Site-dependant effects of tDCS uncover dissociations in the communication network underlying the processing of visual search.

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Abstract

Background - The right posterior parietal cortex (rPPC) and the right frontal eye field (rFEF) form part of a network of brain areas involved in orienting spatial attention. Previous studies using transcranial magnetic stimulation (TMS) have demonstrated that both areas are critically involved in the processing of conjunction visual search tasks, since stimulation of these sites disrupts performance.

Objective - This study investigated the effects of long term neuronal modulation to rPPC and rFEF using transcranial direct current stimulation (tDCS) with the aim of uncovering sharing of these resources in the processing of conjunction visual search tasks.

Methods - Participants completed four blocks of conjunction search trials over the course of 45 minutes. Following the first block they received 15 minutes of either cathodal or anodal stimulation to rPPC or rFEF, or sham stimulation.

Results - A significant interaction between block and stimulation condition was found, indicating that tDCS caused differential effects according to the site (rPPC or rFEF) and type of stimulation (cathodal, anodal, or sham). Practice resulted in a significant reduction in reaction time across the four blocks in all conditions except when cathodal tDCS was applied to rPPC.

Conclusions - The effects of cathodal tDCS over rPPC are more subtle than those seen with TMS, and no effect of tDCS was evident at rFEF. This suggests that rFEF has a more transient role than rPPC in the processing of conjunction visual search and is robust to longer term methods of neuro-disruption. Our results may be explained within the framework of functional connectivity between these, and other, areas.

1. Introduction

Two brain areas that are widely accepted to be engaged in the visual attentional network are the right frontal eye fields (rFEF, 1, 2-4) and the right posterior parietal cortex (rPPC, 3, 4, 5). A basic visual search paradigm can be manipulated to investigate issues relating to stimulus features, the identification and segmentation of targets and distractors, spatial localisation, and the allocation of attention. While imaging studies have shown that both the FEFs and rPPC are involved in visual search (6-8), TMS studies have gone on to demonstrate that their involvement is critical (9-15). However, while we know much about how rPPC and rFEF act in isolation we lack understanding of whether these regions communicate with each other, and evidence to date has been correlative at best (c.f. 16). Here we used transcranial direct current stimulation (tDCS) to investigate possible co-dependencies between these two nodes on the attentional network.

tDCS involves passing an electrical current between two electrodes positioned on the scalp which can modulate the excitability of cortex by decreasing (via anodal stimulation) or increasing (via cathodal stimulation) the threshold of activity of underlying neurons (17-19). More specifically, anodal stimulation results in decreased GABA concentrations and cathodal stimulation creates a reduction in glutamate (20). Thus, cathodal stimulation, after which neurons are less likely to fire, has been likened in its behavioural effect to TMS, albeit by different mechanisms (21, 22). We chose to use tDCS to investigate communication between rPPC and rFEF for two reasons. Firstly, the effects of tDCS are not restricted to the site of the electrode but rather they extend to other functionally relevant and widespread brain areas (23-26), therefore targeting the wider processing loops involved in visuospatial attention. Secondly, the electrophysiological effects of tDCS can outlast application (of 1mA for 9 - 13 minutes) by up to 90 minutes (27-29), allowing us to assess the effect of long term neuro-modulation at our sites of interest.

Based on observations with TMS it is predicted that cathodal stimulation will lead to a slowing in search times in a conjunction search task, while the tDCS literature indicates that faster search times will be observed following anodal stimulation. Furthermore, if rPPC and rFEF are communicating with each other on a task that we know they are both involved in then the same effect of tDCS will be seen regardless of which site the stimulation is applied to. Alternatively, if the effect of tDCS is different depending on the site of application, then the communication between rFEF and rPPC may be one directional.

2. Method

2.1. Participants

35 participants (12 male) from Durham University took part in this experiment (age range 19 to 52 years, mean age 26.1, *SD* = 8.5, 31 right handers). Participants were randomly assigned to one of five conditions. All participants were from Durham University and had normal or corrected-to-normal vision. Participant selection complied with the current guidelines for repetitive tDCS research. Participants gave their signed informed consent in accordance with the Declaration of Helsinki and with the approval of Durham University Ethics Advisory Committee.

2.2. Visual search task

The experiment was run on an IBM compatible personal computer with a 16-inch monitor (1024 by 768 resolution, refresh rate 60 Hz) and was programmed using E-prime (Psychology Software Tools Inc., Pittsburgh, PA, USA). The viewing distance was 57 cm and the centre of the screen was at eye level, with a chin rest used to ensure that this was maintained. The experiment was completed in a dark room.

The search arrays consisted of red and green lines on a black background (Figure 1). The target was always a red forward slash (oriented at 45˚ from vertical) and distractors were green forward slashes and red backslashes (oriented at -45˚ from vertical). Search arrays contained 12 items: in target present trials there was one target and 11 distractors (five red backslashes and six green forward slashes), and in target absent trials there were 12 distractors (six red backslashes and six green forward slashes). The target was present on 50% of trials, with the target appearing on the left and right side of the array equally frequently. Each line measured 2.5˚ of visual angle in length and 0.4˚ of visual angle in width. The whole screen measured 32˚ of visual angle horizontally and 24˚ vertically. The 12

items in each search array were randomly placed into a 10 x 6 virtual grid to prevent them from overlapping.

2.3. Procedure

At the beginning of each trial a white fixation cross (0.5˚of visual angle) was presented centrally for 500 ms. This was followed by the presentation of a search array. Participants had to decide as quickly and as accurately as possible whether the target was present or absent, and make the corresponding key-press response (Cedrus RB-620 button box, San Pedro, California). The search array remained on the screen until participants responded. A blank screen was then presented for a variable duration (from 3000 ms to 5000 ms) before the next trial was initiated. No feedback was provided about the accuracy of the response. Participants completed four blocks of visual search trials (30 target present and 30 target absent trials per block), each block taking approximately six minutes to complete. Upon completion of block 1, the 15 minutes of tDCS (or sham stimulation) started. With the exception of block 2, which participants started after five minutes of stimulation and completed during the stimulation period, participants completed the blocks of trials at 15 minute intervals, with block 3 starting immediately after the 15 minutes of stimulation had finished (see Figure 1). In the time between blocks participants sat quietly in the darkness until they were instructed to start the next block.

2.4. Transcranial direct current stimulation

The two rubber electrodes were placed in two sponge pouches (7 cm x 5 cm) which had been soaking in a physiologically active saline solution. A rubber strap was used to hold the two electrodes in place. tDCS was applied using a Magstim Eldith DC stimulator for 15 minutes at a current intensity of 1.0 mA. This level of stimulation was selected given

previous reports that 1.0mA is sufficient at inducing measureable changes in performance (30-33). Stimulation protocol complied with the current safety guidelines for tDCS (34). There were three stimulation conditions (Cathodal, Anodal, and Sham) and two stimulation sites (rFEF and rPPC). Thus, there were five conditions in total, only one of which each participant received: cathodal stimulation to rPPC (C_rPPC), cathodal stimulation to rFEF (C_rFEF), anodal stimulation to rPPC (A_rPPC), anodal stimulation to rFEF (A_rFEF), or sham stimulation (Sham). Pilot work confirmed previous reports that search performance improves across testing sessions (35); therefore, a between groups design was used whereby participants only completed one of the five stimulation conditions to remove this potential confound.

In the cathodal stimulation condition the cathode was placed over either the rFEF or rPPC and the anode electrode was placed above the participant's left eye. Likewise, in the anodal condition, the anode electrode was placed over the rFEF or rPPC and the cathode was placed above the left eye. A contralateral reference position was used on account that this is most frequently used in the literature (see Table 1 in 36). In the Sham condition, participants received stimulation for only 30 seconds; consequently, they experienced the initial tingling sensation associated with real stimulation but insufficient current for any neuronal modulation. As such, participants were not aware which stimulation condition they were experiencing.

The rPPC location was measured as being 9 cm dorsal and 6 cm lateral to the right of the mastoid-inion, as this corresponds with the angular gyrus known for its role in visual search tasks using TMS (14, 37). The rFEF site was located 5 cm lateral towards the right and 4 cm anterior from the vertex, corresponding with the confluence of the right pre-central and superior frontal gyri, the location of rFEF (38). The locations of the two brain sites are shown in Figure 2. The area of stimulation was defined by the size of the electrodes (39) with

maximum current being discharged directly below the electrodes (40), thus, precise functional localisation of the sites of interest was not necessary and centring the electrode over the known regions was sufficient.

< Figure 1 >

< Figure 2 >

3. Results

3.1. Data analysis

Analyses were concerned with participants' reaction times to target present trials only. Responses to incorrect trials were removed: participants were correct on 94.6% of target present trials and accuracy did not differ across the five stimulation conditions ($p = 0.151$, Kruskal-Wallis test). Reaction times for trials that were more than two standard deviations above or below the individual's mean were also excluded (11.0% of correct trials were excluded); however, the number of trials carried out was robust to such attrition with respect to the matter of power. All data were tested for normality using the Shapiro–Wilk statistic; the data were normal unless otherwise stated. Inferential statistics used a significance level of $p < 0.05$, except when multiple comparisons were performed, when a Bonferonni correction was applied.

3.2. Global analysis

The mean reaction times for the four blocks of trials in each stimulation condition are shown in Figure 3. A one-factor ANOVA comparing reaction times in Block 1 for the five Stimulation Conditions (C_rPPC, C_rFEF, Sham, A_rPPC, A_rFEF) found no difference between the Stimulation Conditions ($M = 873.87$, $SD = 177.1$, $p = 0.989$).

A 4 x 5 ANOVA with the within subject variable of Block (1 - 4) and the between subject variable of Stimulation Condition (C_rPPC, C_rFEF, Sham, A_rPPC, A_rFEF) revealed a statistically significant main effect of Block, $F_{(3, 90)} = 16.82$; $p < 0.05$, and a non-significant main effect of Stimulation Condition ($p = 0.930$). However, the Block by Stimulation Condition interaction was significant, $F_{(12, 90)} = 1.94$; $p < 0.05$, indicating that tDCS effects were modulated by site (rFEF or rPPC) and type of stimulation (Cathodal, Anodal, or Sham). The cathodal and anodal data were therefore analysed separately, with each being compared to the Sham condition.

< Figure 3 >

3.3. Cathodal stimulation

A 4 x 3 ANOVA with the within subject variable of Block (1 - 4) and the between subject variable of Stimulation Condition (C_rPPC, C_rFEF, Sham) revealed a statistically significant main effect of Block, $F_{(3, 54)} = 9.00$; $p < 0.05$, and a non-significant main effect of Stimulation Condition ($p = 0.505$). The Block by Stimulation Condition interaction was significant, $F_{(6, 54)} = 3.78$; $p < 0.05$, suggesting that reaction time patterns across the four blocks of trials varied between the Stimulation Conditions. The main effect of Block was significant in the Sham and rFEF conditions ($F_{(3, 18)} = 6.82$; $p < 0.017$; $F_{(3, 18)} = 7.68$; $p < 0.017$, respectively) but not in the rPPC condition ($p = 0.151$, repeated measures ANOVA for each Stimulation Condition).

To get immediate and overall measures of search performance, reaction time comparisons were made between the first and second blocks and between the first and fourth blocks of trials. In the Sham condition participants became faster between both the first two blocks of trials (reduction of 67.1 ms, $t_{(6)} = 2.99$; $p < 0.025$), and between the first and fourth

blocks of trials (reduction of 89.8 ms, $t_{(6)} = 3.92$; $p < 0.025$, paired sample t-tests). In the rFEF condition, the same pattern was seen (reduction of 72.4 ms between blocks 1 and 2, $t_{(6)} = 4.41$; $p < 0.025$; reduction of 132.9 ms between blocks 1 and 4, $t_{(6)} = 3.42$; $p < 0.025$, see Figure 3B). Conversely, in the rPPC condition there was a trend for an increase in reaction times between blocks 1 and 2 (increase of 40.1 ms, $t_{(6)} = 1.48$; $p = 0.188$), and across the four blocks of trials there was no change in reaction times (reduction of 7.8 ms, $t_{(6)} = .25$; $p = 0.813$, see Figure 3A). Thus, while cathodal stimulation had no effect when applied to rFEF, the same stimulation negated the speeding associated with practice when applied to rPPC.

3.3.1. Normalised effects

Reaction times in the two cathodal stimulation conditions were normalised with respect to sham reaction times in order to compare the relative effect of tDCS at these sites using the following equation: (Cathodal_site y Block y – Sham_site x Block y)/ Sham Block x) * 100/1. These percentage effects of tDCS are shown in Figure 4, with a positive number indicating reaction times were slower when tDCS was applied than in the Sham condition. A mixed ANOVA with the within subject variable of Block (2 - 4) and the between subject variable of Stimulation Condition (C_rPPC, C_rFEF) revealed a significant main effect of Stimulation Condition, $F_{(1,12)} = 4.95$; $p < .05$, indicating that tDCS had a differential effect over the two sites (main effect of Block: $p = 0.270$; Block x Stimulation Condition interaction: $p = 0.618$).

3.4. Anodal stimulation

A 4 x 3 ANOVA with the within subject factor of Block (1 - 4) and the between subject variable of Stimulation Condition (A_rPPC, A_rFEF, Sham) revealed a statistically significant main effect of Block, $F_{(3, 54)} = 12.96$; $p < 0.05$; a non-significant main effect of

Stimulation Condition (p = 0.991); and a non-significant Block by Stimulation Condition interaction (p = 0.656): reaction times decreased across the four blocks of trials in all three stimulation conditions (A_rPPC, A_rFEF, Sham, see Figures 3C and 3D). Owing to the non-significant interaction between Block and Stimulation Condition, comparison of normalised effects is not required (see Figure 4).

< Figure 4 >

4. Discussion

The experiment reported here sought to define the effects of cathodal and anodal tDCS on the processing of an attentional task when current was applied separately to two brain regions known to be involved in this task, namely rPPC and rFEF (12, 15, 41).

4.1. Cathodal stimulation

The results show that only cathodal tDCS over rPPC affects visual search performance. Furthermore, the effects were limited in duration: performance was impaired by cathodal tDCS relative to the sham condition only when the task was performed concurrently or immediately following stimulation (blocks 2 and 3). This is in contrast to other studies with the less conservative measure of motor evoked potential (MEP) that show effects up to 90 minutes later (27, 28). Differences between block 2 (concurrent stimulation) and blocks 3 and 4 (post-stimulation) would be expected given that the effects of online tDCS and offline tDCS are mediated by different mechanisms: online cathodal stimulation alters the resting membrane potential, while effects following a period of cathodal stimulation are driven by the modulation of glutamatergic synapses (42).

Practice in visual search typically leads to a reduction in search times (43). However, following cathodal stimulation to rPPC (block 4) search times were no different to those before stimulation (block 1). It was expected that cathodal tDCS would have the same behavioural effect as TMS owing to the decrease in activity of the underlying neurons, and thus increasing the threshold of activation (TMS in contrast introduces neural “noise” resulting in the same functional effect of a deficit in performance if that area is involved). Therefore, cathodal tDCS would seem to have a more subtle effect on behaviour by negating the decrease in reaction time seen with ensuing blocks (the practice effect). Whilst the practice effect in this experiment cannot be equated with plasticity associated with perceptual

learning, since this typically requires longer term learning over days separated by episodes of REM sleep (35), it is possible that the short-term practice effects are mediated by the distal effect of cathodal tDCS on sub-cortical networks. Using functional connectivity MRI, Eldaief and colleagues (44) have shown that low frequency TMS to the left inferior parietal lobule can modulate connectivity with the hippocampal formation. Although tDCS and rPPC were involved in the current experiment, it remains possible that cortical intervention can lead to effects that are mediated by subcortical mechanisms.

In contrast to the effects we observed at rPPC, we found that cathodal tDCS applied to rFEF had no significant effect of any kind. We considered the possibility that our reaction time measure was not sufficiently sensitive to detect very subtle changes in search performance by conducting a second experiment, this time focusing solely on cathodal stimulation of rFEF. Such a view is supported by a recent study by Muggleton et al. (45) which dissociated the role of rFEF and rPPC with respect to responses involving eye movements and manual responses. We recorded eye movements in a dot localisation task and again found no difference between stimulation conditions: eye movement execution in terms of the speed of onset and duration was not different in the cathodal and sham stimulation conditions (see Supplementary Material). Therefore, it would appear that the involvement of rFEF in conjunction visual search is less clear when investigated with tDCS. This is in contrast to event related TMS which has a detrimental effect on visual search reaction times when applied to rFEF (9-12). The lack of neuro-modulation of rFEF with cathodal tDCS here suggests that rFEF is not amenable to tDCS modulation. Both this, and the findings from TMS that disruption to search performance is observed when stimulation is applied at the point of stimulus onset (12) and after a very brief delay (40 – 80 ms post stimulus onset, 41), indicate that rFEF works transiently. As we have demonstrated here, prolonged stimulation of this region does not have a demonstrable effect on behaviour. This suggests that this region

can overcome such disruption either due to its relatively short and transient input to processing or via hitherto uncovered neuroplastic mechanisms which ensures normal function. Theoretically, such mechanisms could include the recruitment of or compensation by other regions (as seen between v5 and PPC when processing at V5 is disrupted, Ellison et al., 2007). However, we can discount rPPC as a potential substrate since extended stimulation should affect rPPC activity and therefore affect performance, and this was not observed in our study.

Anatomically, both rFEF and rPPC are highly interconnected with other brain regions and each other (4, 46), and in our experiment cathodal tDCS had a functional effect at one site (rPPC) but not the other (rFEF). This leads us to speculate about the complex nature of communication between the two. The effects observed during and following cathodal stimulation to rPPC may be on account of either disruption to rPPC itself or to other components of the network, including FEF or hippocampal regions. The data suggest that rPPC disruption, or disruption along its communication network, cannot be compensated for. Conversely, owing to the lack of behavioural effect following cathodal stimulation to rFEF it is likely that the decrease in neuronal activity at rFEF did not spread to disrupt rPPC (or indeed other regions). Alternatively, other regions, such as left FEF, may have taken over its function (12). These possibilities are currently being examined with functional imaging. Thus, our pattern of results shows that whilst rPPC may interact with rFEF and other regions, tDCS to rFEF does not suggest that this region acts in the same way. Although our findings are less clear than those resulting from an event related TMS study, the more prolonged polarity-dependant neuro-stimulation employed here allows us to make inferences as to the role of the areas of interest within the context of their wider processing loops.

4.2. Anodal Stimulation

Visual search performance was not modulated by anodal stimulation at either site. Anodal stimulation increases the likelihood of neuronal firing, which typically leads to improvements in task performance (for example, 47, 48, 49). With regards to visual search, under non-stimulation conditions performance typically improves after practice (the sham condition here but see also 43, 50), with reaction time eventually plateauing (35, 51). The absence of a difference between the two anodal conditions and the sham condition here suggests that practice plus anodal stimulation did not enhance performance further than would be expected with practice alone: in the neurotypical brain, performance may be at ceiling. However, it is possible that differences may appear between the anodal and sham stimulation conditions after search times have stabilised, that is, in a second testing session where further reductions in search times may be selectively seen in the anodal condition. Supporting this proposal, Dockery et al. (52) found that while cognitive planning ability improved following anodal stimulation, this effect was only observed when anodal stimulation was applied in a later session. Equally, anodal stimulation may only affect performance in more difficult tasks in which practice was not so quick to improve behaviour (53).

On the face of it our findings appear to contradict the "cathodal impairs and anodal improves" dichotomy; however, it is increasingly becoming clear that this may not be the best way to characterise the effects of cathodal and anodal stimulation. tDCS research has focused on the motor and visual cortices, and for example how stimulation affects the amplitude of MEPs or thresholds of phosphene detection (19, 27, 54-58). A meta-analysis of tDCS effects reports that that typical dissociation between anodal enhancing and cathodal impairing performance is consistently observed for motor tasks (59). Conversely, tDCS has

only more recently been used to manipulate cognitive performance (52, 60, 61), with the effects being more variable and with little effect of cathodal stimulation being reported (59). However, based on our findings here for rPPC, solely comparing performance before and after participants undergo tDCS could be misleading about the effectiveness of the stimulation. At first glance it may be tempting to conclude that cathodal stimulation had no effect on search performance when applied to rPPC. However, upon closer inspection, coupled with an understanding of the characteristics of search behaviour with increasing practice and familiarity, it is clear that cathodal tDCS negates the practice effect. While a stronger intensity of stimulation may have given us greater effects and those that match the anodal enhances and cathodal impairs pattern (e.g. 33, 62, 63), we chose to use 1.0mA as this is sufficient to induce measureable changes in performance and allows direct comparison with other studies (30-33).

4.3. Conclusion

We have found that the application of cathodal tDCS to two nodes on the visual attentional network had a functional effect at one site but not the other. Given this difference, and the fact that both rFEF and rPPC are highly interconnected with other brain regions and each other, we can speculate about the complex nature of communication between the two. The effects observed during and following cathodal stimulation to rPPC may be as a consequence of either disruption to rPPC itself or to other components of the network, including FEF or hippocampal regions. The data suggest that rPPC disruption, or disruption along its communication network, cannot be compensated for. Conversely, owing to the lack of behavioural effect following cathodal stimulation to rFEF it is likely that the decrease in neuronal activity at rFEF did not spread to disrupt rPPC (or indeed other regions).

Alternatively, other regions, such as left FEF, may have taken over its function. These possibilities are currently being examined with functional imaging.

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Figures

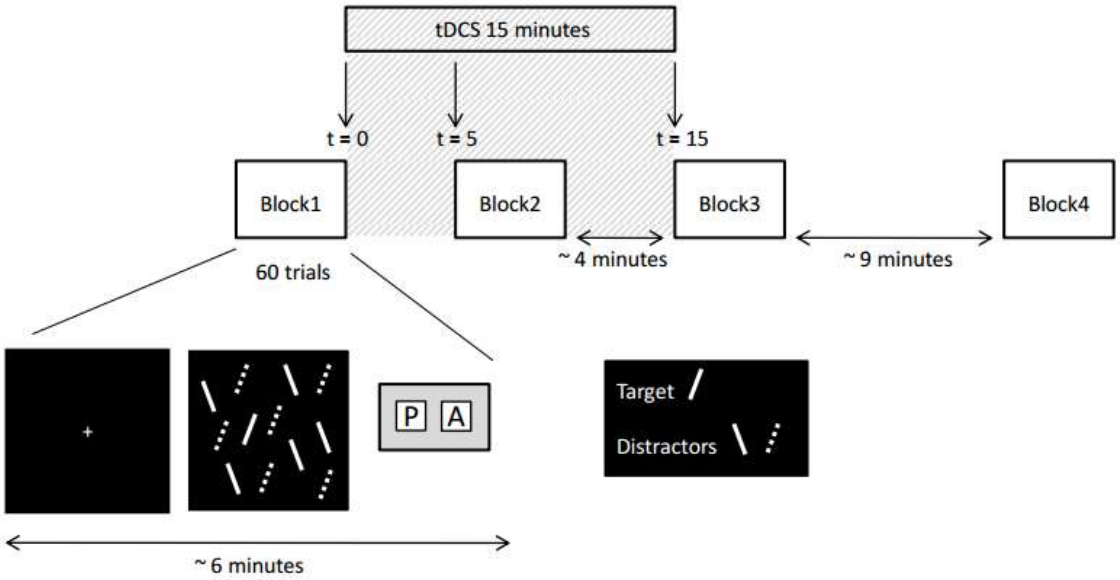

Figure 1. Schematic of the experimental procedure and timing information used and an example visual search display.

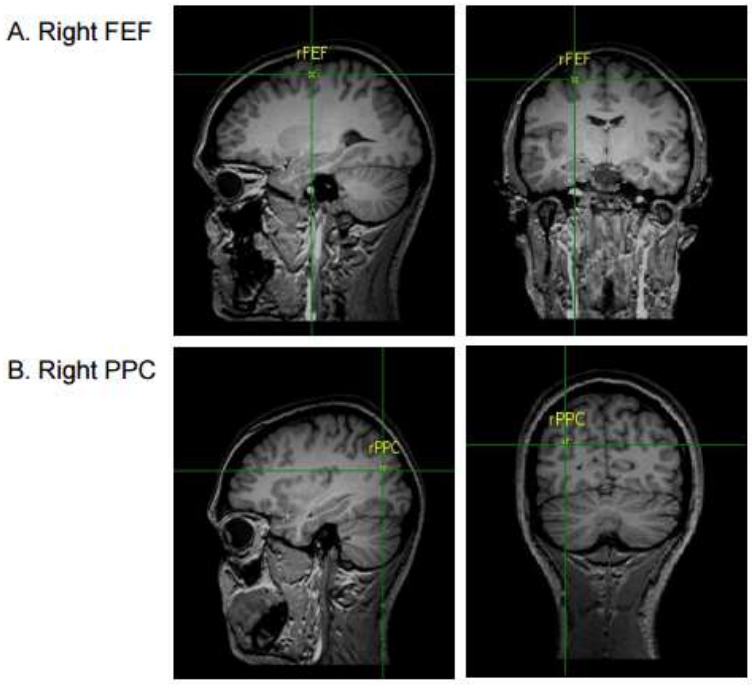

Figure 2. Locations of rPPC and rFEF.

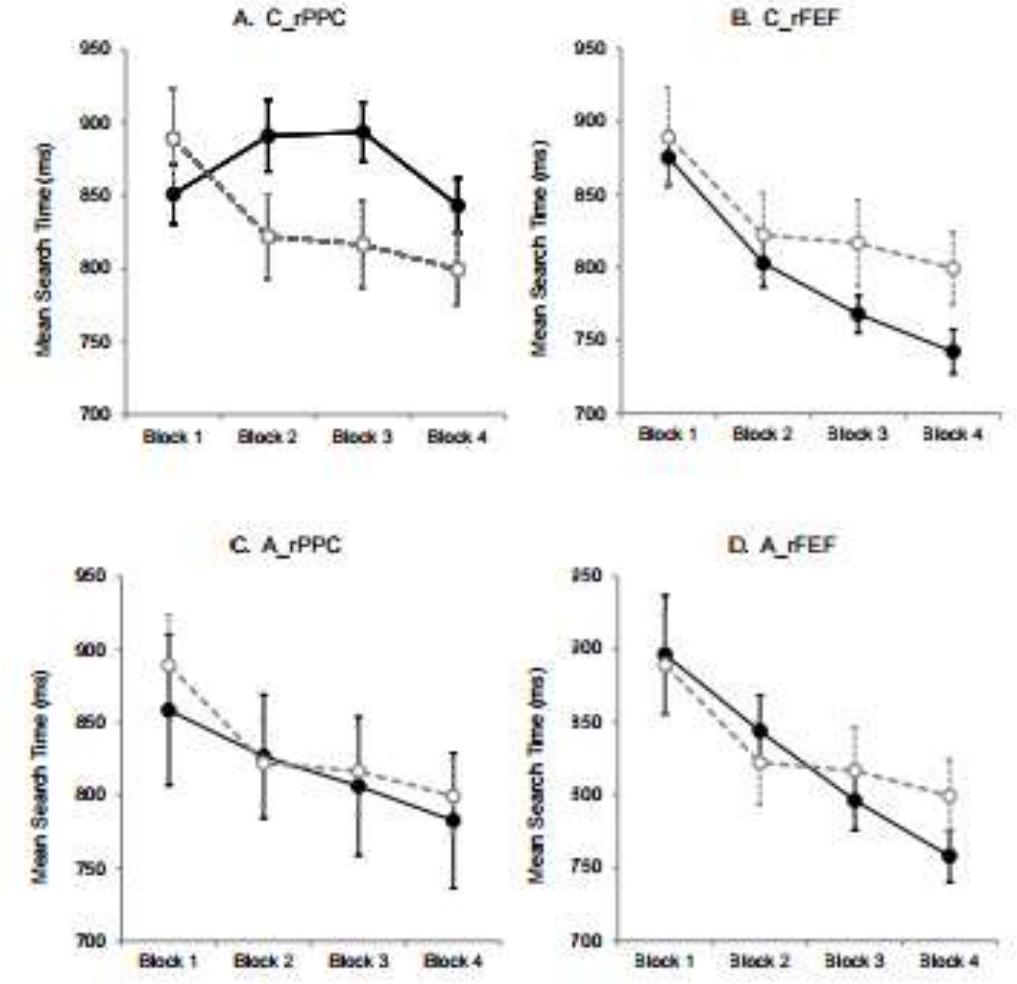

Figure 3. Graphs depicting the mean reaction time (ms) for the four blocks of visual search trials with each stimulation condition compared to the sham condition. (A) Cathodal rPPC, (B) Cathodal rFEF, (C) Anodal rPPC, (D) Anodal rFEF. Error bars represent +/- 1 standard error of the mean for each condition. The grey dashed line denotes the sham condition, and likewise the error bars for the sham condition are represented by a grey dashed line.

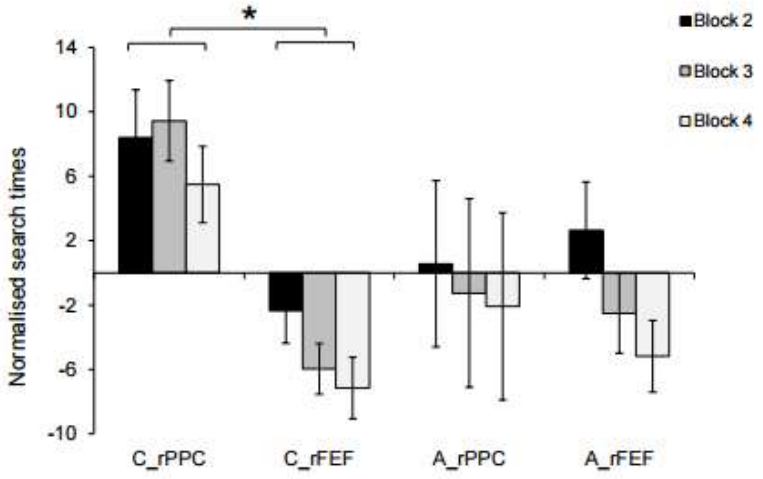

Figure 4. Normalised reaction times for each site expressed as a percentage of sham reaction times. This allows for efficient comparison of tDCS effects across sites. A positive number indicates slower reaction times when tDCS was applied. * denotes $p < .05$. Error bars represent +/- 1 standard error of the mean for each condition.

Supplementary material – EOG and cathodal stimulation to rFEF

Participants

14 participants (7 male) from Durham University took part in Experiment 2 (age range 20 to 53 years, mean age 29.0, *SD* = 8.0; 11 were right handed). Participants were randomly assigned to one of two stimulation conditions (Cathodal and Sham).

Dot localisation task

Participants were required to make an eye movement from a central fixation cross (0.5˚of visual angle) to a white circle (0.5˚ in diameter) presented at one of twelve possible locations. Circles were presented at one of two eccentricities (3.5˚ and 7˚ either to the left or the right of the fixation cross), and at three different heights (3.5˚ above and below the fixation cross and level with fixation cross). The whole screen measured 32˚ of visual angle horizontally and 24˚ vertically.

Procedure

At the beginning of each trial a white fixation cross was presented centrally for 1500 ms. This was followed by the presentation of a dot at one of 12 locations for 2000 ms. Participants had to make an eye movement to the dot and press a button when they were fixating it. A blank screen was then presented for 2000 ms, before the next trial was initiated. Participants completed four blocks of trials, each block consisting of 60 trials and taking approximately six minutes to complete. The dot appeared at each of the 12 possible locations five times per block and the location was randomised across trials. The tDCS procedure was the same as that used in the main experiment (Figure 1).

Transcranial direct current stimulation

The stimulation parameters were the same as those used before with the exception that there were only two stimulation conditions: Cathodal and Sham; and one stimulation site: rFEF. As before rFEF was measured as being 5 cm lateral towards the right and 4 cm anterior from vertex (Figure 2).

Eye movement recording

Electro-oculographic eye movement data were recorded throughout the trials using an MP35 acquisition unit and BSL Pro 3.7 software (Biopac Systems Inc., CA, USA). Six shielded 4 mm AgCl electrodes were attached to the participants' skin using adhesive disks, and electrode gel was used to improve recording conductance. Both vertical and horizontal eye movements were measured. The two vertical recording electrodes were aligned above and below the participant's right eye. The ground electrode for the vertical channel was placed on the right ear lobe of the participant. The two electrodes that measured the horizontal movements were placed adjacent to the temporal canthus of each eye, and the horizontal ground electrode was placed on the left ear lobe. The data was sampled at a rate of 1000 Hz using the software channel presets (.05 – 35 Hz EOG). The first 4000 ms of each trial was recorded, which included the 1500 ms presentation of the central fixation point.

Data analysis

Data analysis was completed off-line using Biopac's ACQKnowledge software. The saccadic response time (SRT) was recorded for each trial, and was defined as the time between the onset of the target dot and the point of the first steep increase relative to the baseline period (fixation) in the EOG record of at least one channel. Two researchers recorded SRT independently, one of whom was blind to condition, and the mean of the two

was then used for analysis. Trials where it was not possible to accurately mark the onset of the first saccade post-stimulus onset were excluded from the analysis. This resulted in the exclusion of 1.3% of all trials (44 out of 3360 trials).

Results

Saccadic response time (SRT)

The mean SRT for both stimulation conditions are shown in the upper half of Table 1. The data were subjected to a mixed ANOVA (4 x 2) with the within subject factor of Block (1 – 4) and the between subject factor of Stimulation Condition (Sham, tDCS). Both the main effect of Block ($p = 0.516$) and the Block by Stimulus Condition interaction were not significant ($p = 0.297$). The main effect of Stimulus Condition was marginally non-significant ($p = 0.067$), with SRT being faster in the Sham condition ($M = 192.57$, $SD = 15.6$) compared to the tDCS condition ($M = 216.65$, $SD = 27.5$). Comparing left and rightward saccades, a global ANOVA with the within subject factors of Block (1 – 4) and Side (Left, Right), and the between subject factor of Stimulation Condition (Sham, tDCS) revealed no significant main effects or interactions.

Saccadic duration

The average duration of the first saccade of each trial was calculated for the two stimulation conditions and is shown in the lower part of Table 1. A mixed ANOVA with the within subject factor of Block and the between subject factor of Stimulation Condition was performed. The main effects of both Block ($p = 0.407$) and Stimulation Condition ($p = 0.152$) were non-significant, as was the interaction ($p = 0.637$). Likewise, no significant main effects or interactions were found when the data considered left and rightward saccades.

Table 1. Mean saccadic response time and duration (ms) for both stimulation conditions as a function of block and broken down by side of presentation. Standard deviations are in parentheses.

	Block 1	Block 2	Block 3	Block 4
SRT - Sham				
Left	194.79 (16.8)	192.76 (13.8)	189.95 (16.8)	190.20 (16.1)
Right	197.50 (21.6)	188.76 (16.9)	192.27 (20.5)	194.34 (16.5)
SRT - tDCS				
Left	217.38 (24.1)	218.79 (35.0)	222.10 (51.9)	207.91 (25.9)
Right	215.58 (21.0)	220.72 (19.4)	217.20 (30.5)	213.54 (27.5)
Duration - Sham				
Left	44.91 (4.5)	44.89 (3.9)	45.35 (3.2)	45.89 (2.9)
Right	45.20 (3.2)	43.87 (4.1)	44.63 (2.5)	45.61 (4.0)
Duration - tDCS				
Left	51.66 (11.2)	49.09 (4.7)	49.53 (3.8)	48.91 (3.9)
Right	51.14 (14.0)	46.84 (7.4)	49.16 (6.6)	49.77 (9.2)