Improved multitasking following prefrontal tDCS

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RUNNING HEAD: Multitasking & Prefrontal Cortex

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Abstract

We have a limited capacity for mapping sensory information onto motor responses. This processing bottleneck is thought to be a key factor in determining our ability to make two decisions simultaneously – i.e., to multitask (Pashler, 1984, 1994; Welford, 1952). Previous functional imaging research (Dux, Ivanoff, Asplund, & Marois, 2006; Dux et al., 2009) has localised this bottleneck to posterior lateral prefrontal cortex (pLPFC) of the left hemisphere. Currently, however, it is unknown whether this region is causally involved in multitasking performance. We investigated the role of the left pLPFC in multitasking using transcranial direct current stimulation (tDCS). The behavioural paradigm included single- and dual-task trials, each requiring a speeded discrimination of visual stimuli alone, auditory stimuli alone, or both visual and auditory stimuli. Reaction times for single- and dual-task trials were compared before, immediately after, and twenty minutes after anodal stimulation (excitatory), cathodal stimulation (inhibitory), or sham stimulation. The cost of responding to two tasks (i.e., the reduction in performance for dual- versus single-task trials) was significantly reduced by cathodal stimulation, but not by anodal or sham stimulation. Overall, the results provide direct evidence that the left pLPFC is a key neural locus of the central bottleneck that limits an individual’s ability to make two simple decisions simultaneously.

Keywords: Posterior lateral prefrontal cortex; Transcranial direct current stimulation; Response selection; Multitasking; Bottleneck
1. Introduction

Humans typically display substantial performance impairments when required to make two decisions simultaneously. Such “multitasking costs” are thought to be associated with the restricted capacity of processes involved in mapping sensory information onto motor responses (Pashler, 1984, 1994; Welford, 1952). This sensory-motor translation stage of information processing, also known as response selection, is relatively independent of sensory and response execution operations, and is thus described as a central attention bottleneck that is stimulus and response amodal (Dux et al., 2006; Dux et al., 2009; Ivanoff, Branning, & Marois, 2009; Jiang & Kanwisher, 2003; Pashler, 1984, 1994; Welford, 1952).

In recent years neuroimaging research has provided considerable correlational evidence that the posterior lateral prefrontal cortex (pLPFC, and in particular the inferior frontal junction, IFJ) plays an important role in response selection (Dux et al., 2006; Dux et al., 2009; Hesselmann, Flandin, & Dehaene, 2011; Ivanoff et al., 2009; Jiang & Kanwisher, 2003; Marois & Ivanoff, 2005; Sigman & Dehaene, 2008). This research includes studies that have employed both dual-task paradigms (Dux et al., 2006; Dux et al., 2009; Hesselmann et al., 2011; Sigman & Dehaene, 2008) and single-task approaches in which response selection demands have been manipulated (Dux et al., 2006; Ivanoff et al., 2009; Jiang & Kanwisher, 2003). Importantly, this work has revealed that the timing of activity in the pLPFC tracks that of response selection (Dux et al., 2006; Dux et al., 2009), and that sensory-
motor training leads to a reduction in activity in the pLPFC that relates to the behavioural gains from training (Dux et al., 2009). This latter finding has led to the proposal that the pLPFC becomes fine-tuned to relevant stimulus-response mappings with training, leading to more efficient and rapid responses (Dux et al., 2009).

Transcranial direct current stimulation (tDCS) can be used to establish causal relationships between the brain and behaviour. tDCS involves two electrodes – one anode and one cathode – being applied to the scalp. Stimulation via the anodal electrode causes increased neural excitability, whereas stimulation via the cathodal electrode is associated with decreased excitability (Antal, Nitsche, et al., 2004; Nitsche et al., 2007; Nitsche & Paulus, 2000). The application of anodal and cathodal stimulation on cortical excitability can lead to distinct effects on behaviour that are specific to the polarity of the stimulation (Nitsche & Paulus, 2000; Utz, Dimova, Oppenländer, & Kerkhoff, 2010). Stimulation can also lead to effects that are the same for anodal and cathodal stimulation (Ferrucci et al., 2008; Rosenkranz, Nitsche, Tergau, & Paulus, 2000).

As discussed above, pLPFC has been highlighted as an important locus for regulating dual-task performance (Dux et al., 2006; Dux et al., 2009; Sigman & Dehaene, 2008). However, the role of this region in dual-tasking has yet to be substantiated causally. Thus, it remains possible that dual-task processing involves a different brain region (or regions), or that left pLPFC is not critical for negotiating multiple tasks concurrently. In short, the neural basis of the
limits and performance costs associated with multitasking are yet to be causally established.

Here we asked whether the left pLPFC is causally involved in giving rise to the bottleneck that limits dual-tasking. We used tDCS, applied to the left pLPFC, paired with a behavioural paradigm that required speeded responses to two sets of stimuli. On some trials a single stimulus was presented and required a response (single-task trials), and on other trials two stimuli were presented simultaneously and both required a response (dual-task trials). If dual-task processing requires the left pLPFC, stimulation should alter performance for the dual-task trials. In addition, any stimulation effect on dual-task performance should be greater than that observed for the single-task performance, as selecting two responses at the same time should put a higher load on response selection processes.

2. Method

2.1. Participants

Eighteen participants took part in the experiment (mean age = 22, range = 18 – 28 years, 3 men). All reported normal or corrected to normal vision, normal hearing, and were right handed. The Human Research Ethics Committee at The University of Queensland approved the study and all participants gave informed, written consent before taking part.
2.2. Materials and Methods

2.2.1. Stimulation Protocol

Each participant completed three testing sessions on separate days. The average time between sessions was 5 days (SD = 1.5). A different type of stimulation was administered in each session (anodal, cathodal and sham). The order in which the different stimulation types were delivered was controlled across participants, so each type of stimulation occurred equally often in each session (between participants) and with each task (see below).

Stimulation was administered with a NeuroConn stimulator, using 5 x 5 cm electrodes. The location for the target electrode was determined using the 10-20 EEG system (Jasper, 1958) and was located 1 cm posterior to F3, the region of the scalp corresponding to the left pLPFC (approximately equivalent the posterior part of Brodmann area 9). The reference electrode was placed over the right supraorbital region. This stimulation montage, depicted in Figure 1A, is a commonly used design in experiments targeting the pLPFC (Boggio et al., 2006; Boggio et al., 2009; Fregni et al., 2005; Javadi & Walsh, 2012; Utz et al., 2010).

Stimulation lasted for a total of nine minutes for the anodal and cathodal conditions, including a 30 second ramp on and a 30 second ramp off time for the current. For sham stimulation, the current lasted for 1 minute 15 seconds. For all three stimulation conditions, participants were asked to sit with their eyes open for nine minutes. The current density for all stimulation types was
0.029 mA/cm² (current intensity = 0.7 mA). This current density has been used in numerous other experiments (Antal, Kincses, Nitsche, Bartfai, & Paulus, 2004; Nitsche et al., 2008; Nitsche et al., 2003; Nitsche & Paulus, 2000; Nitsche & Paulus, 2001; Power et al., 2006) and is well within safety guidelines (Bikson, Datta, & Elwassif, 2009; Nitsche et al., 2008). Participants were not informed of the different types of stimulation, or which type of stimulation they would receive in each session.

2.2.2. Behavioural Tasks

In each session of the experiment participants completed two tasks, each with two different stimuli and response options. One of the tasks was auditory, and the other visual. This design ensured the tasks were of independent sensory modality, and required different motor responses. The specific sounds and images used for these tasks were different for each session to minimise between-session training effects. The images used were two different coloured circles (red, RGB 237 32 36; green, RGB 10 130 65), two typographical symbols (~, ^), and two computer-generated simple line shapes. There were six different sounds, all of which were complex tones used in previous experiments (Dux et al., 2006). Responses were given manually on a standard Macintosh keyboard. Participants were instructed to use the index and middle fingers on both hands, and to respond as quickly and accurately as possible. Each task was assigned a hand for the response, and each stimulus was assigned a response key. The mapping of hand (left or right) to task (auditory or visual) was counterbalanced across participants.
Participants sat 70 cm from a 19” CRT monitor, set at 100 Hz refresh rate. At the start of each session, participants were shown the images and played the sounds they would be using that session. They then completed one block of each of the tasks, and one block where either task could be shown on each trial. For these practice blocks feedback was given to ensure participants learned the appropriate response keys. The main experiment was split into three phases: pre-stimulation, immediately post stimulation, and 20 minutes post stimulation. In each of these phases participants completed 168 trials. The main experiment included three different trial types - auditory single-task, visual single-task, and dual-task conditions (see Figure 1B for a trial outline). Each trial consisted of a fixation period lasting between 200 and 600 ms (varied randomly). Fixation was followed by a visual stimulus only, an auditory stimulus only, or both a visual and an auditory stimulus presented simultaneously. The visual and/or auditory stimuli were presented for 200 ms. The three trial types were randomly intermixed within blocks, and in each phase participants completed a total of 56 trials of each type. Participants were instructed to respond as quickly and accurately as they could, and no feedback on accuracy was given during the main experiment.

3. Results

The reaction time (RT) results are shown in Figures 2 and 3, collapsed across stimulus type, and in Table 1 with each stimulus type presented separately. The error data are shown in Table 2. The variables of trial type (single- and dual-task), stimulus modality (auditory and visual), phase of the experiment
(pre-, immediate post, and 20 mins post stimulation), and stimulation type (anode, cathode, and sham) were entered into a repeated-measures ANOVA. The ANOVA revealed a significant main effect of trial type (F(1, 16) = 125.91, p < 0.001) reflecting slower responses on dual- than single-task trials (mean difference = 284 ms, SEM = 25), confirming the standard result that there was a considerable cost to trying to undertake two tasks at the same time, as opposed to undertaking each task on its own. There was also a significant main effect of stimulus modality (F(1, 16) = 22.82, p < 0.001), with slower responses to the auditory stimuli than to the visual stimuli (mean difference = 88 ms, SEM = 18). Phase of the experiment also showed a significant main effect (F(2, 32) = 11.07, p < 0.001), reflecting generally decreasing RTs with phase, and so supported the presence of an overall training effect in the data. There was no significant main effect of stimulation type (F(2, 32) = 0.45, p = 0.63), indicating no overall differences were present between the stimulation conditions.

Crucially, the main interaction of interest, that of stimulation type x phase of experiment x trial type, was significant for the RT data (F(4, 64) = 2.78, p < 0.05). This interaction was consistent across stimulus modality (F(4, 64) = 0.85, p = 0.5); thus, the present results were not specific to auditory or visual stimuli. Consequently, for the remaining analyses, RT data were collapsed across the two modalities (the RTs for visual and auditory modalities are shown separately in Table 1).
This interaction reflects differential effects of stimulation on the single- and dual-task conditions (see Figure 3), and generally larger effects of stimulation on the latter. For the dual-task trials, performance was improved (i.e., RTs were reduced) immediately after cathodal stimulation, such that the RT difference for pre- versus immediately post-stimulation sessions significantly interacted with the type of stimulation administered ($F(2, 32) = 3.41, p < 0.05$). Follow up t-tests confirmed this pattern, as follows: The change in performance between the phases did not differ between anodal and sham stimulation ($t(16) = 0.08, p = 0.94$, two-tailed). By contrast, the pre- versus immediate post-stimulation change in performance for the cathodal stimulation condition was significantly different from both the sham ($t(16) = 2.32, p < 0.05$, two-tailed) and anodal stimulation trials ($t(16) = 2.15, p < 0.05$, two-tailed). To summarise, dual-task performance was affected by cathodal stimulation, but not by anodal or sham stimulation.

For the single-task data, performance in the sham stimulation condition improved across the three phases. This improvement was disrupted by anodal or cathodal stimulation. Planned t-tests were run on the RT difference between the pre-stimulation and 20 mins post stimulation phases, comparing performance for each active stimulation condition to sham. The difference was marginally significant for the anodal versus sham comparison ($t(16) = 1.64, p = 0.06$, one-tailed) and was significant for the cathodal versus sham comparison ($t(16) = 1.84, p < 0.05$, one-tailed). There was no significant difference between the anodal and cathodal conditions ($t(16) = 0.62, p = 0.27$, one-tailed).
The experiment was designed to minimise transfer of training effects between sessions. To confirm the design was successful, an ANOVA was run on the mean RT per session for the two task types (single and dual). There was no significant main effect of session on RTs ($F(2, 32) = 1.41$, $p = 0.26$), and no significant interaction between session and task type ($F(2, 32) = 0.65$, $p = 0.53$). Thus, there was no evidence for cross-session training effects, demonstrating that our use of distinct tasks in each stimulation session had the desired effect.

Performance for the pre-stimulation phase varied slightly between the three stimulation conditions (see Figure 2). However, these differences were not significant ($F(2, 32) = 0.97$, $p = 0.39$). The single-task RTs for the pre-stimulation phase of the experiment were almost identical ($F(2, 32) = 0.02$, $p = 0.98$).

The interaction between stimulation type, phase of the experiment, and trial type was not significant for the error rates ($F(4, 64) = 1.68$, $p = 0.17$). Therefore the significant interaction in the RTs does not reflect a change in response criteria relating to a speed accuracy trade-off.

4. Discussion

Previous research has provided substantive correlational evidence that the left pLPFC is an important region for dual-task processing, and specifically the
central bottleneck of information processing (Dux et al., 2006; Dux et al., 2009; Hesselmann et al., 2011; Marois & Ivanoff, 2005; Sigman & Dehaene, 2008). Thus, this brain region is associated with performance costs observed when individuals are required to make two or more choices simultaneously. Here we aimed to provide causal evidence for a role of the left pLPFC in dual-tasking using tDCS. We used a paradigm with two speeded-discrimination tasks – one auditory and one visual – each requiring two-alternative-forced choices. These two trial types occurred either on their own (single-task trials) or simultaneously (dual-task trials). Participants ran through the experiment in three phases – pre-stimulation, immediate post-stimulation, and 20 minutes post-stimulation. Overall, the results indicated cathodal stimulation influenced RT performance on dual-task trials. This finding provides causal evidence that the left pLPFC is a critical region in multitasking, and the associated costs and limits to performance.

It should be noted that multitasking RTs obtained in the pre-stimulation period were somewhat variable between stimulation conditions. These differences were not significant, however, and most likely reflect between-participant variability. The patterns of change in RTs across phases of the experiment were the main point of interest, and these yielded the anticipated significant interaction.

Two lines of evidence suggest that the findings are due to disruption of the left pLPFC, and are not a more general effect of arousal or stimulation. First, previous experiments from our group (Filmer, Mattingley, Marois, & Dux,
Submitted) have found response selection effects are specific to the left pLPFC, and do not extend to its right hemisphere homologue. Second, in the current investigation we found no effect of anodal stimulation on multitasking performance, demonstrating that our dual-task results do not reflect a non-specific influence of brain stimulation.

Importantly, the interaction of interest did not vary significantly with stimulus modality (visual vs. auditory), thus ruling out the effect as being due to differences in sensory processing. This supports our assertion that the paradigm used here taps response selection, which is thought to be both stimulus- and response-invariant (Dux et al., 2006; Dux et al., 2009; Ivanoff et al., 2009; Jiang & Kanwisher, 2003; Pashler, 1984, 1994; Welford, 1952). Single- and dual-task performance involved similar motor outputs (simple button presses), but varied in response selection demands. The fact, then, that cathodal stimulation selectively improved performance for the dual-task conditions is further evidence the disruption was not due to a tDCS-induced alteration in motor processing.

However, two alternative explanations, involving central operations that are different to response selection, must be considered. First, the stimulation could have affected response maintenance in working memory. This possibility has already been refuted as an explanation for response selection effects in previous research (Dux et al., 2006; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000; Sigman & Dehaene, 2005). Specifically, a working memory account would predict an effect on performance errors,
which was not found in the experiment reported here. Second, stimulation could have affected response criterion. This explanation predicts a change in the relation between speed and accuracy – i.e., performance becomes faster but less accurate. Such explanations would predict effects on error rates that match those in the RTs. This was not found in the present data. Thus, collectively, the most parsimonious explanation for our findings is that stimulation influenced response selection.

It is also possible that the effects of the stimulation were due to the reference electrode site, and not the left pLPFC. This is unlikely as there is no evidence the right orbitofrontal cortex is involved in multitasking. Indeed, none of the mentioned fMRI studies highlight any role of the orbitofrontal region in mapping sensory information to motor responses (Dux et al., 2006; Dux et al., 2009; Hesselmann et al., 2011; Ivanoff et al., 2009; Jiang & Kanwisher, 2003; Marois & Ivanoff, 2005; Sigman & Dehaene, 2008). It is for this reason that this area was chosen as the site for the reference electrode, as has been the case in many previous studies (Boggio et al., 2006; Boggio et al., 2009; Fregni et al., 2005; Javadi & Walsh, 2012; Utz et al., 2010).

Cathodal stimulation of the left pLPFC selectively improved performance on dual-task trials immediately following stimulation, relative to sham and anode stimulation. The finding of a polarity-specific effect of stimulation, and more specifically improvements in cognitive tasks following an inhibitory (cathodal) stimulation protocol, has been reported previously (Antal, Nitsche, et al., 2004; Dockery, Hueckel-Weng, Birbaumer, & Plewnia, 2009; Moos, Vossel,
The precise mechanism underlying cognitive facilitation following an inhibitory stimulation protocol is unclear. One possibility is that inhibition suppresses neural noise, reducing the signal to noise ratio in the stimulated cortex (Antal, Nitsche, et al., 2004; Dockery et al., 2009; Miniussi, Harris, & Ruzzoli, 2013). To date, there is no compelling evidence or rationale for facilitation following inhibitory stimulation and the mechanism behind such effects remain elusive (Kadosh, 2013). Regardless of the reasons behind the enhancement, the findings of the current study support the involvement of left pLPFC in dual-task response selection, and the associated limits and performance costs.

For the single-task trials, performance was impaired following anodal and cathodal stimulation compared with sham, and this effect became more marked with training. This disruption to training for single-task response selection directly replicates previous findings from our group (Filmer et al., Submitted). However, the reduced training for active stimulation conditions was only marginally significant in the current experiment. This is not surprising, as we have previously found a significant effect of stimulation under high response selection load (with six response options), but no such effect for low response selection load (two response options). In the current experiment, there were two tasks with two possible response options – a total of four response options across tasks. A smaller effect, then, is in line with our previous findings. Indeed, the purpose of the experiment reported here was not to disrupt single-task training, but to investigate dual-task response selection in the left pLPFC.
The reduction in training for single-task performance was approximately equivalent for cathodal (inhibitory) and anodal (excitatory) stimulation. A stimulation effect that is equivalent for both inhibitory and excitatory protocols suggests a mechanism for training that depends on a highly balanced level of excitability. Any departure from this balance disrupts the ability of the region to become more selective following training. This suggestion supports the hypothesis that training leads to a process of fine-tuning in pLPFC and, as a result, improved efficiency for response selection (Dux et al. (2009). Such effects on behavioural gains following training have been shown for other cognitive processes (Ferrucci et al., 2008; Sandrini, Fertonani, Cohen, & Miniussi, 2012) and motor responses (Rosenkranz et al., 2000), indicating that the proposed fine-tuning mechanism could be tapped by other types of training.

Our findings support the hypothesis that the left pLPFC is an important region for both single- and dual-task response selection. However, the contrasting effect of stimulation on the two types of response selection must be considered. It could be that the mechanism for single- and dual-task response selection is different, and whilst both involve the same brain region, the precise operation underlying each differs. The previous literature supports there being a central processing operator that is capacity limited (Dux et al., 2006; Dux et al., 2009; Ivanoff et al., 2009; Jiang & Kanwisher, 2003; Pashler, 1984, 1994; Sigman & Dehaene, 2008; Welford, 1952). This central operator is thought to be involved in both single- and dual-task processes, suggesting
a similar underlying mechanism to response selection across comparable single- and dual-task conditions (Dux et al., 2006; Dux et al., 2009; Ivanoff et al., 2009; Jiang & Kanwisher, 2003). Here we have a hint of some dissociation at the neural level, where multitasking could include a separate mechanism within the same brain region that processes the constituents. Alternatively, the different pattern of results for single- and dual-task trials may relate to the stage of training. In our data, the single-task responses showed training effects in the sham condition, but the dual-task responses showed only small improvements across the phases. If dual-task response selection were at an earlier stage of training, where some initial process of consolidation was taking place, this might account for the different effect. Previous research has indicated the effect of tDCS on performance could change at different stages of training at a planning task (Dockery et al., 2009). Either a different mechanism for dual- and single-task processing within the left pLPFC, or a different influence of stimulation for different phases of training within the left pLPFC, are possible accounts for our data. This topic represents an interesting and important avenue for future research.

To summarise, we have provided evidence that the left pLPFC plays a causal role in the central information-processing bottleneck. Stimulating this brain region with an inhibitory protocol improves multitasking performance. The results support the conclusion that at least part of our limited capacity for multitasking resides in left pLPFC.
Acknowledgments

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References
transcranial direct current stimulation impairs the practice-dependent proficiency increase in working memory. *Journal of cognitive neuroscience, 20*(9), 1687-1697.


**TABLE 1**

**Mean RTs for all conditions.** Mean RTs (ms) shown separately for each stimulation type, experimental phase, trial type, and task modality.

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<th>Auditory</th>
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<th>Visual</th>
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<td></td>
<td>Pre-Stimulation</td>
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<td>Post</td>
<td>20 mins</td>
<td>Pre-Stimulation</td>
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<tr>
<td></td>
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<td>1021</td>
<td>980</td>
<td>916</td>
<td>933</td>
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<tr>
<td>Cathode</td>
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<td>707</td>
<td>707</td>
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<tr>
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<td>Dual</td>
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<td>985</td>
<td>929</td>
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<tr>
<td>Sham</td>
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<td>701</td>
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<td>630</td>
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<td>598</td>
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<tr>
<td></td>
<td>Dual</td>
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<td>997</td>
<td>952</td>
<td>909</td>
<td>915</td>
<td>885</td>
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TABLE 2

Mean error rates for all conditions. Mean error rates (%), shown separately for each stimulation type, experimental phase, trial type, and task modality.

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<td>Pre-Stimulation</td>
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<tr>
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<tr>
<td>Single</td>
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<td>2.31</td>
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<tr>
<td>Dual</td>
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<td>5.78</td>
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<tr>
<td>Dual</td>
<td>8.30</td>
<td>4.62</td>
<td>8.93</td>
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FIGURE 1

Experimental design. (A) Transcranial direct current stimulation (tDCS) electrode montage. The target electrode was placed 1cm posterior to F3 located via the 10-20 EEG system (Jasper, 1958). The reference electrode was placed over the right orbitofrontal cortex. (B) Standard trial outline. Participants were shown a fixation dot centrally on a monitor, followed by an image (a coloured circle, a symbol, or a shape depending on the experimental session), or a sound (a tone), or both an image and a sound. Participants were instructed to respond as quickly and accurately as they could to the stimulus or stimuli.
FIGURE 2

Mean reaction times pre tDCS. The graphs display reaction times (RTs) for each stimulation condition during the pre tDCS phase. The RTs are shown separately for the single-task (A) and dual-task (B) trials. The error bars represent the SEM of the mean RT.
FIGURE 3
Influence of tDCS on single- and dual-task reaction times. A) and C) show the difference in RTs between the before tDCS and the immediately post tDCS experimental phases, separately for the single- and dual-task trials. B) and D) show the difference in RTs between the before tDCS and 20-minute post tDCS experimental phases, separately for the single- and dual-task trials. The error bars represent the SEM of the RT difference.