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The Role of the Left Dorsolateral Prefrontal Cortex in Attentional Bias

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20

## Abstract

21 The DLPFC is thought to be critically involved in maintaining attention away from behaviourally  
22 irrelevant information, and in the establishment of attentional control settings. These play an  
23 important role in the phenomenon of top-down bias to features in the visual field – also known as  
24 attentional bias. This paper probes the involvement of the left DLPFC in attentional bias by  
25 manipulating its cortical excitability via tDCS and then analysing these effects following an induced  
26 attentional bias towards the colour green. Although both anodal and cathodal tDCS over the left DLPFC  
27 decrease distractibility caused by biased but irrelevant objects, further interrogation of our data  
28 reveals theoretically differential mechanisms for each type of stimulation. Anodal tDCS appears to  
29 increase cognitive control over attentional bias-related items that are behaviourally irrelevant,  
30 allowing for their efficient disregard. In contrast, cathodal tDCS appears to lessen the overall effect of  
31 the induced attentional bias, potentially by reducing the influence of top-down modulated attentional  
32 control settings thus preventing the implementation of the control setting favouring green items.  
33 These results suggest a potential causal role of the left DLPFC in the cognitive mechanism underlying  
34 attentional bias.

35 **Keywords:** tDCS; attentional bias; attentional control; induced bias; left dorsolateral prefrontal cortex

36 An essential requirement of everyday life is the ability to navigate the world around us. However, it is  
37 widely acknowledged that there is too much sensory information to be able to process everything in  
38 the environment at once (Broadbent, 1958; Treisman, 1969). Thus, there must be some form of  
39 selective processing that filters out the irrelevant information from the relevant; otherwise known as  
40 attention. A plethora of evidence suggests an involvement of both bottom-up processing, such as a  
41 flashing light or unique singleton among a scene (Theeuwes, 1991, 1992, 1994, 2004; Theeuwes &  
42 Godijn, 2002; Theeuwes, Kramer, & Kingstone, 2004), and top-down processing, such as past  
43 experiences and the contents of working memory (Bacon & Egeth, 1994; Folk & Remington, 1998;  
44 Folk, Remington, & Johnston, 1992; Leber & Egeth, 2006b; Soto, Humphreys, & Heinke, 2006) on the  
45 capture of visual attention.

46

47 Despite the debate surrounding the extent to which bottom-up and top-down processing can  
48 influence attention (Folk, et al., 1992; Theeuwes, 2004), a number of authors have attempted to  
49 understand these interactions in terms of cognitive constructs called priority maps. In this view, the  
50 physical properties of incoming sensory signals are rapidly analysed in parallel across the visual field  
51 to generate a bottom-up 'saliency map' (Itti & Koch, 2000) which identifies spatial locations that are  
52 highly salient. Activation in this saliency map is modulated by top-down influences such as the content  
53 of working memory, previously learned associations, current goals and behavioural relevance to  
54 produce a priority map (Awh, Belopolsky, & Theeuwes, 2012; J. H. Fecteau & Munoz, 2006; Hopfinger,  
55 Buonocore, & Mangun, 2000). The peaks of activation of the priority map compete to determine which  
56 locations have priority for the allocation of attentional resources. In this way, both bottom-up and  
57 top-down processes have an influence on initial attentional capture.

58

59 One attentional phenomenon that fits within this framework is attentional bias. Attentional bias is a  
60 phenomenon wherein certain categories of items are more frequently and persistently processed at  
61 the cost of other items in a visual field, based upon their top-down qualities via a previously learned

62 association rather than their bottom-up saliency (Field & Cox, 2008; Macleod, Mathews, & Tata, 1986).  
63 It plays an important role in guiding visual behaviour, however the vast majority of research only  
64 studies the phenomenon from within abnormal psychology. Recently, we demonstrated that it is  
65 relatively easy to induce an attentional bias towards an arbitrary stimulus (the colour green) in healthy  
66 participants (Knight, Smith, Knight, & Ellison, 2016). This study confirmed that findings cannot be  
67 explained by a natural bias towards green stimuli and that green stimuli do not elicit an conscious  
68 emotional response. We also observed that the effects of this induced bias can be negated in healthy  
69 participants with uncompromised neural processing in areas associated with executive control who  
70 have practiced control mechanisms (Knight, Smith, Knight, & Ellison, 2018). The following experiment  
71 expands upon this latter finding by using transcranial direct current stimulation (tDCS) to further  
72 examine the underlying neurobiology of the cognitive control of attentional bias, providing an  
73 opportunity to probe the genesis of these processes.

74

75 Evidence from neuroimaging studies suggests that the dorsolateral prefrontal cortex (DLPFC) plays a  
76 role in controlling the effects of incoming information in individuals with pathological attentional  
77 biases. For example, general anxiety disorder is categorised by persistent attentional biases to threat-  
78 related information (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007;  
79 Macleod, et al., 1986). Consistent evidence suggests that these attentional biases are linked to  
80 enhanced amygdala activity (Monk, et al., 2008; Van den Heuvel, et al., 2005). However, some  
81 evidence suggests that this enhanced amygdala activity is actually driven by reduced DLPFC activity.  
82 Highly anxious individuals have a reduction in DLPFC (and increase in amygdala) activity when  
83 confronted with threat-related images compared to low state anxiety participants (Bishop, Duncan,  
84 Brett, & Lawrence, 2004), suggesting that anxious individuals are less able to recruit the necessary  
85 neural circuitry to exert control over their threat-related attentional bias.

86

87 Reduced DLPFC functioning could therefore be a key feature of anxiety since it allows for less control  
88 over amygdala activation, magnifying the processing of threat-related information. Similar results are  
89 found in addicted populations. For example, cocaine addicts with reduced PFC activity were less able  
90 to exert control over irrelevant cocaine-related information than addicts with higher PFC activity  
91 (Hester & Garavan, 2009). A DLPFC-mediated lack of control over irrelevant, bias-related objects may  
92 therefore account for the behavioural effects of attentional bias. This control is likely driven by the  
93 left DLPFC over the right. Increased activity of the left DLPFC is associated with a greater need for  
94 attentional control (Liu, Banich, Jacobson, & Tanabe, 2006). Moreover, while right DLPFC is related to  
95 inhibiting responses, left DLPFC is involved in corrections of behaviour following an error (Garavan,  
96 Ross, Murphy, Roche, & Stein, 2002). As such, manipulating the left DLPFC during a task involving  
97 irrelevant bias-related items could theoretically manipulate the amount of control it is able to exert  
98 over these items, altering the extent to which they affect behaviour. The current study will therefore  
99 use established tasks (Knight, et al., 2016, 2018) alongside tDCS over the left DLPFC, to investigate this  
100 issue.

101

102 As in our previous studies, participants are asked to read an information sheet to induce an attentional  
103 bias towards green items and complete a colour task to ascertain if this was successful. Following this,  
104 participants complete a shape change detection task while receiving either anodal, cathodal or sham  
105 tDCS stimulation. Anodal tDCS over the left DLPFC is predicted to raise the amount of cognitive control  
106 participants have over irrelevant bias-related information, whereas cathodal tDCS is predicted to  
107 decrease this control. Finally, as sham tDCS involves no stimulation, participants in this group should  
108 mirror the effects previously observed in our existing studies (Knight, et al., 2016, 2018).

109

## 110 **Method**

### 111 **Participants**

112 In total, 36 participants (14 male) recruited from staff and students at Durham University took part,  
113 with 12 participants in each of the three tDCS stimulation groups (4 male in the anodal group, 6 male  
114 in the cathodal group, 4 male in the sham group). Overall ages ranged from 19-41 (M: 24.72, SD: 5.42).  
115 In the group who received anodal stimulation, ages ranged from 20-41 (M: 25, SD: 5.56). In the group  
116 who received cathodal stimulation, ages ranged from 19-38 (M: 24.67, SD: 5.79). In the group who  
117 received sham stimulation, ages ranged from 21-36 (M: 24.5, SD: 4.59). All participants had normal  
118 or corrected to normal vision, no colour blindness (assessed via self-report), and gave informed  
119 consent with the approval of Durham University Ethics Advisory Committee. Participants were  
120 compensated for their time in the form of Amazon vouchers.

## 121 **Design**

122 Participants were assigned to one of 3 groups. All groups received the same biasing information at the  
123 start of the experiment and completed the colour change detection task. All groups were then  
124 immediately presented with the shape information sheet and asked to complete the second task  
125 whilst their left DLPFC was being stimulated via tDCS. Group 1 had the anodal electrode over left  
126 DLPFC; Group 2 had the cathodal electrode over left DLPFC; Group 3 received sham stimulation.  
127 Following existing protocols (Ball, Lane, Smith, & Ellison, 2013; Ellison, Ball, & Lane, 2017), the  
128 reference electrode for all participants was above the contralateral eye.

## 129 **Colour Change Detection Task: Stimuli, Apparatus & Procedure**

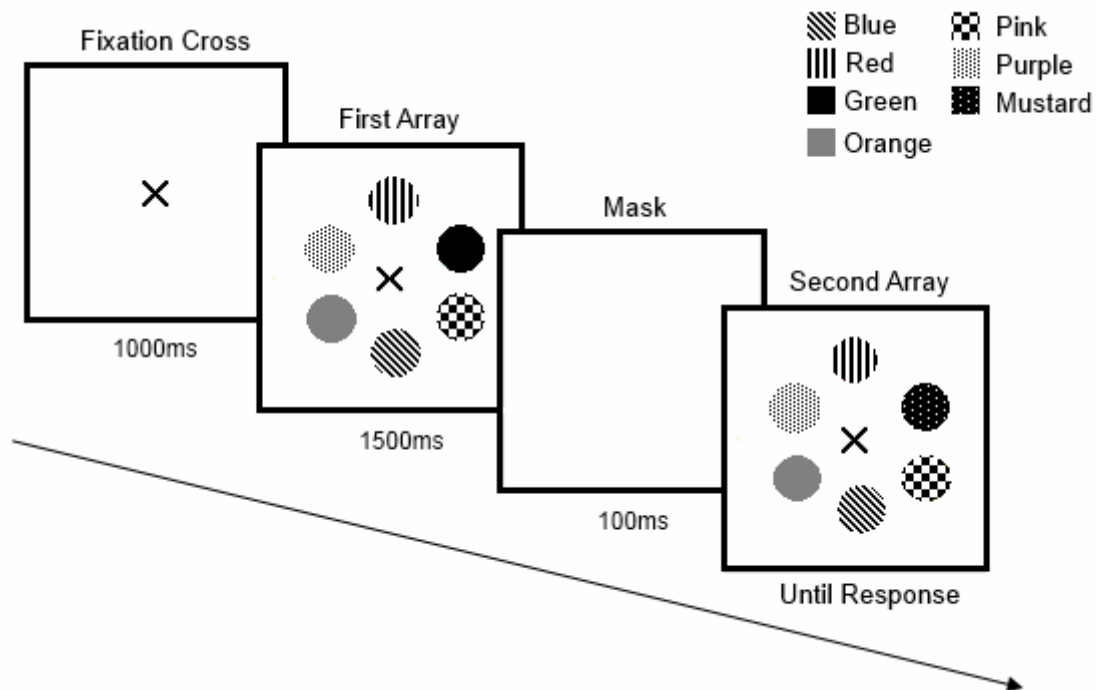
130 Participants completed a first change detection task. Stimuli for this were programmed in C++ using  
131 Borland C++ builder and produced via a VSG ViSaGe box and custom graphics card (Cambridge  
132 Research Systems, Rochester, England). They were displayed using a 19" Sony Trinitron monitor with  
133 a resolution of 1024x768 and a refresh rate of 100Hz. Responses were collected via a custom-made  
134 two-button button box. A biasing information sheet and consent form were also used, which  
135 mentioned the word 'green' several times (see supplementary material). A white fixation cross  
136 situated in the centre of a black screen (0.704° x 0.704° visual angle) preceded the test array consisting  
137 of a circular (radius 5.1cm) composition of six circles (2.5° x 2.5° visual angle) each of which was one

138 of 8 different equiluminous colours (green, red, blue, pink, purple, grey, mustard or orange, all 34  
139 cd/m<sup>2</sup>). The mask was a black screen.

140

141 Testing occurred in a darkened room. Participants read the biasing information sheet, and were seated  
142 57cm away from the screen with their head in a chin rest. They were informed that their goal was to  
143 detect any changes between two sequentially presented arrays. A change was defined as one coloured  
144 stimulus changing into a different colour not already present. The experiment began with the  
145 presentation of a fixation cross for 1000ms followed by the stimulus array for 1500ms. The array was  
146 then masked for 100ms, before reappearing. Stimuli remained present until a response was made. On  
147 25% (45 trials) of trials a green item was present and changed colour (Congruent Change Trials), on  
148 25% of trials a green item was present in the display but a different item changed colour (Incongruent  
149 Change Trials), on 25% of trials no green item was present but a stimulus changed colour (Neutral  
150 Change Trials) and on 25% of trials a green item was present but no change occurred (No Change  
151 Trials). The position of the coloured items varied randomly across trials (see Figure 1). Participants  
152 were asked to respond as quickly but as accurately as possible if they perceived a change or not, and  
153 completed 3 blocks of 60 trials with a 5 minute break between each block. The whole Colour Change  
154 Detection task took participants between 24.25 minutes and 26.54 minutes to complete.





156

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**Figure 1: Procedure of a typical Congruent Change trial in the first Change Detection Task.** A fixation cross was presented for 1000ms, followed by the first array for 1500ms. This was then masked for 100ms before reappearing, where participants had to make their response using the index finger of each hand.

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### Shape Change Detection Task: Stimuli, Apparatus & Procedure

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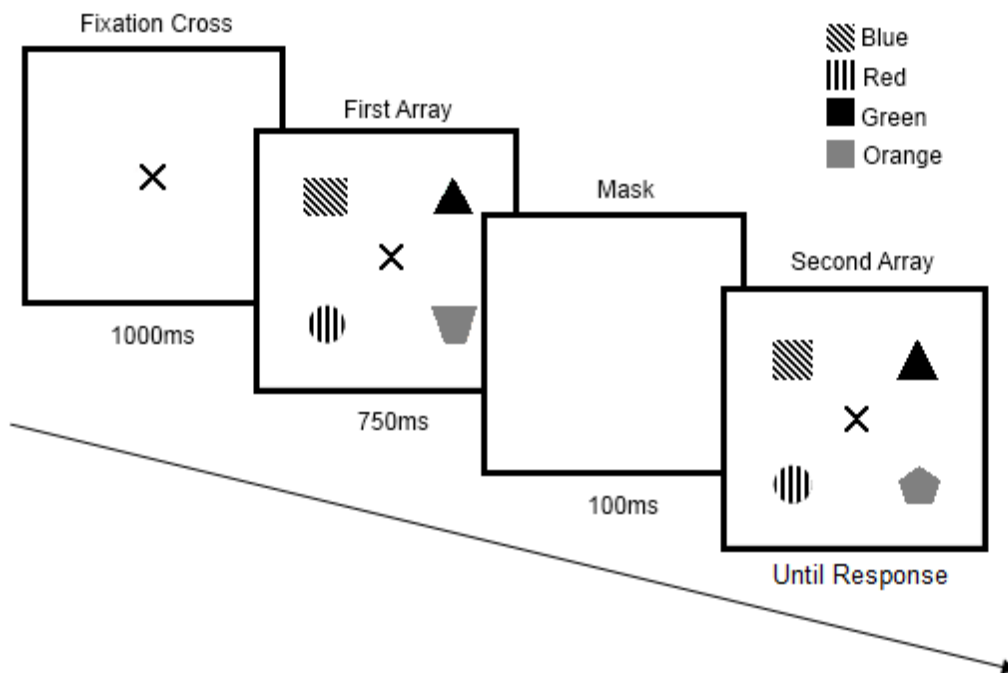
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Following the colour change detection task, participants were connected to the tDCS machine before completing a second, shape change detection task. Stimuli production and presentation apparatus were the same as before. However, the shape task information and consent forms substituted the word colours for shapes and green for shape (see supplementary material). There was also an additional paragraph stressing the focus on shape and emphasising that colour was irrelevant. The sheet did not mention the word green. For the shape task, the array (radius 5.1cm) comprised four different shapes (square, circle, triangle, pentagon or trapezium: visual angle:  $2.5^\circ \times 2.5^\circ$ ), all of a different equiluminescent colour (34 cd/m<sup>2</sup>). The mask was black screen. Participants were again asked to detect changes between two sequentially presented arrays of stimuli, separated by a mask. Here, changes were defined as a shape changing into a different shape, with the colour of shape never changing. After reading the information sheet about this task, participants were stimulated via tDCS

171 for 5 minutes, and then completed 6 blocks of 60 trials with each block commencing after every 5  
172 minutes. Each individual block of trials took between 2.43 minutes and 2.85 minutes to complete, with  
173 the inter-block interval ranging from between 2.56 minutes to 2.15 minutes.

174

175 The shape experiment began with the presentation of a fixation cross for 1000ms followed by the  
176 stimulus array for 750ms. The array was then masked for 100ms before reappearing. Stimuli remained  
177 present until a response was made. On 25% (120 trials) of trials a green shape was present, but a  
178 different shape changed shape (Green Present Change Trials), on 25% of trials a green item was  
179 present but no change occurred (Green Present No Change Trials), on 25% of trials no green item was  
180 present and one of the shapes changed shape (Green Absent Change Trials) and on 25% of trials no  
181 green item was present and no change occurred (Green Absent No Change Trials). The position of the  
182 coloured items varied randomly across trials (see Figure 2). Participants were told that colour in the  
183 shape task was irrelevant via the information sheet, but the rule that a green object never changed  
184 shape was not made explicit.

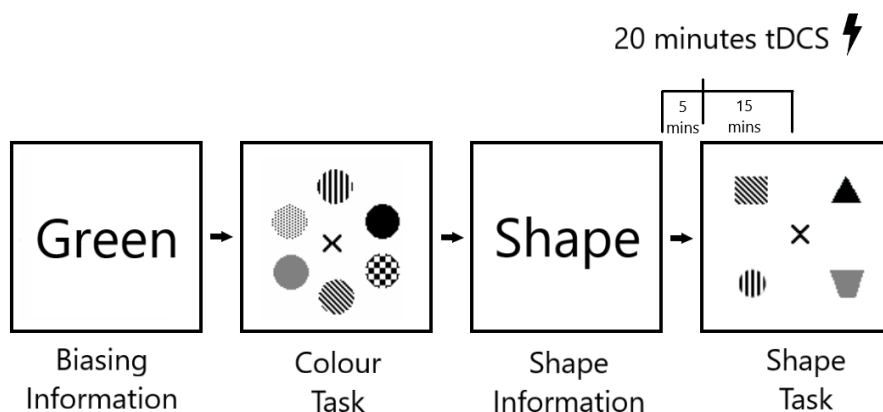


185 **Figure 2: Procedure of a typical trial in Experiment 2.** Figure shows a Green Present Change trial. A fixation  
186 cross was presented for 1000ms, followed the first array for 750ms. This was then masked for 100ms  
before reappearing, where participants had to make their response, using the index finger of each hand

187 **Transcranial Direct Current Stimulation**

188 A direct current of 1.5mA was generated using a Magstim Eldith DC stimulator. This was delivered  
189 using two rubber electrodes which were placed inside two saline soaked sponge pouches (7cm x 5cm).  
190 The electrodes were held in place using two rubber straps. To manipulate excitability of left DLPFC,  
191 the relevant Anodal or Cathodal (depending on experimental group) electrode was secured on the  
192 scalp over F3 according to the international 10-20 system of electrode placement, following previous  
193 research stimulating this area (Wolkenstein & Plewnia, 2013). The reference electrode was placed  
194 above the participant’s contralateral (right) eye (Ball, et al., 2013; Ellison, et al., 2017). For the first 8  
195 seconds of stimulation, the current was gradually increased to 1.5mA then continuously delivered at  
196 this intensity for 20 minutes. In the sham condition, this was reduced to 30 seconds so that  
197 participants in this group received the initial stimulation sensation and thus were not aware that they  
198 were in the sham condition. After 20 minutes, the current was gradually reduced over another 8  
199 seconds to 0mA. Figure 3 shows a schematic of the full experimental procedure.

200



201 **Figure 3: Schematic of the tDCS experimental procedure.** Participants read the biasing information sheet then complete the colour task. They then read the shape information sheet before being stimulated for tDCS for 20 minutes. After 5 minutes of stimulation, the shape task commenced.

202 **Results**

203 **Statistical Analyses**

204 Bayesian analyses were conducted alongside Frequentist analyses to allow for the further  
205 interrogation of evidence in support of the alternative hypothesis vs the null hypothesis. Frequentist

206 statistics were run using SPSS Version 25 (for ANOVAs and t-tests), with JASP Version 0.12.02 (JASP-  
207 Team, 2020) for Bayesian analyses. For ANOVAs, partial eta-squared and the 90% CI of the effect size  
208 (recommended when there is an alpha level of 5%) were calculated (Smithson, 2002). For paired-t-  
209 tests, Hedges's G and the recommended 95% CI of the effect size were calculated.

210

211 For the Bayesian analyses, the default priors in JASP – generally accepted to be suitable for  
212 psychological research – were used (Quintana & Williams, 2018). Here, an Inclusion Bayes Factor  
213 ( $BF_{incl}$ ) was computed, quantifying the change from prior to posterior inclusion odds, which can be  
214 interpreted as the evidence in the data for including a particular predictor (van den Bergh, et al., 2020).  
215 Following further protocols from van den Bergh et al. (2020), the inclusion Bayes Factors were  
216 computed for matched models only, meaning that each model effect was compared to the same  
217 model with each term of interest removed – this is ideal for comparability with SPSS ANOVAs which  
218 use type III sums of squares to partition out variance amongst all relevant terms at the same time.

219

## 220 **Biasing to Colour**

### 221 **d' Scores**

222 D-Prime ( $d'$ ) scores were calculated as  $z(\text{FA}) - z(\text{H})$ , or z-scores for False Alarm rates (where a change  
223 was not present but participants indicated that there was) minus z-scores for Hit rates (where a change  
224 was present and participants accurately responded as such). These calculated  $d'$  scores offering a  
225 measurement of participants' sensitivity to detect changes were then entered into a 3 (tDCS:  
226 Anodal/Cathodal/Sham) x 3 (Trial: Congruent/Incongruent/Neutral) Mixed Factorial ANOVA. tDCS was  
227 a between groups factor, Trial was within groups. There was a significant main effect of Trial:  $F(2, 66)$   
228  $= 64.199, p < .001, \eta p^2 = .66$  (90% CI: .54 - .73),  $BF_{incl} = 3.514 \times 10^{13}$ , error = 0.934%. Bonferroni corrected  
229 pairwise comparisons revealed that  $d'$  scores for Congruent change trials was significantly higher (M:  
230 2.771) than  $d'$  scores for both Incongruent (M: 1.728,  $p < .001$ ) and Neutral (M: 1.963,  $p < .001$ ) change  
231 trials. Furthermore,  $d'$  scores for Neutral Change trials were significantly higher than  $d'$  scores of

232 Incongruent Change trials ( $p = .002$ ). No main effect of tDCS was present ( $F(2, 33) = .568, p = .562, \eta^2$   
233  $= .03$  (90% CI: 0 - .14),  $BF_{incl} = 0.451$ , error = 0.431%), and there was no tDCS x Trial interaction ( $F(4,$   
234  $66) = .847, p = .501, \eta^2 = .05$  (90% CI: 0 - .10),  $BF_{incl} = 0.184$ , error = 2.076%). Thus, participants were  
235 significantly more sensitive at detecting changes when a green stimulus changed, but were less  
236 sensitive when a green item was present but did not change. This suggests successful inducement of  
237 a green attentional bias, with no natural difference in this between our three tDCS groups before tDCS  
238 was applied.

239

## 240 **Shape Change Detection**

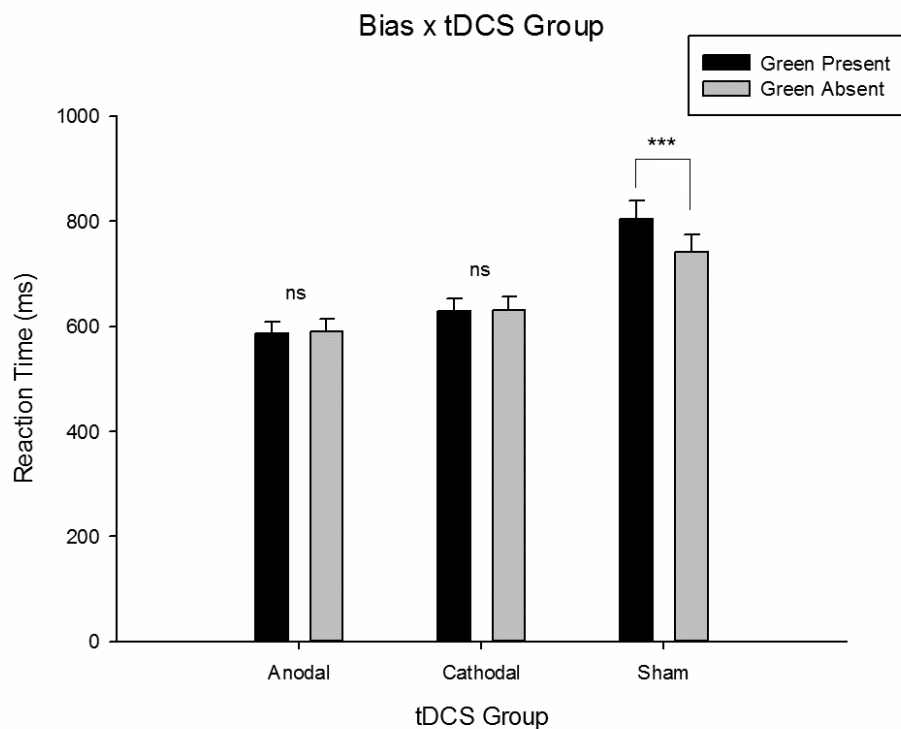
### 241 **Reaction Time**

242 Overall reaction times were entered into a 3 (tDCS: Anodal/Cathodal/Sham) x 2 (Bias: Green  
243 Present/Green Absent) x 2 (Trial: Change/No Change) Mixed Factorial ANOVA. tDCS was a between  
244 groups factor, Bias and Trial were both within groups factors. There was a significant main effect of  
245 tDCS:  $F(2, 33) = 6.531, p = .004, \eta^2 = .28$  (90% CI: .06 - .44),  $BF_{incl} = 8.975$ , error = 2.960%. Bonferroni  
246 corrected pairwise comparisons revealed that participants in the Sham group were significantly slower  
247 (M: 772.676ms, SD: 157.927ms) than those in the Anodal (M: 587.876ms, SD: 116.897ms,  $p = .002$ )  
248 and Cathodal (M: 629.516ms, SD: 112.875ms,  $p = .012$ ) groups. Secondly, there was a main effect of  
249 Trial:  $F(1, 33) = 6.317, p = .017, \eta^2 = .16$  (90% CI: .02 - .34),  $BF_{incl} = 1.471$ , error = 1.161%. Reaction  
250 times for Change trials were significantly faster (M: 647.300ms, SD: 165.977ms) than No Change trials  
251 (M: 679.413ms, SD: 149.013ms). A main effect of Bias was also present:  $F(1, 33) = 12.214, p = .001,$   
252  $\eta^2 = .27$  (90% CI: .07 - .44),  $BF_{incl} = 64.578$ , 5.617%. Overall reaction times when a green shape was  
253 present were significantly slower (M: 673.061ms, SD: 171.143ms) than when a green shape was  
254 absent (M: 653.651ms, SD: 153.207ms).

255

256 Finally, Bias and tDCS interacted:  $F(2, 33) = 16.089, p < .001, \eta^2 = .49$  (90% CI: .26 - .61),  $BF_{incl} = 6.098,$   
257 error = 3.476. To investigate further, the effect of a green shape on reaction time was examined for

258 each tDCS group separately via three paired-samples t-tests (Green Shape Present/Green Shape  
259 Absent, corrected  $\alpha$ : 0.0167). The t-test for the Anodal group was non-significant:  $t(23) = -.607$ ,  $p =$   
260  $.550$ , *Hedges' g* = 0.03 (95% CI: -0.14 – 0.07), as was the t-test for the Cathodal group:  $t(23) = -.213$ ,  $p$   
261  $= .833$  *Hedges' g* = 0.02 (95% CI: -0.16 – 0.13). However, the t-test for the Sham group was significant:  
262  $t(23) = 6.888$ ,  $p < .001$ , *Hedges' g* = 0.37 (95% CI: 0.23 – 0.54). Here, reaction times when a green shape  
263 was present were significantly slower (M: 804.6544ms, SD: 190.269ms) than when no green shape  
264 was present (M: 740.6985, SD: 167.265ms). These are seen in Figure 4. This suggests that tDCS  
265 stimulation (both anodal and cathodal) is affecting participant behaviour in the Shape Change  
266 Detection task.  
267



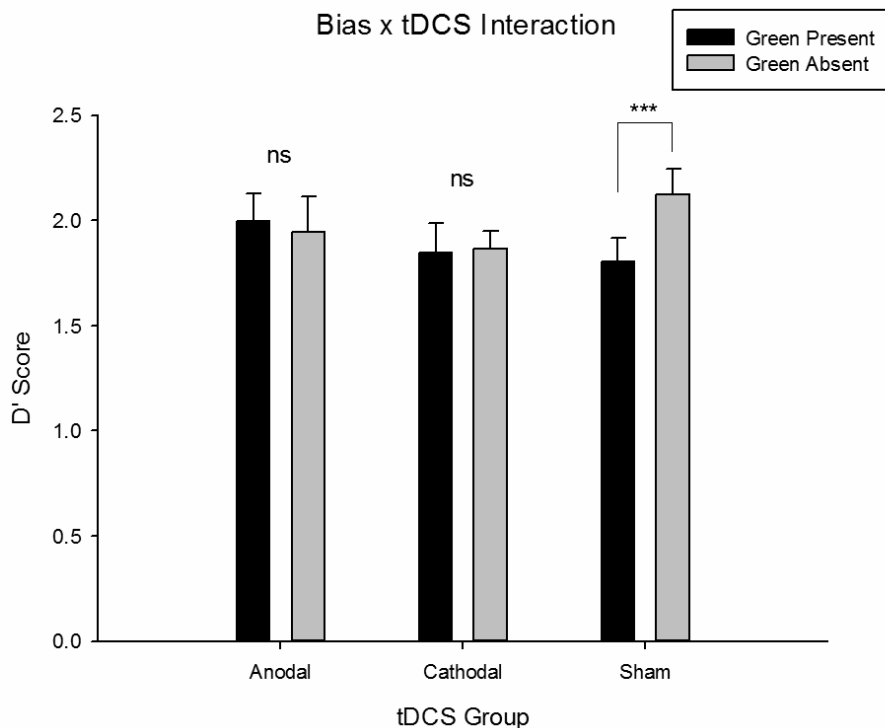
268 **Figure 4: Differences in reaction time in the Shape task observed across all tDCS groups.** There is no  
269 difference in reaction time when a green shape is present versus absent in the Anodal or Cathodal tDCS group.  
However, the Sham group were significantly slower when a green shape was present. *Note*, \*\*\*  $p < .001$ .

270 **d' Scores**

271 Calculated  $d'$  scores for the shape task were entered into a 3 (tDCS: Anodal/Cathodal/Sham) x 2 (Bias:  
272 Green Present/Green Absent) Mixed Factorial ANOVA. tDCS was a between groups factor, Bias was a  
273 within groups factor. The application of tDCS had no main effect on overall  $d'$  scores:  $F(2, 33) = .279$ ,  
274  $p = .758$ ,  $\eta^2 = .02$  (90% CI: 0 - .09),  $BF_{incl} = 0.371$ , error = 1.966. There was also no significant main  
275 effect of Bias:  $F(1, 33) = 3.441$ ,  $p = .073$ ,  $\eta^2 = .17$  (90% CI: .01 - .33),  $BF_{incl} = 0.765$ , error = 2.143. There  
276 was a significant interaction between tDCS and Bias:  $F(2, 33) = 4.885$ ,  $p = .014$ ,  $\eta^2 = .23$  (90% CI: .03 -  
277 .38),  $BF_{incl} = 4.545$ , error = 2.772. This was examined via three paired t-tests (corrected  $\alpha$ : 0.0167);  
278 each examined the difference in  $d'$  scores between Green Present and Green Absent trials separately  
279 for each tDCS group.

280

281 The t-test for the Anodal group was non-significant:  $t(11) = .469$ ,  $p = .648$ , *Hedges' g* = 0.09 (95% CI: -  
282 0.31 – 0.50), as was the t-test for the Cathodal group:  $t(11) = -.215$ ,  $p = .832$ , *Hedges' g* = -.04 (95%  
283 CI: -0.47 – 0.38). However, the t-test for the Sham group was significant:  $t(11) = -4.515$ ,  $p = .001$ ,  
284 *Hedges' g* = -0.73 (95% CI: -1.24 – -0.31). Here,  $d'$  scores for Green Present trials were significantly  
285 lower (M: 1.806, SD: .393) than those of Green Absent trials (M: 2.125, SD: .422). Since a lower  $d'$  score  
286 is indicative of reduced perceptual sensitivity, this demonstrates that our Sham tDCS group showed  
287 the same pattern of behaviour as our previous studies (Knight, et al., 2016, 2018): when participants  
288 have an induced attentional bias towards a type of stimulus, objects that share this property cause a  
289 reduction in sensitivity when other changes occur. However, it appears as if the application of tDCS of  
290 either polarity over the left DLPFC negates this effect. These effects can be seen in Figure 5.



**Figure 5: Differences in perceptual sensitivity ( $d'$ ) in the Shape task observed across all tDCS groups.** There is no difference in perceptual sensitivity when a green shape is present in the Anodal or Cathodal tDCS group. However, the Sham group were significantly less sensitive at detecting changes when a green shape was present. *Note*, \*\*\*  $p < .001$

291

## 292 Discussion

293 This study used tDCS to investigate the role of the left DLPFC in the cognitive control of an induced  
 294 attentional bias towards green stimuli. Ordinarily, the presence of an irrelevant bias-related stimulus  
 295 in a change detection task acts as a distraction, causing both a slowing of reaction time and reduced  
 296 sensitivity to detect changes (Knight et al., 2016; 2018). Participants in our current study who received  
 297 sham tDCS stimulation followed this behavioural pattern, however when the excitability of the left  
 298 DLPFC was manipulated using both anodal and cathodal tDCS, the distractions normally caused by  
 299 irrelevant bias-related stimuli (in this case, green shapes) appeared to diminish. Although sample size  
 300 is small, reported Bayes factors suggest that taking tDCS into account provides supporting evidence to  
 301 reject the null hypothesis over the alternative hypothesis. Moreover, the similarity in behaviour  
 302 between the sham tDCS group and findings in previous studies using the same experimental protocol



303 (Knight et al. 2016; 2018), compared to the two active tDCS groups in the current study (anodal and  
304 cathodal), merit an appraisal of these results in light of existing literature.

305

306 The left DLPFC is believed to play a directive role in orienting and allocating attention (Corbetta &  
307 Shulman, 2002; Liu, et al., 2006; MacDonald, Cohen, Stenger, & Carter, 2000). Thus, ordinarily the left  
308 DLPFC is in direct communication with the attention network (including the IPS and FEF), and can  
309 direct this network in a top-down manner to allocate higher processing priority to task-congruent  
310 information (Belopolsky & Theeuwes, 2010; Corbetta, Kincade, & Shulman, 2002; Reynolds & Chelazzi,  
311 2004). With attentional bias, it appears as if the DLPFC is unable to exert enough control over the  
312 attention network, thus bias-related items capture and hold attention even when behaviourally  
313 inconsistent (Bar-Haim, et al., 2007; Faunce, 2002; Field & Cox, 2008). In our task, participants have  
314 an attentional bias towards green induced, which is then tested in a shape task. Here, it is crucial to  
315 recall that if a green shape was present, it never changed shape – thus not only was colour explicitly  
316 irrelevant (outlined in task instructions), green was even more implicitly irrelevant. When left DLPFC  
317 activity is not manipulated, green shapes distract participants from detecting changes elsewhere, as  
318 evidenced in both our sham data, and in data from our previous experiments (Knight et al., 2016;  
319 2018). However, when we manipulated the left DLPFC via anodal tDCS, the reaction time and  
320 perceptual sensitivity differences normally observed in green present shape trials appeared to wane.  
321 On first inspection, this might suggest a non-specific effect of tDCS since overall reaction times were  
322 faster in our active tDCS groups (averaged across green present and green absent trials). However, we  
323 believe there are reasons for offering a more nuanced interpretation of the results with respect to the  
324 psychology of attentional bias, and the fact that our sham group behave differently when a biased  
325 stimulus is present versus absent.

326

327 The attentional bias literature demonstrates that when an individual has an attentional bias towards  
328 a particular stimulus (and little control over said bias), items relating to the bias are detected more

329 frequently and persistently than others. All of our participants are engaging in experimental blocks  
330 where 50% of randomly presented trials have a biased stimulus present and 50% do not. It is very  
331 possible that participants who have had an attentional bias induced that is currently active, and who  
332 do not have suitable control mechanisms over it, will be constantly monitoring for the presence of a  
333 biased stimulus (given that it has a 50% chance of being present). We believe that this is the case for  
334 our sham group, demonstrated in faster reaction times when a biased shape is not present (mirroring  
335 findings from our previous papers). However, this bias is evident not in comparing their behaviour  
336 against the tDCS groups, but by comparing behaviour when a biased stimulus is present or absent  
337 within this group only. With anodal tDCS (see later in the discussion for an overview of cathodal tDCS),  
338 given the discussed role of the left DLPFC in attention, we posit that these findings are a result of  
339 reduced distraction from explicitly irrelevant stimuli, suggestive of a potential causative executive role  
340 of this region in cognitively controlling for attentional bias-related distractions (Fassbender, et al.,  
341 2004; Garavan, et al., 2002; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013). Thus for this group,  
342 reaction times in both bias present and bias absent trials are significantly faster than reaction time in  
343 general for our sham group, potentially due to decreased distractions not only from biased stimuli,  
344 but from monitoring for said stimuli as well.

345

346 Further support for this explanation stems from the consistency between our findings and previous  
347 studies investigating the link between the left DLPFC and the executive control of attention. For  
348 example, anodal tDCS over left DLPFC decreased emotional discomfort experienced by participants  
349 when viewing images of other humans in pain, by enabling the left DLPFC to exert control over the  
350 environment (Boggio, Zaghi, & Fregni, 2009). This arguably inhibited the extent to which other regions  
351 associated with pain perception – such as the amygdala or anterior cingulate cortex (ACC) – were  
352 activated in order to minimise negative emotional discomfort. Furthermore, anodal tDCS over left  
353 DLPFC improved the working memory and cognitive control abilities of patients with major depressive  
354 disorder to such a degree that it was claimed to have eliminated patients' negative-emotive

355 attentional biases (Wolkenstein & Plewnia, 2013). It was argued that this improved participants'  
356 working memory and cognitive control abilities (Botvinick, Braver, Barch, Carter, & Cohen, 2001;  
357 Botvinick, Cohen, & Carter, 2004) allowing them to more successfully ignore the emotive images and  
358 focus on the task-relevant aspects of the experiment (Wolkenstein & Plewnia, 2013). Importantly, our  
359 findings not only offer cautious support, but also potentially clarify the effect observed in Wolkenstein  
360 and Plewnia (2013) whose research is somewhat muddied by the issue that over half of their sample  
361 of patients were taking a wide variety of anti-depressive and anti-anxiety medications – many of which  
362 alter neurochemistry (Carr & Lucki, 2011; Millan, 2004; Musazzi, Racagni, & Popoli, 2011).

363

364 While our discussed findings so far were predicted, the observed effect of cathodal stimulation of the  
365 left DLPFC were less expected. The application of cathodal tDCS over left DLPFC also appears to have  
366 lessened the behavioural effects of irrelevant green shapes; however the underlying reasons for this  
367 are arguably distinct from the effects of anodal tDCS. There is debate in the literature surrounding the  
368 classic anodal-excitation/cathodal-inhibition assumption of tDCS modulation (Jacobson, Koslowsky, &  
369 Lavidor, 2012; Nitsche, Boggio, Fregni, & Pascual-Leone, 2009; Nitsche, et al., 2008; Nitsche & Paulus,  
370 2000), and further debate surrounding the effectiveness of single-session tDCS stimulation within the  
371 cognitive domain (Horvath, Forte, & Carter, 2015). Nevertheless, there is evidence of different  
372 mechanisms driving behavioural outcomes of anodal vs cathodal stimulation, with anodal tDCS linked  
373 to reduced GABA (an inhibitory neurotransmitter), and cathodal tDCS related to reduced excitatory  
374 glutamateric neuronal activity (Stagg, et al., 2009; Stagg & Nitsche, 2011). Furthermore, while a recent  
375 paper (Parkin, Bhandari, Glen, & Walsh, 2019) has suggested that bilaterally stimulating regions of  
376 interest (i.e., using anodal tDCS over left DLPFC while cathodally stimulating right DLPFC) may not  
377 produce expected changes in evoked potentials, unilateral stimulation (having one electrode over a  
378 region of interest and the other above the contralateral orbit) did. This latter design is the one adopted  
379 in the current study, though it must be noted that Parkin et al. (2019) examined unilateral 1mA  
380 stimulation, whereas the current paper used 1.5mA. Finally, one meta-analysis found that although

381 anodal-excitation results are often exhibited, the cathodal-inhibitory effect is less common (Jacobson,  
382 et al., 2012). This analysis suggests that while our findings from anodal stimulation of the left DLPFC  
383 may be due to increased excitation in this region, our findings from cathodal stimulation of the left  
384 DLPFC may not be related to inhibition in this area.

385

386 Given the authoritative role of the left DLPFC in the allocation of attention, it was originally predicted  
387 that cathodal tDCS would result in reduced cognitive control over the attention system, meaning that  
388 distractions caused by irrelevant green shapes following an induced attentional bias towards green  
389 would be exacerbated in the cathodal group. However, both reaction time and sensitivity to detect  
390 change in the cathodal group suggest that green shapes were less distracting than for participants in  
391 the sham group (and in our previous studies). Instead, overall reaction times in our cathodal group  
392 were faster than those of the sham group. More importantly, unlike participants who received sham  
393 tDCS, there was no statistical difference between reaction times of Green Present and Green Absent  
394 trials, nor any difference in perceptual sensitivity between these types of trials in the cathodal group  
395 – though again, the low statistical power of the current study must be acknowledged. As discussed,  
396 overall reaction times did not differ between our cathodal and anodal groups, which could be  
397 suggestive of a non-specific tDCS effect. We outlined previously that while a non-specific tDCS effect  
398 is a possibility, an examination of the psychology underpinning attentional bias could suggest an  
399 alternative explanation for anodal stimulation. This is also the case for cathodal stimulation, where  
400 the psychological basis of attentional bias could suggest an alternative account for these findings.  
401 Here, one possibility is that cathodal tDCS over the left DLPFC reduces the overall effects of attentional  
402 biases. In other words, the application of cathodal tDCS may have reduced or potentially even  
403 removed the initial mechanisms for activating an attentional bias, thus with a weaker bias (or even no  
404 bias at all), bias-related information causes fewer behavioural effects. To examine this potential  
405 explanation, the cognitive foundation of attentional biases needs to be addressed.

406

407 It has been theorised that attentional biases are actually persistent alterations to top-down mediated  
408 attentional control settings (Bacon & Egeth, 1994; Folk, et al., 1992; Knight, et al., 2016; Leber & Egeth,  
409 2006a, 2006b; Leber, Kawahara, & Gabari, 2009), which are consistently reinforced by long-term  
410 memory representations (Carlisle, Arita, Pardo, & Woodman, 2011) and contextual cuing (Cosman &  
411 Vecera, 2013; Knight, et al., 2016). Thus an individual with an alcohol-related attentional bias has an  
412 attentional set favouring alcohol-related information which is constantly activated, resulting in  
413 alcohol-related information capturing attention more frequently and persistently than normal. In our  
414 current study, it is possible that manipulating the left DLPFC via cathodal stimulation has significantly  
415 reduced the influence of top-down mediated attentional control settings, preventing the  
416 implementation of an attentional setting towards green stimuli (Folk, et al., 1992; Leber & Egeth,  
417 2006b). If so, it would mean that bottom-up influences on the priority map carry more weight than  
418 top-down influences favouring green (Awh, et al., 2012; J. H. Fecteau & Munoz, 2006; Itti & Koch,  
419 2000).

420

421 All of the shapes in our shape task are of the same visual angle, and all of the colours are equiluminant.  
422 Thus, there is little difference to their bottom-up signals and as such, their bottom-up influences mean  
423 that they are all similarly represented on the priority map. Suppressing top-down attentional control  
424 settings and relying on this bottom-up information means the usual differences in reaction time and  
425 perceptual sensitivity caused by an attentional bias has dissipated. Thus, cathodal tDCS over left DLPFC  
426 has potentially removed the distracting effect of an irrelevant green shape by reducing top-down  
427 control over attentional capture. This possibility would render the induced bias inconsequential, and  
428 thus offers an explanation of the observed behavioural effects. Support for this explanation comes  
429 from several neuroimaging studies examining the link between the DLPFC and implementing and  
430 maintaining an attentional set. Prefrontal regions appear to play a greater role in implementing an  
431 attentional set, and activation in prefrontal regions is higher when the attentional set was more  
432 challenging to impose (Banich, et al., 2000). Likewise, the DLPFC has been associated with holding

433 behavioural goals in working memory, and directing the necessary neural networks to processing  
434 information that meet with those behavioural goals (Luks, Simpson, Dale, & Hough, 2007; Luks,  
435 Simpson, Feiwell, & Miller, 2002). The current study builds upon these correlational findings, finding  
436 cautious evidence of a causal link between the left DLPFC and the implementation of a preparatory  
437 attentional setting that alters the effects of top-down modulation on visual attention.

438

439 An alternative but complementary account stems from Antal et al. (2005), who argue that the  
440 improvements in performance on some cognitive tasks following cathodal tDCS may be due to a  
441 decrease in global excitation levels which then decrease neuronal competition (Andrea, et al., 2004;  
442 Desimone & Duncan, 1995; Jacobson, et al., 2012). In our current study, reducing biased competition  
443 for green stimuli would improve performance on green-present trials because – as mentioned –  
444 changes never happen to green shapes, thus with a green attentional bias, these shapes are normally  
445 distracting and impede performance. It is therefore possible that either cathodal stimulation of the  
446 left DLPFC has prevented an attentional setting for green being activated, or (or even potentially, by)  
447 reducing neuronal competition meaning that bottom-up influences outweigh top-down influences on  
448 the priority map.

449

450 While the current study appears to provide early evidence of a neural region causally relating to the  
451 implementation and cognitive control of a current attentional set, caution must be made when  
452 directly attributing these findings to the left DLPFC. Although the current study stimulated the left  
453 DLPFC anodally and cathodally – and included a sham condition as a control – the location of the  
454 reference electrode during stimulation must also be taken into consideration. Following previous  
455 studies (Ball, et al., 2013; S. Fecteau, Knoch, et al., 2007; S. Fecteau, Pascual-Leone, et al., 2007; Fregni,  
456 et al., 2005; Knoch, et al., 2008), the chosen site for the reference electrode was above the  
457 contralateral eye. As the primary electrode was placed over the left DLPFC, this meant that the  
458 reference electrode was placed above the right eye. However, it is important to note that tDCS works

459 by passing a current between the two electrodes, meaning that while one electrode is named the  
460 “reference” electrode it is still actively involved in the tDCS stimulation. The brain region under the  
461 right eye is the right orbitofrontal cortex (rOFC), thus when the left DLPFC was being anodally  
462 stimulated, the rOFC was being cathodally stimulated and vice versa.

463

464 There are strong links between the OFC and reward-based decision making (Bolla, et al., 2003; Rolls &  
465 Grabenhorst, 2008; Volkow & Fowler, 2000). Specifically, evidence suggests that the OFC is required  
466 in converging information from multiple sources – including sensory and cognitive – to form a goal-  
467 value that a decision is then made based upon (Camus, et al., 2009; Padoa-Schioppa & Assad, 2006;  
468 Rangel, Camerer, & Montague, 2008; Wallis, 2007; Wallis & Miller, 2003). This suggests that the OFC  
469 receives input from the DLPFC as part of the multisensory information that converges here. tDCS over  
470 the DLPFC will then not only effect the information that is sent to the OFC, but stimulation of the OFC  
471 will have an effect on the decision making that results from this. Specifically, cathodal stimulation of  
472 the OFC could result in poorer decision making and the area being less able to receive and process the  
473 multisensory and cognitive information sent to it (Camus, et al., 2009).

474

475 In the current study, this multisensory information would include the attentional setting informing the  
476 attention system in a top-down manner what information to prioritise, as well as the cognitive control  
477 input from the DLPFC, stemming from the explicit instructions to ignore colour in the shape task. It is  
478 therefore possible that anodal DLPFC (theoretically affecting cognitive control of the task) alongside  
479 cathodal OFC stimulation (theoretically affecting the ability to make decisions from multisensory,  
480 affective and cognitive information) has magnified the observed effects, meaning that cognitive  
481 control over irrelevant colour in the shape task was amplified because there was less input from the  
482 OFC. Similarly, cathodal DLPFC (affecting the attentional control setting for green) and anodal OFC  
483 stimulation (affecting the ability to make decision from multisensory information) may have had a  
484 magnified effect in the shape task. Here, the OFC potentially not only received little information of an

485 attentional control setting, but was able to make more behaviourally effective decisions from the  
486 information it did receive – resulting in the increased perceptual sensitivity observed in the cathodal  
487 DLPFC group. Due to the fact that the OFC and DLPFC are anatomically interconnected (Feil, et al.,  
488 2010), and that DC stimulations of one area may have an effect on the other (Ellison, et al., 2014) it is  
489 difficult to state with certainty if the results of this experiment stem from DLPFC stimulation, OFC  
490 stimulation or a combination of both. However, it must also be noted that one previous study (Ellison,  
491 et al., 2017), investigated the placement of the reference electrode finding that it provided the same  
492 effect on behaviour. The most efficient route to clarify this issue would be to apply tDCS in a scanner  
493 and correlate activity with behavioural markers to begin to address issues of causality, thus  
494 encouraging further investigation into the area.

495

496 We have found a potential causative role of the left DLPFC in attentional bias which is arguably  
497 supported by existing literature – both from our own previous findings using the same protocols used  
498 here, and from a range of evidence from other labs. Given the importance of attentional bias in a  
499 range of psychopathological populations, this merits further exploration and we hope that this early  
500 paper provides a catalyst to encourage such exploration to occur.

501

502 In conclusion, modulating the excitability of left DLPFC appears to affect behaviour towards biased  
503 objects irrespective of polarity but via arguably different mechanisms. Anodal DC stimulation over the  
504 left DLPFC has likely increased the amount of executive control participants had over the task, which  
505 negated the biasing properties of green shapes observed in the no stimulation group. Cathodal DC  
506 stimulation over the left DLPFC however, has potentially prevented participants from adopting an  
507 attentional setting towards green, causing behaviour in the task to be bottom-up modulated with  
508 negligible top-down control. Thus, the left DLPFC appears to play a critical role in the implementation  
509 of an attentional bias, and in the control of attentional biases, if active. Manipulating this region to  
510 either prevent the control settings from being adopted or allowing individuals to have greater



511 executive control over incoming information in psychopathological populations may provide an  
512 effective avenue for future research into treatment.

513

514

515 **Conflict of Interest**

516 None declared

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520

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