL/IFG. For each site, the second electrode was placed over the contralateral (right) supraorbital region, which is a very common reference site for stimulation of frontal and parietal cortex (Nitsche et al., 2008).

#### 2.2.2. Transcranial magnetic stimulation

IMR was assessed via TMS of the left primary motor cortex, and the EMG recording of subsequent activity in the right first dorsal interosseous (FDI), during video presentation of static and active hands. Stimulation was achieved using a Magstim-200 stimulator (Magstim Company Ltd., UK) and a handheld figure-of-eight coil that was positioned against the scalp. EMG was recorded using self-adhesive electrodes, amplified and filtered (low pass: 500 Hz; high pass: 10 Hz) using PowerLab/4SP (AD Instruments, Colorado Springs, CO), and sampled via a CED Micro 1401 mk II analogue-to-digital converting unit (Cambridge Electronic Design, Cambridge, UK).

At the beginning of each session, TMS was used to determine both M1 and the minimum intensity required to produce a motor-evoked potential (MEP) of

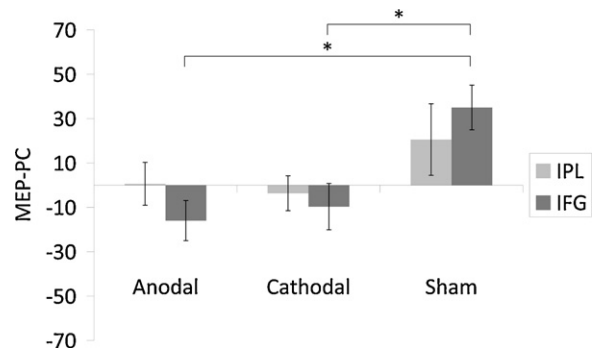


**Fig. 1.** MEP-PC (±SE) for the tDCS conditions. While there was the expected increase in MEP-PC following sham stimulation, this was significantly reduced (and suggestive of absent interpersonal motor resonance) following anodal and cathodal stimulation of IFG.

approximately 1 mV (mean TMS intensity: 47.71 [SD = 8.19]). This site and intensity was used to index IMR. We employed the same stimulus set as that described in Enticott et al. (2010), which involves the presentation of a static hand (with or without a mug present), a hand performing an intransitive action (i.e., pantomimed grasp) (with or without a mug present), and a hand performing a transitive action (i.e., grasping a mug). Each of the videos was presented 10 times in a quasi-random order. A single TMS pulse was administered 1000–1500 ms into each clip; for the motion conditions, this was immediately prior to contact between the thumb and index finger in the grasping motion. While we have previously found motor resonance for only the transitive action (Enticott et al., 2010, 2012), we employed the entire video sequence to offer increased variation in the stimulus presentation and thereby lessen potential habituation. The entire video sequence lasted 4 min and 39 s, which ensured that our index of motor resonance was completed within 6 min of the completion of tDCS. This was critical given the relatively short lasting effects of tDCS (Stagg & Nitsche, 2011).

### 2.3. Data analysis

Consistent with our previous studies (Enticott et al., 2010, 2012), IMR was indexed by first extracting the median MEP amplitude for the “static hand” and “transitive hand action” conditions, and then calculating the MEP percentage change (MEP-PC):

$$\text{MEP-PC} = \frac{\text{transitive MEP} - \text{static MEP}}{\text{static MEP}} \times 100$$

A higher MEP-PC is indicative of greater IMR. We then conducted one-way repeated measures ANOVAs for each of the stimulation sites (IPL, IFG) examining the influence of tDCS (anodal, cathodal, sham), with MEP-PC serving as the dependent measure. Extraction of MEP amplitudes and the calculation of MEP-PC were blinded, but data analysis was not.

## 3. Results

There was no effect of tDCS for those undergoing IPL stimulation,  $F(2, 22) = 1.49$ ,  $p = 0.246$ . There was, however, an effect of tDCS for those undergoing IFG stimulation,  $F(2, 22) = 7.91$ ,  $p = 0.003$ . Paired samples *t*-tests (two-tailed;  $\alpha = 0.017$  [simple Bonferroni]) revealed a greater MEP-PC for the sham condition relative to both anodal,  $t(11) = -3.19$ ,  $p = 0.009$ , and cathodal stimulation,  $t(11) = -3.15$ ,  $p = 0.009$ , but no difference between anodal and cathodal conditions,  $t(11) = -0.55$ ,  $p = 0.591$  (see Fig. 1). Inspection of mean values for those undergoing IFG stimulation reveals the expected increase above 0 in MEP-PC following sham stimulation (as there was for those undergoing IPL stimulation), which reflects IMR, but a negative value following anodal and cathodal stimulation, which reflects an absence of motor resonance.

To test whether there was a general effect of tDCS on CSE (i.e., whether IFG stimulation might directly affect motor cortical activity due to its proximity to M1, which could then affect our measure of IMR), we completed the same analysis for the IFG group with MEP amplitude (mV) during the observation of the static hand (i.e., raw baseline data) as the dependent measure. There was no effect of tDCS,  $F(2, 18) = 0.43$ ,  $p = 0.656$ .

#### 4. Discussion

IMR was reduced after both anodal and cathodal tDCS to IFG, but there was no effect of stimulation to IPL. Specifically, while sham tDCS revealed the expected increase in CSE during transitive action observation (relative to static observation) for both stimulation conditions, this effect was essentially eliminated (i.e., MEP-PC < 0) by both anodal and cathodal stimulation to IFG. That both anodal and cathodal reduced IMR were somewhat inconsistent with our hypotheses, as the former is typically associated with an increase in cortical excitability, and was thus expected to enhance IMR. In any case, this suggests that this region is critical to CSE facilitation during transitive action observation, and that any modulation of CSE (whether excitatory [anodal] or inhibitory [cathodal]) on IFG has an adverse impact on IMR. Analyses also revealed that this effect of tDCS was specific to our index of IMR, and did not reflect a broader impact on CSE or simple disruption of motor cortical activity.

These findings are consistent with the idea that IFG is critical to IMR. As noted, IFG is thought to be intrinsically involved in the human MNS, and as IMR often serves as a putative measure of mirror neuron activity, these findings might be seen as further evidence for this involvement. With respect to function, IFG has been discussed in relation to the matching of motor plans (Iacoboni et al., 1999; Rizzolatti, Fogassi, & Gallese, 2001) through the encoding and representation of goals and intentions from observed actions (e.g., the goal or intention to drink from the grasping of a cup) (Cattaneo, Caruana, Jezzini, & Rizzolatti, 2009; Gallese & Sinigaglia, 2011; Rizzolatti & Sinigaglia, 2010). In this respect, it is therefore not surprising that stimulation of IFG affected IMR in the current study. Although not assessed here, this would suggest that disrupted motor resonance could lead to disrupted goal representation. Indeed, there is already some data to support this; for instance, blocking automatic facial mimicry (e.g., through biting on a pen or the administration of botox), itself thought to reflect IMR, appears to reduce one's ability to accurately recognise emotion from facial expressions (Neal & Chartrand, 2011; Oberman et al., 2007). TMS to ventral premotor cortex, which is adjacent to IFG and considered part of the same frontal mirror neuron region, has also been shown to disrupt processing of body postures and forms (Urgesi, Calvo-Merino, Haggard, & Aglioti, 2007).

Given the effect on IFG it was somewhat surprising that no significant effect was seen for IPL. It is possible that IPL is less critical to our measure of IMR, or that disruption of this region is not sufficient to significantly affect IMR. It is also possible that parietal mirror neurons are less susceptible to brain stimulation (e.g., buried within sulci, differences in resting cortical excitability). Assuming appropriate stimulation, this result is inconsistent with the circuitry typically implicated in the MNS, which emphasises reciprocal connections between IFG and IPL (in which case disruption of either site might be expected to affect the subsequent outcome measure) (Gallese, Gernsbacher, Heyes, Hickok, & Iacoboni, 2011; Iacoboni & Dapretto, 2006). This model, however, is not universally accepted. For instance, Hamilton (Hamilton, 2008) proposes a neural framework in which there are alternate routes of information flow between 'modes' that comprise the MNS (middle temporal gyrus, IPL, IFG). One such route involves a relatively automatic and direct occipital-temporal-frontal network that presumably bypasses IPL, and is thought to form associations between visual and motor representations (thereby facilitating mimicry). It may be this particular neural pathway that is responsible for IMR as measured via TMS at M1. An alternate route in Hamilton's model concerns the more traditional occipital-temporal-parietal-frontal pathway, which involves controlled processes and is thought to be more relevant to goal emulation (including action understanding) and planning. Support for this network, and parietal involvement, comes from neuroimaging studies (e.g., Hamilton & Grafton, 2006;

Newman-Norlund, van Schie, van Hoek, Cuijpers, & Bekkering, 2010). Our TMS measure of IMR may actually reflect activity within both pathways, but only produce an effect of IFG because of its involvement in both pathways. In this respect, it is possible that our IPL results are underpowered; inspection of mean values for the IPL condition (Fig. 1) would suggest that there could be an effect of cathodal stimulation. In any event, IPL stimulation is certainly associated with a lesser effect size than IFG stimulation.

Our findings, however, certainly do not inform as to the supposed function of mirror neurons or 'mirror systems' (see Gallese et al., 2011 for a recent discussion). While the precise role of each of the regions is unclear with respect to the MNS, a neuroimaging paradigm (repetition suppression) appears to suggest that transitive (i.e., object-related, goal-directed) actions, such as that used in the current study, are particularly relevant to the IFG component of the MNS (Kilner, Neal, Weiskopf, Friston, & Frith, 2009), while intransitive or pantomimed actions are more likely to yield parietal mirror neuron activity (Chong, Cunnington, Williams, Kanwisher, & Mattingley, 2008; Dinse, Hasson, Rubin, & Heeger, 2007). This may suggest the importance of IPL in mapping visual and motor representations, and the importance of IFG in affordances and understanding goals. Regions adjacent to the traditional frontal and parietal mirror neuron regions have also been shown to have different functions with respect to visuomotor integration and remapping of actions during cooperative behaviour (Kokal, Gazzola, & Keysers, 2009).

With respect to the effects of polarity, when applied to motor cortex, anodal stimulation is typically associated with increased cortical excitability (and therefore enhanced outputs), while cathodal stimulation is typically associated with decreased cortical excitability (and therefore reduced outputs). This has been extensively demonstrated with stimulation of motor regions (Nitsche & Fregni, 2007) but has also been demonstrated in other brain regions such as occipital cortex (Nitsche et al., 2008). That both modes of stimulation of IFG appeared to disrupt IMR was unexpected, but is not unprecedented; several studies report a disruption of processes following both polarities (Ferrucci et al., 2008; Marshall, Molle, Siebner, & Born, 2005). This is thought to be particularly relevant for paradigms involving 'cortico-cortical processing' (Baudewig, Nitsche, Paulus, & Frahm, 2001) and 'cognitive' experimentation (Marshall et al., 2005), both of which are highly relevant to the current study, and is in accord with classic neurophysiological experiments suggesting a loss of function can be associated with both depolarisation and hyperpolarisation of brain tissue (Lorente De No, 1947). Polarity-independent effects of tDCS have also been found in some clinical trials (Zaghi, Acar, Hultgren, Boggio, & Fregni, 2010). Thus, it is entirely conceivable that IMR cannot be enhanced via neuromodulation of MNS regions, be it excitatory or inhibitory, and that any stimulation will interfere with its successful operation. Alternatively, it may only be possible to enhance this function when it is already disrupted by a pathological process.

Limitations of this research include the examination of only one cerebral hemisphere, a failure to index IMR prior to tDCS administration (which was done to further minimise possible habituation to stimuli), and the selection of stimulation sites according to the 10–20 system rather than magnetic resonance imaging (MRI)-guided neuronavigation. IMR tends to be associated with a moderate degree of variability, and because we used separate samples for IFG and IPL these conditions could not be directly compared. Finally, the relatively small sample size means that these findings should be interpreted with caution, and it is possible that some comparisons are underpowered; for example, and as noted, it is possible that an effect on IPL might be found with a larger sample size, but any effect seems associated with a substantially smaller effect size.

In summary, tDCS to the IFG disrupts MEP facilitation during transitive action observation, which provides among the first causal evidence for the role of IFG in IMR. As the function of the human MNS is highly controversial, it will be useful to now examine whether there are functional consequences of this presumed cortical disruption (e.g., mimicry, complex action and intention understanding, facial emotion recognition). It will also be of benefit to determine whether these findings are replicated with alternative measures of IMR, including behavioural (e.g., automatic mimicry) and neurophysiological (e.g., mu suppression during action observation), all of which are often presumed to reflect the activity of mirror neurons.

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