The Role of the Left Dorsolateral Prefrontal Cortex in Attentional Bias

Helen C. Knight*[a], Daniel T. Smith[b] & Amanda Ellison[b]

a School of Psychology, University of Sunderland, Chester Road, Sunderland, SR1 3SD, United Kingdom

b Psychology Department, Durham University, Upper Mountjoy, South Road, Durham, DH1 3LE, United Kingdom

* Correspondence to: helen.knight@sunderland.ac.uk Tel: +44 (0)191 515 2571

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Abstract

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

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

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

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

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

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

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

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

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

Method

Participants

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

Design

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

Colour Change Detection Task: Stimuli, Apparatus & Procedure

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

of 8 different equiluminescent colours (green, red, blue, pink, purple, grey, mustard or orange, all 34 cd/m^2). The mask was a black screen.

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

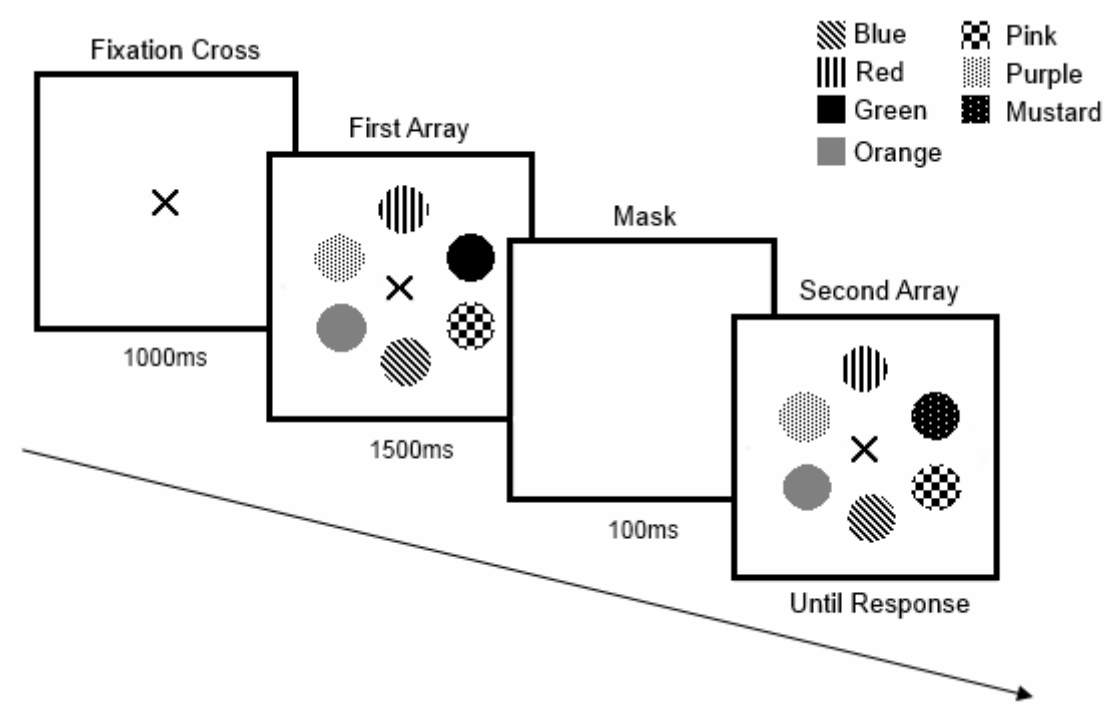

Figure 1: Procedure of a typical Congruent Change trial in the first Change Detection Task. A fixation cross was presented for 1000ms, followed by the first array for 1500ms. This was then masked for 100ms before reappearing, where participants had to make their response using the index finger of each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

Shape Change Detection Task: Stimuli, Apparatus & Procedure

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° x 2.5°), all of a different equiluminescent colour (34 cd/m2). 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

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

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

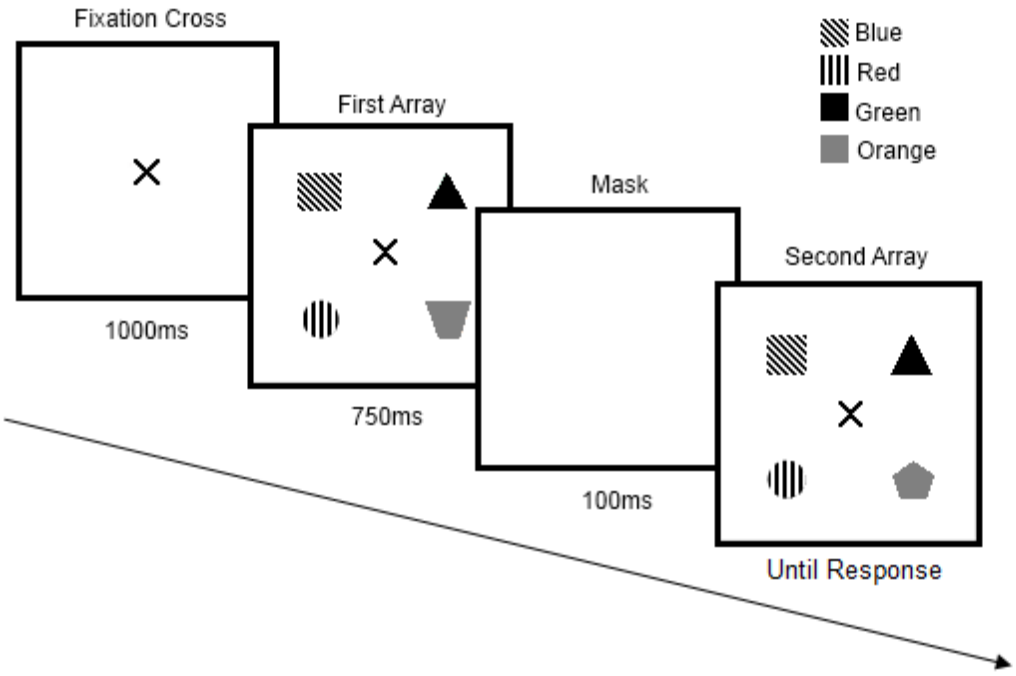

Figure 2: Procedure of a typical trial in Experiment 2. Figure shows a Green Present Change trial. A fixation cross was presented for 1000ms, followed the first array for 750ms. This was then masked for 100ms before reappearing, where participants had to make their response, using the index finger of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

Transcranial Direct Current Stimulation

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

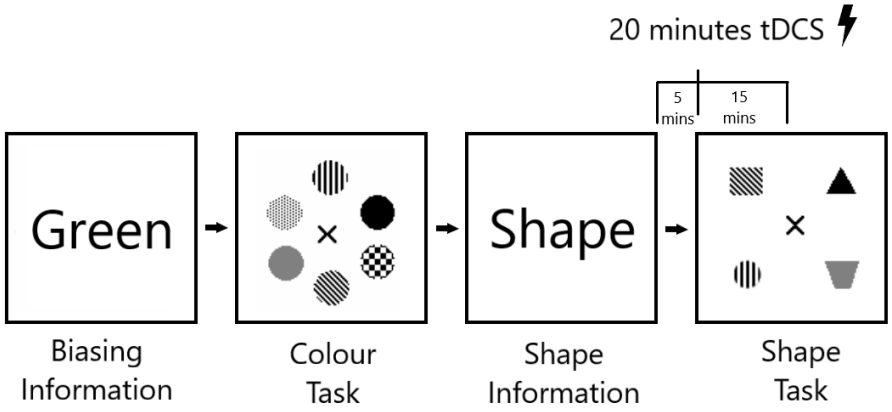

Figure 3: Schematic of the tDCS experimental procedure. Participants read the biasing information sheet then complete the colour task. They then read the shape information sheet before being stimulated for tDCS for 20 minutes. After 5 minutes of stimulation, the shape task commenced.

Results

Statistical Analyses

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

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

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

Biasing to Colour

d' Scores

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

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

Shape Change Detection

Reaction Time

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

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

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

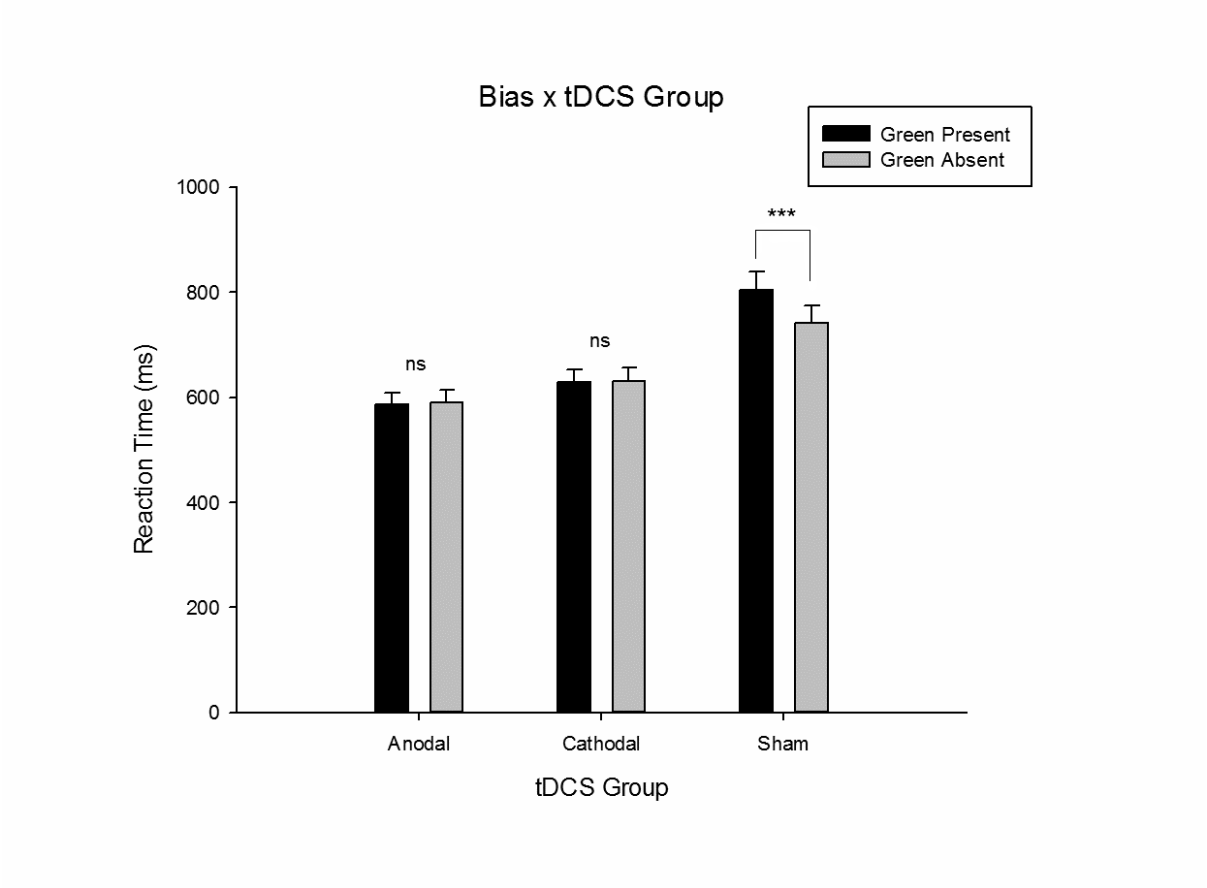

Figure 4: Differences in reaction time in the Shape task observed across all tDCS groups. There is no difference in reaction time when a green shape is present versus absent in the Anodal or Cathodal tDCS group. However, the Sham group were significantly slower when a green shape was present. *Note*,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

d' Scores

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

The t-test for the Anodal group was non-significant: $t(11) = .469$, $p = .648$, *Hedges' g* = 0.09 (95% CI: -0.31 – 0.50), as was the t-test for the Cathodal group: $t(11) = -.215$, $p = .832$, *Hedges' g* = .-0.04 (95% CI: -0.47 – 0.38). However, the t-test for the Sham group was significant: $t(11) = -4.515$, $p = .001$, *Hedges' g* = -0.73 (95% CI: -1.24 – -0.31). Here, d' scores for Green Present trials were significantly lower (M: 1.806, SD: .393) than those of Green Absent trials (M: 2.125, SD: .422). Since a lower d' score is indicative of reduced perceptual sensitivity, this demonstrates that our Sham tDCS group showed the same pattern of behaviour as our previous studies (Knight, et al., 2016, 2018): when participants have an induced attentional bias towards a type of stimulus, objects that share this property cause a reduction in sensitivity when other changes occur. However, it appears as if the application of tDCS of either polarity over the left DLPFC negates this effect. These effects can be seen in Figure 5.

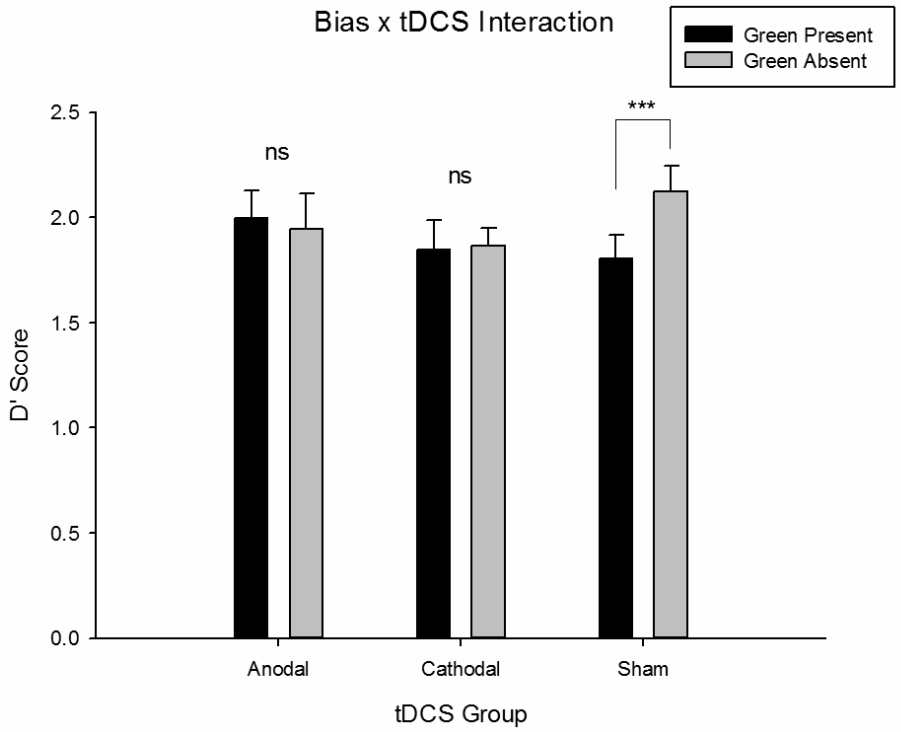

Figure 5: Differences in perceptual sensitivity (d') in the Shape task observed across all tDCS groups. There is no difference in perceptual sensitivity when a green shape is present in the Anodal or Cathodal tDCS group. However, the Sham group were significantly less sensitive at detecting changes when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

Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Conflict of Interest

None declared

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