

# Polarity-dependent Effects of Biparietal Transcranial Direct Current Stimulation on the Interplay between Target Location and Distractor Saliency in Visual Attention

Magdalena Chechlacz<sup>1,2</sup>, Peter C. Hansen<sup>1</sup>, Joy J. Geng<sup>3</sup>, and Dario Cazzoli<sup>4</sup>

## Abstract

■ Visual attention allows the allocation of limited neural processing resources to stimuli based on their behavioral priorities. The selection of task-relevant visual targets entails the processing of multiple competing stimuli and the suppression of distractors that may be either perceptually salient or perceptually similar to targets. The posterior parietal cortex controls the interaction between top-down (task-driven) and bottom-up (stimulus-driven) processes competing for attentional selection, as well as spatial distribution of attention. Here, we examined whether biparietal transcranial direct current stimulation (tDCS) would modulate the interaction between top-down and bottom-up processes in visual attention. Visual attention function was assessed with a visual discrimination task, in which a lateralized target was presented alone or together with a contralateral, similar or salient, distractor. The accuracy and RTs were measured before and during three stimulation sessions

(sham, right anodal/left cathodal, left anodal/right cathodal). The analyses demonstrated (i) polarity-dependent effects of tDCS on the accuracy of target discrimination, but only when the target was presented with a similar distractor; (ii) the tDCS-triggered effects on the accuracy of discriminating targets, accompanied by a similar distractor, varied according to the target location; and (iii) overall detrimental effects of tDCS on RTs were observed, regardless of target location, distractor type, and polarity of the stimulation. We conclude that the observed polarity, distractor type, and target location-dependent effects of biparietal tDCS on the accuracy of target detection resulted from both a modulation of the interaction between top-down and bottom-up attentional processes and the interhemispheric competition mechanisms guiding attentional selection and spatial deployment of attention. ■

## INTRODUCTION

The surrounding environment continuously bombards us with an overwhelming amount of visual information, significantly exceeding our capacity to efficiently analyze it and respond to it. Thus, thriving in a complex visual world depends on the ability to quickly prioritize incoming information. The term visual attention refers to a set of cognitive mechanisms facilitating the allocation of limited neural processing resources, according to the current behavioral goals, and subserved by specialized frontoparietal neural networks (Corbetta, Kincade, & Shulman, 2002; Corbetta & Shulman, 2002). Visual attention enables the rapid detection of and the response to behaviorally relevant (task-relevant) visual stimuli while ignoring irrelevant information. In a complex visual scene, this rapid selection of task-relevant visual targets requires the processing of multiple competing stimuli and also entails the suppression of task-irrelevant stimuli (distractors), which may be either perceptually salient or perceptually similar to the targets (Geng, 2014; Wolfe & Horowitz, 2004; Corbetta & Shulman, 2002; Yantis &

Egeth, 1999; Bundesen, 1990; Duncan & Humphreys, 1989; Wolfe, Cave, & Franzel, 1989; Duncan, 1980).

The attentional selection process is commonly studied using various visual search tasks, in which participants are asked to respond to predefined targets presented among various distractors (Wolfe, 1998). These visual search tasks do not fully capture the complexity of real-world situations but enable us to isolate and study essential properties of the real-world visual scenes and attentional selection mechanisms. One implementation of such paradigms, specifically used to explore the interplay between top-down and bottom-up processes in attentional selection, employs a direct competition between perceptual saliency and task relevance (e.g., Zehetleitner, Koch, Goschy, & Müller, 2013; Geng & Mangun, 2011; Mazaheri, DiQuattro, Bengson, & Geng, 2011; Geng & DiQuattro, 2010; Theeuwes, 1992). On the basis of the findings derived from the behavioral performance in such paradigms, it has been suggested that the initial capture of attention is stimulus-driven (i.e., bottom-up, determined by stimuli saliency) and that a top-down, goal-directed selection only occurs later in time (for a review, see Theeuwes, 2010). Although it is debatable whether the capture of attention is predominantly stimulus-driven, it has been repeatedly

<sup>1</sup>University of Birmingham, <sup>2</sup>University of Oxford, <sup>3</sup>University of California, Davis, <sup>4</sup>University of Bern

shown that there is always some combination of bottom-up and top-down influences that determines the deployment of visual attention (for a review, see Theeuwes, 2010; Corbetta & Shulman, 2002; Yantis, 2000, 2002). Furthermore, the results of prior studies strongly indicate that top-down and bottom-up attentional processes exert a mutual and flexible modulation on each other. Specifically, the attentional capture exerted by a salient distractor (i.e., a known nontarget) can also guide the subsequent deployment of top-down attention and thus facilitate target detection (DiQuattro & Geng, 2011; Geng & DiQuattro, 2010).

In the human brain, visual attention is controlled by several interconnected cortical areas, which are organized into two functionally specialized frontoparietal networks (Corbetta & Shulman, 2002). It is generally thought that the dorsal network controls the ability to orient attention in space, whereas the ventral network is predominantly involved in target detection and attentional reorienting to salient but unexpected stimuli. However, this strict dorsal-ventral dichotomy has been frequently questioned, and it has been also suggested that the two systems are not entirely independent (for a review, see Shomstein, 2012; Singh-Curry & Husain, 2009). The key cortical region, functionally engaged in visual attention, is the posterior parietal cortex (PPC). This large and highly specialized cortical area is thought to control both the interaction between top-down (task-driven) and bottom-up (stimulus-driven) processes competing for attentional selection, as well as the spatial distribution of visual attention. In fact, the aforementioned models of networks subserving visual attention incorporate the PPC into both the dorsal and ventral systems. This is based on the evidence from functional neuroimaging studies as well as from neuropsychological data (from patients with attentional deficits), suggesting that distinct PPC subregions control discrete attentional processes (Corbetta & Shulman, 2002, 2011; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000). Specifically, the PPC subregion along the intraparietal sulcus (including both the inferior and the superior parietal lobule) controls the voluntary orienting of attention to given spatial locations and is involved in top-down attentional control, whereas a more ventral PPC subregion along the TPJ is necessary for reorienting attention to unattended/unexpected visual targets and is involved in bottom-up attentional control (Doricchi, Macci, Silvetti, & Macaluso, 2010; Mevorach, Hodson, Allen, Shalev, & Humphreys, 2010; Shulman et al., 2010; Corbetta & Shulman, 1998, 2002; Corbetta et al., 1998, 2000, 2002; Friedrich, Egly, Rafal, & Beck, 1998; Nobre et al., 1997; Vandenberghe et al., 1996; Posner, Walker, Friedrich, & Rafal, 1984; Mesulam, 1981). Although clear evidence for a functional specialization within the PPC subregions exists, several functional neuroimaging studies and investigations in neurological patients also suggest that these two attention systems strongly interact with each other, enabling

a dynamic and flexible control of attention in both top-down and bottom-up fashion (for review, see Vossel, Geng, & Fink, 2014; Shomstein, 2012). Finally, although the PPC is traditionally associated with the control of attention, this region is also involved in a range of other cognitive functions, including learning, memory, decision-making, planning, and reward (for a review, see Constantinidis, Bucci, & Rugg, 2013).

The attention networks are functionally lateralized (i.e., the allocation of attention to the left vs. right visual field is controlled by the respective contralateral hemisphere), as well as asymmetrically organized, with a right hemispheric dominance. Relevant evidence, supporting the functional lateralization and right hemispheric dominance in spatial attention, comes from pseudoneglect in healthy participants and from neurological patients with visual attention disorders, such as neglect and extinction (Corbetta & Shulman, 2011; Halligan, Fink, Marshall, & Vallar, 2003; Jewell & McCourt, 2000; McCourt & Jewell, 1999; Driver & Mattingley, 1998; Vallar, 1998; Bowers & Heilman, 1980; Heilman & Valenstein, 1979). In addition to evidence for the lateralization of spatial attention, there also appears to be evidence for a hemispheric asymmetry in attentional processing of salient stimuli. For example, based on behavioral findings in patients with brain damage and on experimental manipulations using TMS, Mevorach and colleagues demonstrated a specific involvement of the left parietal cortex in the attentional suppression of salient, but task-irrelevant, information (Mevorach, Shalev, Allen, & Humphreys, 2009; Mevorach, Humphreys, & Shalev, 2006a, 2006b).

Transcranial direct current stimulation (tDCS) has been shown to modulate performance in various behavioral tasks by affecting the excitability of cortical areas subserving the corresponding cognitive processes. In particular, it has been shown that the anodal stimulation increases while the cathodal stimulation decreases cortical excitability, and thus, tDCS allows to trigger differential outcomes in a polarity-dependent manner (Nitsche et al., 2008; Nitsche & Paulus, 2000, 2001). Furthermore, it has been demonstrated that the effects triggered by tDCS may persist for up to few hours after the delivery of stimulation and that these effects strongly depend on the stimulation parameters, that is, the intensity, duration, and timing of the stimulation with respect to the administered behavioral task (Pirulli, Fertonani, & Miniussi, 2013; Moos, Vossel, Weidner, Sparing, & Fink, 2012; Teo, Hoy, Daskalakis, & Fitzgerald, 2011; Miranda, Faria, & Hallett, 2009; Sparing et al., 2009; Sparing & Mottaghy, 2008). Numerous prior studies have indicated that tDCS applied over the PPC can modulate visuospatial attention. However, the reported effects seem to be somewhat inconsistent and also to be highly dependent on the stimulation parameters employed by different studies, in particular the stimulation site (i.e., left vs. right PPC) and polarity (e.g., Benwell, Learmonth, Miniussi, Harvey, & Thut, 2015; Filmer, Dux, & Mattingley, 2015;

Roy, Sparing, Fink, & Hesse, 2015; Wright & Krekelberg, 2014; Moos et al., 2012; Weiss & Lavidor, 2012; Giglia et al., 2011; Bolognini, Fregni, Casati, Olgiati, & Vallar, 2010; Sparing et al., 2009). For example, Moos et al. (2012) have shown that tDCS applied over the right PPC can modulate the top-down control of attention, but a facilitatory effect was only observed after cathodal, but not anodal, stimulation, and only with a current strength of 2 mA (but not 1 mA). Furthermore, Roy et al. (2015) have reported strongly lateralized effects (as measured by efficiency of target detection in the left vs. right visual field) after anodal tDCS was applied over the right but not the left PPC. These results support two previously proposed accounts of the asymmetrical organization of visual attention and right-hemispheric dominance, that is, the notion of a differential involvement of the two hemispheres in attentional control (Heilman & Van Den Abell, 1980) and the Kinsbourne's interhemispheric rivalry model (Kinsbourne, 1987, 1993).

Overall, the results of several prior studies indicate that tDCS applied over the PPC can be used to modulate both spatial and nonspatial aspects of visual attention, including detection of lateralized targets, spatial reorienting, top-down control of attention, and attentional capacity (e.g., Benwell et al., 2015; Filmer et al., 2015; Roy et al., 2015; Wright & Krekelberg, 2014; Moos et al., 2012; Weiss & Lavidor, 2012; Giglia et al., 2011; Bolognini et al., 2010; Sparing et al., 2009). However, it should be noted that the spatial focality of tDCS, when applied using conventional rectangular or square electrodes (standard size  $7 \times 5$  or  $5 \times 5$  cm; as in the studies cited above), does not allow to precisely target distinct subregions within the PPC or to dissociate specific, differential influences on the dorsal and ventral attention systems.

In the current study, we examined whether and how biparietal tDCS (over the left and the right PPC) would modulate the interaction between top-down and bottom-up processes in visual attention. We opted for a biparietal tDCS stimulation approach to differentially modulate the activity of the left and the right PPC and to alter interhemispheric dynamics by simultaneously inhibiting one side and exciting the other. This would not be possible with the more commonly used unilateral tDCS stimulation approach. We assessed the effects of stimulation by means of a simple visual discrimination task, in which a lateralized (left or right visual hemifield) target was presented alone or together with a similar or salient distractor (appearing in the opposite hemifield). The two tDCS electrodes, with opposite polarities, were applied over the PPC of either hemisphere (i.e., anode on the right PPC and cathode on the left PPC, or vice versa) to differentially modulate the activity of these regions. This allowed us to examine whether shifting the interhemispheric balance between the posterior parietal regions of the two hemispheres would (i) have an impact on the functional lateralization of visual attention (left-right asymmetry in the target detection) and/or (ii) mod-

ulate the effect of distractor saliency on target detection. Furthermore, the biparietal approach enabled us to examine whether right/left hemispheric asymmetry has any influence on the interplay between top-down and bottom-up processes in visual attention.

As the target and the distractor were simultaneously presented within the opposite visual hemifields, we hypothesized that we would find an opposite influence of stimulation with reverse polarity (i.e., right anodal/left cathodal vs. left anodal/right cathodal tDCS) on the effects exerted by the two types of distractors (i.e., either the perceptually salient or the perceptually similar distractors or both) on target detection. Moreover, taking into account hemispheric asymmetries in visual attention, we anticipated potential differential effects of stimulation with reverse polarity on the detection of left versus right targets.

## METHODS

### Participants

Twenty-one healthy volunteers (10 men; mean age = 25.8 years,  $SD = 5.3$  years) took part in the study, which consisted of three separate brain stimulation sessions. Exclusion criteria included any previous history of neurological or psychiatric disorders and any contraindication to tDCS (Poreisz, Boros, Antal, & Paulus, 2007). Both left- and right-handed participants were recruited for the study, and hand dominance was assessed by means of the Edinburgh handedness inventory (Oldfield, 1971). All participants had either normal or corrected-to-normal vision. All study participants provided written informed consent, in compliance with the relevant protocols approved by the University of Oxford Central University research ethics committee. All experimental procedures were conducted in accordance with the latest version of the Declaration of Helsinki.

### Study Design and Procedure

The study consisted of three experimental sessions, each entailing a different type of tDCS, separated by at least 1 week. Each experimental session included a short practice version of the task, the full versions of the visual discrimination task (see Experimental Task section) performed without stimulation (as a baseline), followed by the repetition of the full experimental task performed during the tDCS application. tDCS was administered by means of a battery-powered, constant current stimulation device (neuroConn DC-STIMULATOR, GmbH, Illmenau, Germany), using  $5 \times 5$  cm rubber electrodes placed in saline soaked sponges. The saline was used to minimize the risk of skin irritation and to reduce impedance. The elastic strap was used to secure electrodes in place and to ensure a good contact with the scalp. A 1.5-mA tDCS was applied bilaterally over the left and the right PPC, the placement of the electrodes being determined according

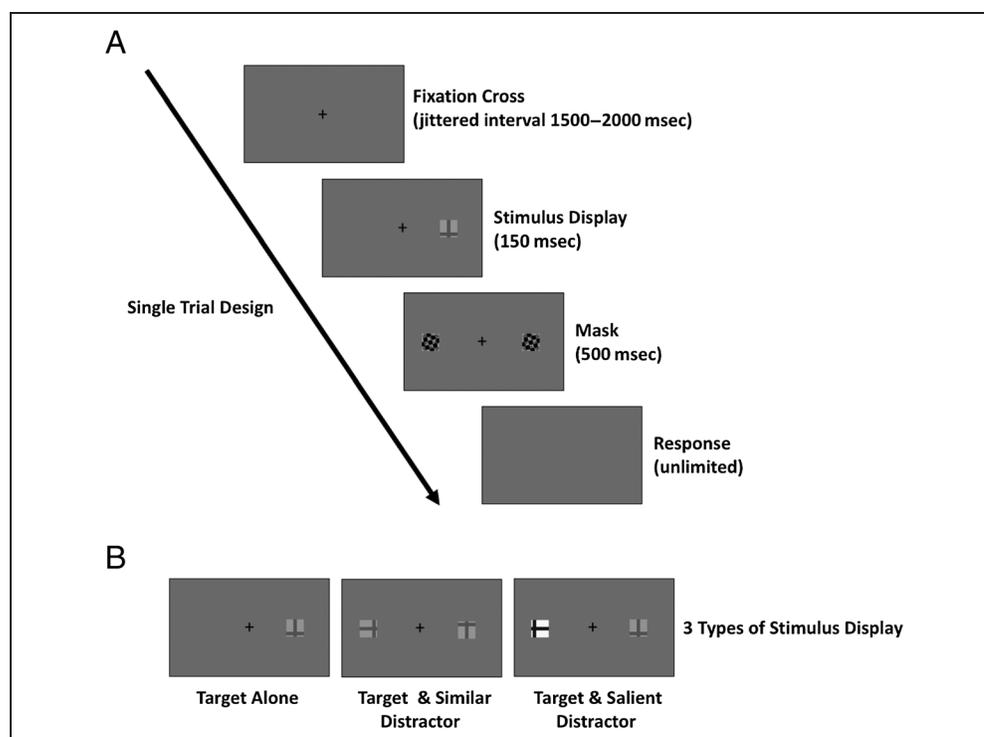
to the 10–20 EEG system (P3 and P4, respectively; Jasper, 1958). Each of the three sessions included a different stimulation condition: (i) right hemisphere (RH) anodal/left hemisphere (LH) cathodal, that is, right PPC anodal and left PPC cathodal tDCS stimulation lasting 1200 sec (20 min); (ii) LH anodal/RH cathodal, that is, left PPC anodal and right PPC cathodal tDCS stimulation lasting 1200 sec; and (iii) sham stimulation. Sham stimulation consisted of an initial 30 sec of real left PPC cathodal and right PPC anodal tDCS stimulation (applied to induce the itching/tingling sensation on the scalp under the electrodes, which is occasionally experienced by participants at the beginning of tDCS application) and of a subsequent automatic switching off of the device. Both the 1200-sec and 30-sec tDCS stimulation was flanked by a gradual 15 sec upward and 15 sec downward current ramp. The order of the three stimulation sessions was randomized across participants, and the study was conducted in a single-blind fashion, that is, only the experimenter but not the participant knew which stimulation type was delivered during each session. The start of the experimental task was always triggered 3 min after the onset of either the sham or the real tDCS stimulation. This ensured that, for the experimental sessions entailing real tDCS, the stimulation lasted for the whole duration of the task.

### Experimental Task

Participants were assessed on a visual discrimination task (for a modified version of a previously published task, see Geng & DiQuattro, 2010), in which a lateralized target,

presented either within the left or the right visual field, appeared alone or together with a contralateral distractor. Each trial began with a central black fixation cross presented for an interval randomly varying between 1500 and 2000 msec and followed by a visual display. The visual display consisted of either one (target alone) or two (target plus distractor) “t-like” stimuli (see Figure 1), presented for 150 msec and subsequently masked for 500 msec. The target was present on every trial, and the distractor, if present, always appeared simultaneously with the target. The fixation cross remained visible during the whole visual display duration, and the next trial began only after the participant responded. In each visual display, the target was presented randomly within the left or the right visual field on the horizontal meridian of the screen. The target was either an upright or an inverted “†.” The distractors were 90° rotations of the target stimuli. The distractor was randomly selected and equally likely to be rotated clockwise or counterclockwise when presented with either the left or the right target. The targets were always low contrast (Michelson contrast ratio = 0.51; foreground luminance = 5.4 cd/m<sup>2</sup>; background luminance = 16.8 cd/m<sup>2</sup>). The distractors were either low contrast like the targets, that is, similar distractors (Michelson contrast ratio = 0.51; foreground luminance = 5.4 cd/m<sup>2</sup>; background luminance = 16.8 cd/m<sup>2</sup>) or high contrast, that is, salient distractors (Michelson contrast ratio = 0.96; foreground luminance = 0.54 cd/m<sup>2</sup>; background luminance = 30.5 cd/m<sup>2</sup>). The subsequent mask was created from scrambled stimuli (see Figure 1). The black fixation cross and the stimuli were presented

**Figure 1.** Visual target discrimination task. (A) Each trial began with a fixation cross followed by a stimulus display, which was subsequently masked. Participants were asked to respond to target orientation, that is, upright or inverted “†” (modified from Geng & DiQuattro, 2010). (B) Examples of stimulus display: target alone, target & similar distractor, target & salient distractor. The target was presented randomly either within the left or the right visual hemifield.



on a gray background ( $9.8 \text{ cd/m}^2$ ). The three main types of stimulus display were target alone, target plus salient distractor, and target plus similar distractor (see Figure 1). The target was equally likely to be presented in the upright or inverted position, to appear in the left or the right visual hemifield, as well as equally likely to appear either alone or together with a contralateral similar or contralateral salient distractor. Both targets and distractors were  $1.4 \times 1.4^\circ$  in size and were presented at  $7.3^\circ$  eccentricity to the left or to the right of the central fixation cross. There was a total of 432 trials in the experimental task and 36 trials in the practice task. Participants were instructed to maintain central fixation and to respond, as quickly and as accurately as possible, to the target orientation on each trial (i.e., upright or inverted “+”) by pressing the upward or downward arrow keys on a computer keyboard, respectively. Both the RTs and the accuracy data were recorded for each trial and entered into data analysis.

### Data Analysis

For the purpose of the data analysis, we calculated mean accuracy and mean RT (for correct trials only) separately for each main task condition (type of stimulus display) and target location (i.e., left target alone, right target alone, left target with salient distractor, right target with salient distractor, left target with similar distractor, and right target with similar distractor). The same calculations were applied to the experimental task data collected prior and during each stimulation session. To evaluate the overall performance on the visual discrimination task, we combined (averaged) all the baseline data sets from each participant (i.e., experimental task performed before stimulation) separately for RT and accuracy measures. The merged data were then entered into a  $2 \times 3$  repeated-measures ANOVA, with the within-subject factors defined as the Target location (left hemifield, right hemifield) and the Distractor type (salient distractor, similar distractor, no distractor). To account for any inter-session variability in performance, before the analyses of the effects of stimulation, we normalized data across stimulation conditions. This was done by creating an index of performance change, defined by subtracting (RT and accuracy) baseline performance (i.e., before the application of the stimulation within the same testing session) from performance measured during stimulation, separately for each session, that is, RH anodal/LH cathodal, LH anodal/RH cathodal, and sham. Positive values indicate higher accuracy and longer RTs during stimulation compared with baseline, and negative numbers indicate lower accuracy and shorter RTs (faster performance) during stimulation than baseline. These calculated scores were entered into a  $3 \times 3 \times 2$  repeated-measures ANOVA, with the within-subject factors defined by the Stimulation type (RH anodal and LH cathodal, LH anodal and RH cathodal, sham stimulation), the Distractor type (salient

distractor, similar distractor, no distractor) and the Target location (left hemifield, right hemifield). The statistical analyses were performed separately for accuracy and RT data using SPSS 21 (IBM SPSS Statistics, Armonk, NY). All subsequent pairwise post hoc tests were performed using Statistica 6.0 (StatSoft Inc., Tulsa, OK), applying the Bonferroni correction.

The two key ANOVA analyses (i.e., examining the effects of the different stimulation conditions on the accuracy and RTs of target detection) were supplemented by a Bayesian inference approach, which allows to quantify the strength of the evidence from the data in support of the observed effects of the active stimulation (Wagenmakers et al., 2018b; Wetzels et al., 2011). We only employed the additional Bayesian statistics for these two key analyses to avoid unnecessary lengthening of the article. Bayesian paired samples *t* tests (Rouder, Speckman, Sun, Morey, & Iverson, 2009) were conducted using an open source statistical software JASP (JASP version 0.8.1.2, JASP Team, 2017; Wagenmakers et al., 2018a). For all reported Bayesian *t* tests, we used a default prior on the effect size for the alternative hypothesis, with Cauchy distribution centered on zero, with scale parameter  $r = .707$ . We reported Bayes factors ( $\text{BF}_{10}$ ) in favor of the alternative hypothesis, expressing the probability of the data given  $H_1$  relative to  $H_0$  (i.e., values larger than 1 are in favor of  $H_1$ ). The Bayes factors ( $\text{BF}_{10}$ ) were subsequently interpreted in accordance to Jeffreys (1961) and Wetzels et al. (2011). In addition, we performed robustness checks by recalculating the Bayes factors across a wide range of priors, that is, by varying the scale parameter  $r$  (range 0–1.5). All the conducted checks confirmed that the reported Bayes factors were robust and not influenced by prior choice.

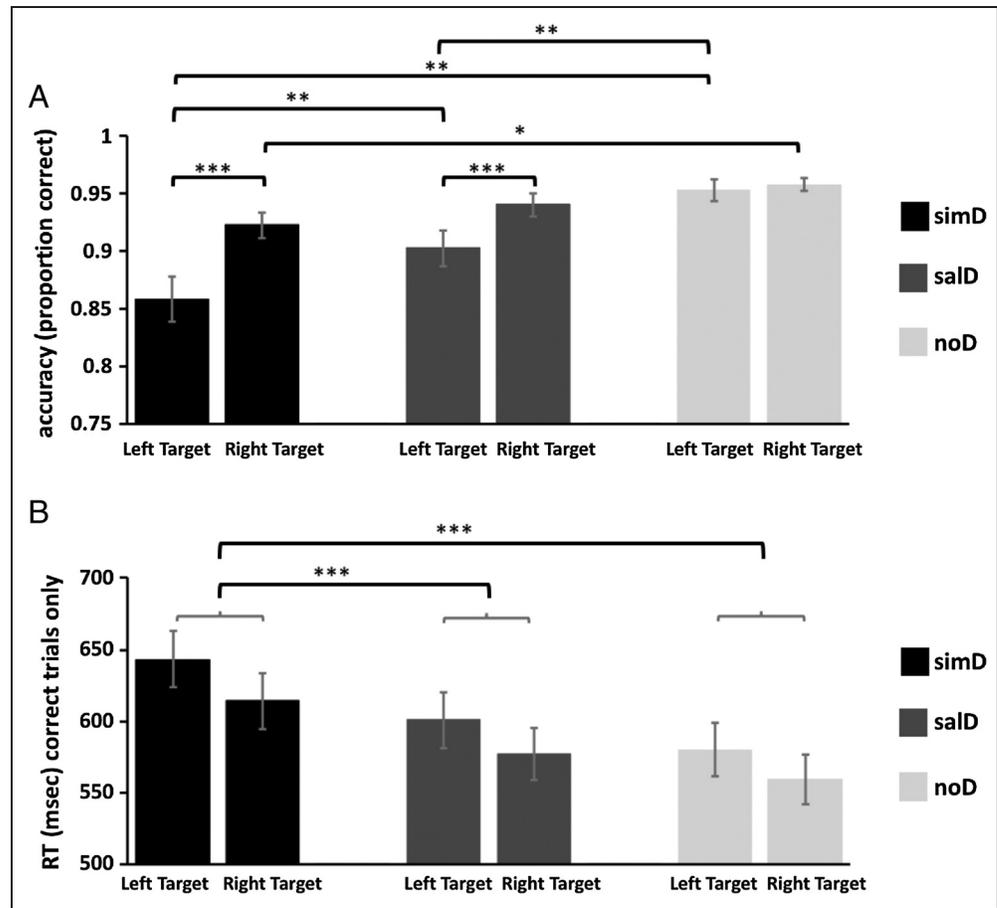
## RESULTS

### Baseline

In agreement with prior reports (DiQuattro & Geng, 2011; Geng & DiQuattro, 2010), the repeated-measures ANOVAs showed that accuracy was significantly higher and RTs were significantly shorter in the salient distractor condition and in the no distractor condition compared with the similar distractor condition (Figure 2A–B; a significant main effect of Distractor type on performance accuracy,  $F(2, 40) = 35.7, p < .0001$ , partial  $\eta^2 = .641$ , and on RTs,  $F(2, 40) = 43.6, p < .0001$ , partial  $\eta^2 = .685$ ).

In addition to main effect of Distractor type on the performance accuracy,  $F(2, 40) = 35.7, p < .0001$ , partial  $\eta^2 = .641$ , we also found a significant main effect of Target location,  $F(1, 20) = 8.8, p < .001$ , partial  $\eta^2 = .305$ , and a significant interaction between Target location and Distractor type,  $F(2, 40) = 9.8, p < .0001$ , partial  $\eta^2 = .328$  (Figure 2A). Subsequent pairwise post hoc tests revealed that this interaction was mainly attributable to a significant effect of Distractor type on targets located on

**Figure 2.** Baseline accuracy (A) and RTs (B) of target detection for each type of stimulus display. simD = similar distractor condition; salD = salient distractor condition; noD = no distractor condition; \* $p < .01$ , \*\* $p < .001$ , \*\*\* $p < .0005$  significant post hoc pairwise comparisons after Bonferroni correction.



the left (all  $p$ s  $< .001$ ; Figure 2A). For the target located on the right, participants were more accurate only on trials with no distractor compared with trials with similar distractors ( $p < .01$ ; other  $p$ s  $> .1$ ). Furthermore, accuracy was significantly lower for targets located on the left compared with targets located on the right in the presence of a distractor ( $p < .0005$ ), but not when the targets were presented alone ( $p > .1$ ).

The subsequent RT analysis revealed significant main effects of both Distractor type,  $F(2, 40) = 43.6$ ,  $p < .0001$ , partial  $\eta^2 = .685$ , and Target location,  $F(1, 20) = 12.9$ ,  $p < .005$ , partial  $\eta^2 = .393$ , but in contrast to the accuracy data, there was no significant interaction between Target location and Distractor type (Figure 2B). As indicated by subsequent post hoc tests, participants were significantly slower on trials in which targets were presented with similar distractors compared with trials with salient distractors or no distractors ( $p < .0005$ ). However, there was no significant difference between trials with salient distractors and trials with no distractors ( $p > .5$ ).

To test for differences in baseline performance between the three separate experimental sessions and for a potential effect of session order on RTs and accuracy (the order of the three experimental sessions was randomized across participants), we performed a mixed-model repeated-measures ANOVA with Session type (baseline testing before the three types of stimu-

lation: RH anodal/LH cathodal, LH anodal/RH cathodal, sham), Distractor type, and Target location as within-subject factors and Session order as a between-subject factor. Both RT and accuracy data showed neither an effect of Session (no significant difference in the baseline performance, i.e., before application of the stimulation, between the three sessions) nor an effect of Session order. Furthermore, no significant interactions between either target location or distractor type with session order were observed (all  $p$ s  $> .1$ ). However, we found a significant interaction between Session type and Distractor type,  $F(4, 56) = 2.52$ ,  $p = .05$ , partial  $\eta^2 = .144$ , when analyzing RT data. No other interactions with Session type were significant (all  $p$ s  $> .1$ ). Post hoc tests revealed that the significant interaction was driven by a baseline difference between trials with salient distractors and trials with no distractors in one of the three sessions, that is, RH anodal/LH cathodal ( $p < .05$ ). In all baseline sessions (RH anodal/LH cathodal, LH anodal/RH cathodal, sham), participants were significantly slower on trials in which targets were presented with similar distractors compared with trials with salient distractors or no distractors ( $p < .0001$ ). However, on trials with salient distractors compared with trials with no distractors, this difference was only significant in case of RH anodal/LH cathodal session ( $p < .05$ ).

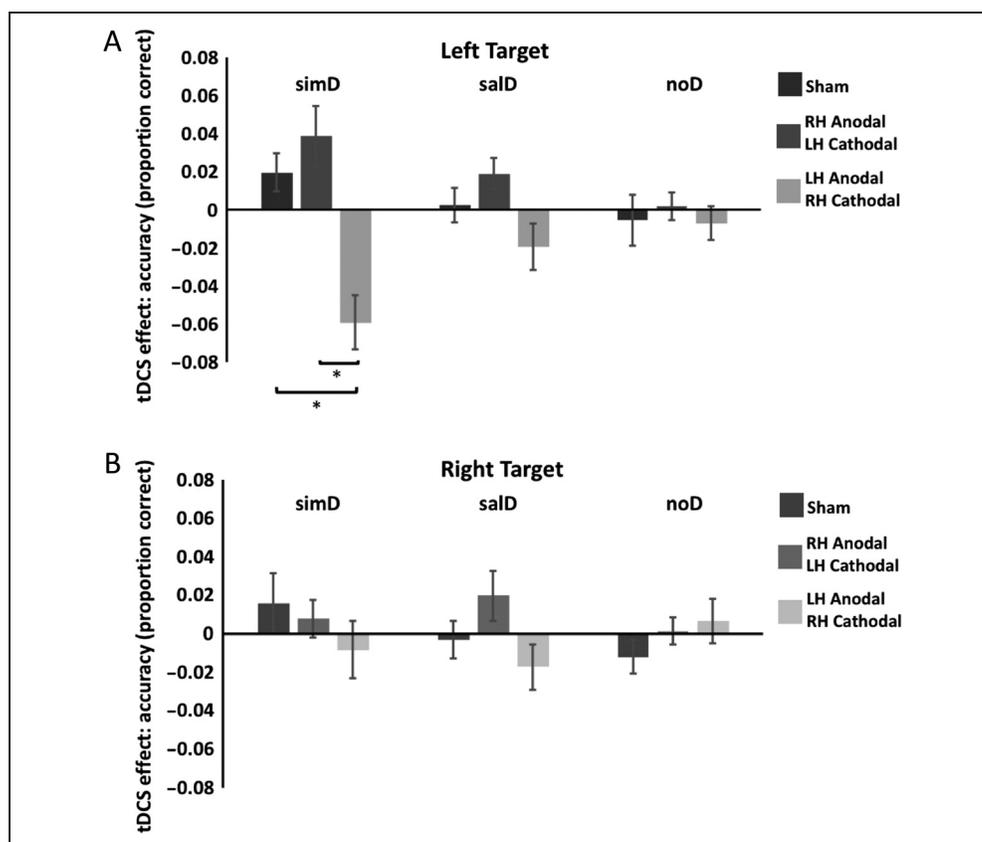
### tDCS Effects

The examination of the accuracy data suggested a polarity-dependent (polarity-specific) effect of the biparietal stimulation (Figure 3). Specifically, a repeated-measures ANOVA showed a significant main effect of Stimulation type,  $F(2, 40) = 7.1, p < .005$ , partial  $\eta^2 = .262$ , and a significant interaction between Stimulation type and Distractor type,  $F(4, 80) = 5.95, p < .0001$ , partial  $\eta^2 = .229$ . Furthermore, a significant three-way interaction between Stimulation type, Target location, and Distractor type was observed,  $F(4, 80) = 2.7, p < .05$ , partial  $\eta^2 = .119$ , indicating that the relationship between stimulation type and distractor saliency differed depending on the target location. Post hoc analyses showed that the biparietal stimulation only affected detection of targets located on the left ( $p < .0001$ ), but not on the right ( $p > .1$ ; Figure 3A–B). The post hoc tests demonstrated that LH anodal/RH cathodal stimulation (as compared with sham) decreased accuracy detection of left targets presented with similar distractors ( $p < .0001$ ), but not of left targets presented either with salient distractors or alone ( $p > .1$ ). The post hoc analyses indicated significant polarity-specific (polarity-dependent) effects of stimulation on the accuracy. Specifically, the LH anodal/RH cathodal stimulation significantly decreased the accuracy of left targets presented with similar distractors as opposed to not only the sham condition but also the RH anodal/LH cathodal stimulation ( $p < .0001$ ; Figure 3A). Moreover, the stimulation effects on

the detection of left targets accompanied by perceptually similar distractors tended to be opposite for the two active tDCS conditions (i.e., LH anodal/RH cathodal and RH anodal/LH cathodal stimulation). However, it should be noted that only the LH anodal/RH cathodal stimulation significantly decreased accuracy, whereas the improvement in accuracy following the RH anodal/LH cathodal stimulation did not reach statistical significance, as compared with sham condition (Figure 3A).

In agreement with the above post hoc analyses, the Bayesian paired  $t$  tests, comparing the effects of sham versus LH anodal/RH cathodal versus RH anodal/LH cathodal stimulation on the detection of either left or right targets accompanied by salient and similar distractors (Table 1), demonstrated very strong evidence in favor of the alternative hypothesis. These tests indicated significant polarity specific effects of stimulation on the accuracy, namely, that LH anodal/RH cathodal stimulation as compared with both sham ( $BF_{10} = 86.249$ ) and RH anodal/LH cathodal ( $BF_{10} = 100.208$ ) stimulation, substantially decreased accuracy detection of left targets presented with similar distractors.<sup>1</sup> In contrast to “classic” inferential analysis (as above), using Bayesian statistics we also found moderate evidence in favor of a difference between LH anodal/RH cathodal versus RH anodal/LH cathodal stimulation on the detection of left targets accompanied by salient distractors ( $BF_{10} = 5.398$ ). The above results might be suggestive of the

**Figure 3.** Effects of tDCS (difference in performance during stimulation minus pre stimulation, i.e., at baseline) on the accuracy of (A) left and (B) right target detection, plotted for each type of distractor. Positive values indicate higher accuracy during stimulation compared with baseline, and negative values indicate lower accuracy during stimulation than baseline. simD = similar distractor condition; salD = salient distractor condition; noD = no distractor condition;  $*p < .0001$  significant post hoc pairwise comparisons after Bonferroni correction.



**Table 1.** Bayesian Paired Samples *t* Tests Comparing the Effects of Stimulation on the Accuracy of Target Detection

			$BF_{10}$	Error %
<i>Left Target</i>				
<b>simD</b>				
Sham	versus	RH anodal/LH cathodal	0.345	0.024
Sham	versus	LH anodal/RH cathodal	<b>86.249</b>	<0.00001
RH anodal/LH cathodal	versus	LH anodal/RH cathodal	<b>100.208</b>	<0.00001
<b>salD</b>				
Sham	versus	RH anodal/LH cathodal	0.496	0.016
Sham	versus	LH anodal/RH cathodal	0.540	0.014
RH anodal/LH cathodal	versus	LH anodal/RH cathodal	<b>5.398</b>	0.002
<i>Right Target</i>				
<b>simD</b>				
Sham	versus	RH anodal/LH cathodal	0.242	0.027
Sham	versus	LH anodal/RH cathodal	0.357	0.024
RH anodal/LH cathodal	versus	LH anodal/RH cathodal	0.346	0.024
<b>salD</b>				
Sham	versus	RH anodal/LH cathodal	0.544	0.014
Sham	versus	LH anodal/RH cathodal	0.282	0.027
RH anodal/LH cathodal	versus	LH anodal/RH cathodal	1.543	<0.00001

simD = similar distractor condition; salD = salient distractor condition; noD = no distractor condition. **Boldface** indicates evidence in support of the alternative hypothesis.

two active stimulation conditions producing opposite effects (Figure 3A) on the detection of left targets. However, the notion of the opposite effects (LH anodal/RH cathodal vs. RH anodal/LH cathodal) should be interpreted with caution as the comparisons of the effects of RH anodal/LH cathodal stimulation versus sham provided only anecdotal (very weak) evidence in the support of alternative hypothesis ( $BF_{10} = 0.345$  for left targets presented with similar distractors;  $BF_{10} = 0.496$  for left targets presented with salient distractors). All other comparisons provided either weak evidence in favor of the alternative hypothesis ( $BF_{10} > 1/3$  and  $<3$ ) or moderate evidence in favor of the null hypothesis ( $BF_{10} < 1/3$ ).<sup>2</sup>

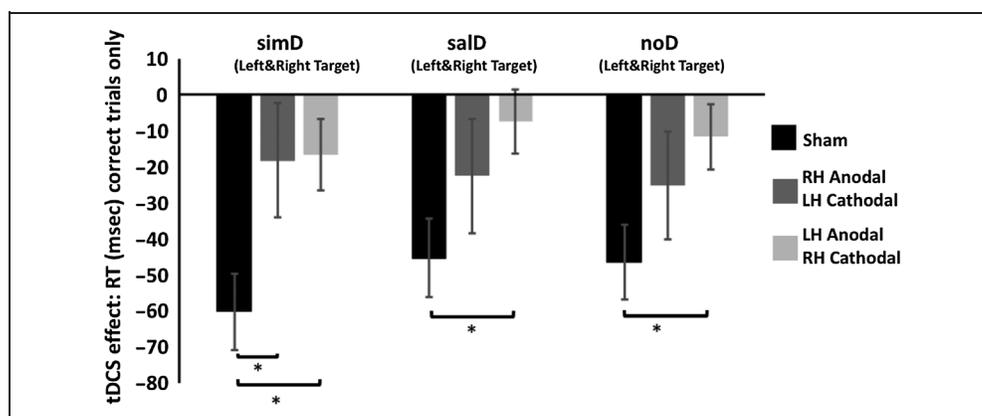
Finally, to test whether there was a link between session order and the observed effects of stimulation type on accuracy measures, we repeated our analysis using a mixed-model repeated-measures ANOVA with the Session order as a between-subject factor and with the Stimulation type, Distractor type, and Target locations as within-subject factors. We found neither a significant effect of Session order nor any significant interactions with this factor (all  $ps > .1$ ).

The subsequent analysis of the effects of stimulation on RTs (correct trials only) suggested a detrimental effect

of biparietal tDCS stimulation, regardless of its polarity. Overall, participants responded faster when performing the task for the second time during each session (i.e., task performance during stimulation, both real and sham, as compared with baseline performance), with the faster RTs being observed for all types of stimulus display, that is, regardless of both stimulation type and target location. Nevertheless, this decrease in RTs was significantly smaller when real tDCS was applied (irrespective of its polarity) as compared with the sham condition (Figure 4; please note that larger negative values plotted on Figure 4 indicate the faster performance during the second session compared with baseline).

Although a repeated-measures ANOVA showed no main effect of Stimulation, we found a significant interaction between Stimulation type and Distractor type,  $F(4, 80) = 2.5$ ,  $p < .05$ , partial  $\eta^2 = .112$ . The pairwise post hoc tests demonstrated that this interaction was driven by (i) the LH anodal/RH cathodal stimulation having a significant detrimental effect on the decrease in RTs as compared with sham in all distractor type conditions and (ii) the RH anodal/LH cathodal stimulation having a significant detrimental effect on the decrease in RT compared with sham condition only when the target was presented with a similar distractor (Figure 4 depicts the

**Figure 4.** Effects of tDCS (difference in performance during stimulation minus prestimulation, i.e., at baseline) on the RTs of target detection plotted for each type of distractor (collapsed across target location). The larger negative value plotted here, the faster performance during the stimulation compared with baseline. simD = similar distractor condition; salD = salient distractor condition; noD = no distractor condition; \* $p < .0001$  significant post hoc pairwise comparisons after Bonferroni correction.



significant post hoc pairwise comparisons after Bonferroni correction). Interestingly, interference effects on RT by LH anodal/ RH cathodal stimulation was present in all distractor conditions and target locations; this differed from the more specific effects that LH anodal/RH cathodal stimulation had on accuracy. Similarly, whereas RH anodal/LH cathodal stimulation only interfered with RT when the distractor was similar, there were no effects of target location. Together these results indicate that the effects of tDCS stimulation on RTs are more general across conditions than on accuracy.

In agreement with the above post hoc analyses, the Bayesian paired  $t$  tests, comparing the effects of sham versus LH anodal/RH cathodal versus RH anodal/LH cathodal stimulation on the RTs (Table 2), demonstrated moderate evidence in favor of the alternative hypothesis, namely, that the LH anodal/RH cathodal stimulation had a significant detrimental effect on

the decrease in RTs as compared with sham condition, regardless of the distractor type (salient distractor  $BF_{10} = 5.173$ , similar distractor  $BF_{10} = 4.223$ , no distractor  $BF_{10} = 3.942$ ). Furthermore, the Bayesian analysis provided weak evidence ( $BF_{10} > 1/3$  and  $< 3$ ) that RH anodal/LH cathodal stimulation had a significant detrimental effect on the decrease in RT compared with sham stimulation when the target was presented with a similar distractor ( $BF_{10} = 1.449$ ). All other comparisons provided negligible evidence in support of alternative hypothesis or moderate evidence in favor of the null hypothesis.

Finally, to test for a potential effect of session order on the impact of stimulation on RTs, we repeated our analysis using a mixed-model repeated-measures ANOVA with the Session order as a between-subject factor and, as before, with the Stimulation type, Distractor type, and Target locations as within-subject factors. We found

**Table 2.** Bayesian Paired Samples  $t$  Tests Comparing the Effects of Stimulation on the RTs of Target Detection

			$BF_{10}$	Error %
<b>simD</b>				
Sham	versus	RH anodal/LH cathodal	1.449	<0.00001
Sham	versus	LH anodal/RH cathodal	<b>5.173</b>	0.002
RH anodal/LH cathodal	versus	LH anodal/RH cathodal	0.228	0.027
<b>salD</b>				
Sham	versus	RH anodal/LH cathodal	0.375	0.023
Sham	versus	LH anodal/RH cathodal	<b>4.223</b>	0.002
RH anodal/LH cathodal	versus	LH anodal/RH cathodal	0.314	0.026
<b>noD</b>				
Sham	versus	RH anodal/LH cathodal	0.370	0.023
Sham	versus	LH anodal/RH cathodal	<b>3.942</b>	0.002
RH anodal/LH cathodal	versus	LH anodal/RH cathodal	0.290	0.026

simD = similar distractor condition; salD = salient distractor condition; noD = no distractor condition. **Boldface** indicates evidence in support of the alternative hypothesis.

neither an effect of Session order and nor any significant interactions with the latter (all  $ps > .1$ ).

## DISCUSSION

In this study, we employed biparietal tDCS to modulate the interaction between top-down and bottom-up processes in visual attention, as assessed by a visual target discrimination task, in which a lateralized (to either the left or the right visual hemifield) target was presented alone or together with a contralateral similar or salient distractor. In addition to examining whether the biparietal stimulation would modulate the effect of saliency of the contralateral distractor on the detection of target (e.g., DiQuattro & Geng, 2011; Geng & DiQuattro, 2010; Theeuwes, 2010; Leblanc, Prime, & Jolicoeur, 2008; Proulx & Egeth, 2006, 2008; Hickey, McDonald, & Theeuwes, 2006; Jewell & McCourt, 2000), we also aimed to explore whether shifting the interhemispheric balance between the posterior parietal regions of the two hemispheres would have an impact on the functional lateralization of visual attention (i.e., left-right asymmetry in the target detection; see Jewell & McCourt, 2000; Nicholls, Bradshaw, & Mattingley, 1999; Kinsbourne, 1987, 1993; Mesulam, 1981; Heilman & Van Den Abell, 1980). On the whole, the results showed (i) polarity-dependent effects of tDCS stimulation on the accuracy of target discrimination but only when the target was presented with a perceptually similar distractor and (ii) overall detrimental effects of tDCS on RTs, regardless of stimulation polarity. Interestingly, we not only found that the tDCS affected the accuracy of target detection in polarity-dependent manner but also that these effects varied according to the target location and distractor type. By contrast, the effects of the tDCS on RTs of target detection were influenced by neither the stimulation polarity nor the target location nor distractor type. This suggests that the effect of tDCS on accuracy was highly specific and only affected the most difficult condition in which the target was paired with a similar distractor and the target was contralateral to the hemisphere undergoing cathodal stimulation. In contrast, the effect of RT appeared to be more general, affecting performance across conditions irrespective of attentional competition.

For the purpose of the current study, we employed a modified version of the task (shorter presentation of visual display and visual masking), which was previously used to demonstrate, based on the analysis of behavioral performance and eye-tracking data, that a strong attentional bottom-up capture exerted by a salient distractor (“known nontarget”) guides the deployment of top-down attention and thus assists target detection (DiQuattro & Geng, 2011; Geng & DiQuattro, 2010). Specifically, prior experiments conducted by Geng and DiQuattro (2010) indicated that, whereas the first saccade was more likely to be directed toward a salient object (despite prior

knowledge that only a distractor but not a target could be salient), the salient distractor seemed to facilitate rather than interfere with target detection (see also Leblanc et al., 2008; Proulx & Egeth, 2006, 2008; Hickey et al., 2006, for further arguments in relation to the effects of nontarget/distractor saliency on target detection). Furthermore, eye-tracking data showed that this facilitation was driven by two strategies: (i) inhibition when the first saccade was directed toward a target (fewer additional saccades to salient nontarget once the target was detected) and (ii) rapid rejection when the first saccade was captured by a salient distractor (Geng & DiQuattro, 2010). In agreement with these prior studies (DiQuattro & Geng, 2011; Geng & DiQuattro, 2010), our baseline behavioral data indicated that a perceptually salient distractor facilitated, and a similar distractor hampered, target detection. Although in the current study we did not employ eye-tracking (and thus, we were unable to distinguish the time course of attentional competition between targets and distractors), our data do seem to support the idea that, whereas the similar distractor hampers target discrimination, the rapid rejection of salient distractor provides information allowing to quickly reorient attention toward the target and thus facilitate target discrimination (upright or inverted “†”). These findings are also consistent with the assumption that the initial capture of visual attention can be stimulus-driven (i.e., bottom-up, determined by stimuli saliency), with the top-down, goal-directed selection occurring later in time (for a review, see Theeuwes, 2010). It should be also noted that the lack of eye-tracking impeded the ability to (1) distinguish between trials with first saccade directed towards distractor versus trials with first saccade directed towards target and (2) measure if the first saccade was directed towards the left versus the right hemifield. Although this is a potential limitation of the current study (i.e., eye tracking could have aided the interpretation of the results), the observed effects were robust against the more subtle effects of attentional competition that can be teased out with eye tracking.

We also show (baseline data) that the effect of distractor type on the accuracy but not the RTs of targets detection varied depending on target location. Specifically, the accuracy was significantly lower for targets located on the left compared with the right targets. But this “striking lateralization” was only observed in the presence of contralateral either salient or similar distractor, but not when targets were presented alone. This finding is difficult to explain in terms of the left spatial bias in the allocation of visual attention resulting from the right hemispheric dominance (pseudoneglect; see, e.g., Jewell & McCourt, 2000; Nicholls et al., 1999), as accordingly we would expect higher accuracy and/or faster responses for targets located on the left. The majority of prior studies suggest that the preferential activation of the right ventral frontoparietal network, consisting of TPJ and ventral frontal cortex, underlies target detection and attentional orienting

and constitutes the neural basis of pseudoneglect and neglect (e.g., Corbetta & Shulman, 2011; Shulman et al., 2010; Corbetta, Patel, & Shulman, 2008; Fox, Corbetta, Snyder, Vincent, & Raichle, 2006; Vossel, Thiel, & Fink, 2006; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005). By contrast, some recent studies have proposed that the left frontoparietal network, in particular the TPJ, is involved in attentional orienting driven by nonspatial features and that the left TPJ integrates top-down and bottom-up processes in guiding attention (DiQuattro & Geng, 2011; Hodson, Mevorach, & Humphreys, 2009; Weidner, Krummenacher, Reimann, Müller, & Fink, 2009; Mevorach et al., 2006b). Our findings seem to be consistent with these reports and with the idea that the left and not the right frontoparietal network guides attention based on nonspatial features with contextual relevance (see Geng & Vossel, 2013, for further evidence and discussion).

The most striking finding of the current study is the observed polarity and target location-dependent effect of tDCS on the accuracy of target detection. Specifically, we showed that biparietal tDCS affected the detection of targets located within the left but not the right hemifield and only targets accompanied by perceptually similar distractors. Furthermore, the effects of stimulation were polarity specific, that is, the LH anodal/RH cathodal stimulation significantly decreased the detection accuracy of left targets presented with similar distractors as opposed to the sham and the RH anodal/LH cathodal stimulation conditions. It should be noted that Bayesian analyses also provided moderate evidence suggesting distinct effects of LH anodal/RH cathodal versus RH anodal/LH stimulation on detection accuracy of left targets accompanied by perceptually salient distractors. But taking into account the results of other reported tests, this finding should be considered with caution.

Taking into account the relatively low spatial selectivity (resolution) of the employed tDCS protocol, we cannot separate the effects of the stimulation on discrete neural substrates of attention within either the dorsal or the ventral frontoparietal networks. Consequently, it is very improbable that the stimulation uniquely targeted a single attentional process. Based on the functional organization of the neural networks subserving visual attention (Corbetta & Shulman, 2002), the employed here biparietal tDCS likely affected multiple attentional mechanisms, including the interplay between top-down and bottom-up processes as well as interhemispheric balance mechanisms controlling the spatial allocation of visual attention. Therefore, the reported findings could be understood in terms of simultaneous modulation of these separate aspects of visual attention.

It is generally assumed that the effects of tDCS result from changes in cortical excitability and that tDCS triggers differential outcomes in a polarity dependent manner, with the anodal stimulation increasing whereas the cathodal stimulation decreasing cortical excitability,

resulting in facilitation and inhibition of cognitive processes, respectively (Nitsche et al., 2008; Nitsche & Paulus, 2000, 2001). Although this striking dichotomy in the polarity-dependent effects of tDCS has been quite consistently replicated in the motor system (O'Shea et al., 2014; Stagg & Nitsche, 2011; Nitsche et al., 2008; Nitsche & Paulus, 2000, 2001), the findings reported in studies examining the effects of tDCS on visual attention are often contradictory and the effects seem to be highly dependent on the stimulation site (i.e., left vs. right hemisphere; Benwell et al., 2015; Filmer et al., 2015; Roy et al., 2015; Wright & Krekelberg, 2014; Moos et al., 2012; Weiss & Lavidor, 2012; Giglia et al., 2011; Bolognini et al., 2010; Sparing et al., 2009). Some studies have indeed shown that anodal tDCS, applied over the PPC, seems to improve attentional functions, similar to tDCS modulation observed for other cognitive domains; (e.g., Roy et al., 2015; Chi, Fregni, & Snyder, 2010; Cerruti & Schlaug, 2009; Sparing et al., 2009; although see Filmer et al., 2015, for opposite effects). By contrast, the cathodal stimulation (applied over the PPC) has been shown to either deteriorate or enhance performance in tasks measuring visual attention functions (e.g., Giglia et al., 2011 vs. Moos et al., 2012; Weiss & Lavidor, 2012). However, whereas both Moos et al. (2012) and Giglia et al. (2011) employed tDCS applied over the right PPC, the first study reported the tDCS-induced enhancement of the top-down control of attention, whereas the latter measured the effects of stimulation on the interhemispheric balance and the shift in the spatial allocation of visual attention. Furthermore, it should be noted that the effects of tDCS on attention have been frequently observed only when stimulation is applied to the right but not the left hemisphere (e.g., Filmer et al., 2015; Roy et al., 2015). Interestingly, Filmer et al. (2015) demonstrated that, regardless of the stimulation polarity, tDCS applied over the right PPC disrupted detection of competing stimuli, simultaneously presented within the left and the right visual hemifields. Finally, Giglia et al. (2011) also showed that, whereas biparietal tDCS (i.e., right cathodal and left anodal tDCS), similar to unilateral right cathodal tDCS, resulted in a rightward spatial bias of attention, the effects of bilateral stimulation were significantly stronger compared with unilateral stimulation (see also O'Shea et al., 2014, for contradictory findings concerning the effects of unilateral vs. bilateral stimulation). Taking together all prior evidence and our findings, we suggest that overall bilateral tDCS stimulation, regardless of polarity, seems to exert stronger effects on the attentional control compared with the effects on the shift (lateralization) in the allocation of visual attention. Subsequently, we suggest that LH anodal/RH cathodal stimulation significantly decreased accuracy of detecting left targets accompanied by contralateral similar distractors because this stimulation resulted in both a rightward shift in the allocation of visual attention (i.e., toward distractor) and an increased bottom-up control enhancing

attentional capture by the similar distractor in the right visual hemifield. In contrast, LH anodal/RH cathodal stimulation had no significant effect on the accuracy of detecting left targets accompanied by contralateral salient distractors because, whereas this stimulation resulted in both a rightward shift in the allocation of visual attention and an increased bottom-up capture by salient distractor, the latter likely resulted in an enhanced distractor rejection causing a rapid reorientation of attention toward the left targets and thus having an opposite effect with respect to the rightward spatial shift. Furthermore, LH anodal/RH cathodal stimulation had no significant effects on the accuracy of detecting the right targets accompanied by contralateral either similar or salient distractors due to likely opposite effects on an increased bottom-up capture and the rightward shift in the allocation of visual attention, with the former being a significantly stronger effect. Finally, we suggest that RH anodal/LH cathodal stimulation significantly increased accuracy of detecting the left targets accompanied by contralateral similar distractors because this stimulation resulted in both a weak leftward shift in the allocation of visual attention and a decreased bottom-up control, lessening attentional capture by the similar distractor in the right visual hemifield. We also suggest that overall both anodal and cathodal tDCS stimulation seems to exert stronger effects on the bottom-up control compared with the effects on the shift in the allocation of visual attention. However, an alternative explanation of the reported findings could be proposed. It could be suggested that the findings are in line with an overall tDCS effect on distractor suppression in conditions of high competition (i.e., target presented with similar distractor). Such an effect could be explained by a field-specific impact of tDCS on attentional priority of the target, which manifests only in conditions of high similarity between target and distractor.

Overall, the accuracy results suggest that LH anodal/RH cathodal stimulation had a detrimental effect on performance when the target was on the left and the distractor was similar. This result might indicate that left parietal excitation (and right parietal inhibition) impairs detection of targets in the left visual field, especially when there is a strong distractor competition. Why such effects were observed only for left targets under the condition of the left parietal excitation/right parietal inhibition and not for right targets under the condition of the right parietal excitation/left parietal inhibition is unclear. Perhaps the explanation lies in the combined hemispheric-specific and polarity-specific effects of biparietal stimulation. However, as stated above prior studies examining the effects of either unilateral or bilateral tDCS on visual attention provided contradictory evidence with regard to stimulation site (left vs. right hemisphere) and polarity (anodal vs. cathodal), and thus, any interpretation would not be straightforward.

In addition to assessing the effects of biparietal tDCS on the accuracy of target detection, we also measured

tDCS-induced changes in speed of performance (RTs). Prior studies examining the effects of tDCS on visual attention as measured by changes in RTs are largely inconsistent, with some reporting polarity-dependent (anodal vs. cathodal) or stimulus location-dependent (with respect to stimulation site, i.e., ipsilateral or contralateral hemifield) effects, whereas others reporting no effects or effects independent of stimulation type/polarity (e.g., Filmer et al., 2015; Li et al., 2015; Roy et al., 2015; Medina et al., 2013; Weiss & Lavidor, 2012; Sparing et al., 2009). Thus, the presented in the current study findings that the effects of stimulation on RT were not polarity dependent are in agreement with some prior reports. Specifically, we found that both biparietal RH anodal/LH cathodal and LH anodal/RH cathodal tDCS (but not sham stimulation) had detrimental effects on the speed of target detection. Whereas there was an overall effect of practice (participants were faster in correctly detecting targets when performing the task for the second time during each session, i.e., during tDCS or sham stimulation, compared with baseline), but this increase in speed of performance was significantly smaller when either RH anodal/LH cathodal or LH anodal/RH cathodal tDCS were applied compared with sham stimulation. This suggests detrimental effect of biparietal tDCS regardless of its polarity. Although, it should be noted that a subsequent analyses based on Bayesian *t* tests provided only weak evidence that RH anodal/LH cathodal stimulation had a significant effect compared with sham stimulation and only when the target was presented with a similar distractor. By contrast, some prior studies reported that uniparietal anodal tDCS speeded RTs in visual attention tasks (e.g., Roy et al., 2015; Bolognini et al., 2010; Sparing et al., 2009). But whereas such effects (i.e., faster RTs) could be triggered regardless of whether anodal tDCS was applied over the left or the right PPC, the stimulation differentially affected the detection of stimuli presented unilaterally versus bilaterally (slower vs. faster RTs, respectively; see Sparing et al., 2009). In this study, we assessed attentional selection using a paradigm in which a lateralized (left or right visual hemifield) target was presented alone or together with a contralateral, similar or salient, distractor. It is thus plausible that biparietal and bidirectional (RH anodal/LH cathodal or LH anodal/RH cathodal) tDCS simultaneously affected the interplay between bottom-up and top-down processes in attentional selection, and the interhemispheric competition mechanisms allocating attention to the contralateral versus the ipsilateral hemifield (Kinsbourne, 1987, 1993; Heilman & Van Den Abell, 1980). Thus, biparietal tDCS resulted in detrimental rather than beneficial effects on RTs regardless of polarity.

The fact that the application of biparietal tDCS resulted in polarity specific effect on the accuracy but not on the RT requires further consideration. Our ability to interpret the effects of stimulation on the RT versus the accuracy is significantly hampered by the fact that most studies only

report either the RT or the accuracy data. Nevertheless, there are two tDCS studies of potential relevance. First, in addition to testing healthy controls, Sparing et al. (2009) also examined the effects of stimulation on visual neglect symptoms in a small group of stroke patients ( $n = 10$ ). Taking into account a relatively small number of neglect patients and a large variability in response to stimulation, not surprisingly no statistically significant changes in visual attention task (from the Tests of Attentional Performance, the TAP battery) were observed. Nevertheless, Sparing et al. (2009) reported two interesting trends: (i) when active tDCS, regardless of polarity, was applied over either the intact or the damaged hemisphere, patients responded faster compared with the application of sham stimulation; (ii) cathodal tDCS applied over the intact hemisphere tended to increase, whereas anodal tDCS applied over the intact hemisphere tended to decrease, the number of stimuli detected by patients compared with sham stimulation. Therefore, similar to our findings, there was a stimulation-specific effect on accuracy, but only a generic one on RT. A second study by Li et al. (2015) examined the effects of biparietal tDCS on accuracy and RT in performance on CRT (choice reaction task). Interestingly, Li et al. (2015) reported that there were no effects of stimulation on accuracy (CRT error rate) but found distinct effects on vigilance (measured by change in RT), depending on polarity of biparietal tDCS (improvement vs. decrement in vigilance level; although the actual ANOVA only showed borderline significance). Thus, both studies report a discrepancy between accuracy and RT results, in line with our findings. These studies and our own results that stimulation produces different patterns of results on RT and accuracy are also in agreement with the notion that accuracy and RT might operate via different cognitive and neural processes (see Mulder & van Maanen, 2013; van Ede, de Lange, & Maris, 2012; Prinzmetal, McCool, & Park, 2005). It is commonly assumed that results for both the accuracy and the RT should produce the same interpretation (e.g., faster and more accurate responses both indicate better performance) and reflect the same underlying mechanisms. However, a recent study by van Ede et al. (2012) using a cued somatosensory discrimination task and measuring both behavioral performance and magnetoencephalography elegantly demonstrated that the accuracy and RT are affected by an attentional cue via distinct cognitive and neural processes underlying the decision reflected by the recorded responses.

### Final Remarks and Conclusions

The presented findings suggest that biparietal tDCS can modulate some, but not all, aspects of the interplay between task-driven and stimulus-driven attentional selection in a polarity-dependent manner, as indicated by the differential tDCS effects on RTs and accuracy in task performance. Specifically, we have shown polarity and

target location-dependent effects of tDCS on accuracy, but not RTs, in the detection of targets presented with similar distractors. Because of the low spatial resolution of the applied tDCS technique (also commonly used in other studies; see e.g., Benwell et al., 2015; Filmer et al., 2015; Roy et al., 2015; Wright & Krekelberg, 2014; Moos et al., 2012; Weiss & Lavidor, 2012; Giglia et al., 2011; Bolognini et al., 2010; Sparing et al., 2009), it was impossible to specifically target distinct cortical regions controlling different attentional mechanisms. Based on prior evidence, we suggest that the polarity and target location-dependent effects of biparietal tDCS on the accuracy of detection of targets presented with a similar distractor resulted from simultaneous modulation of the interaction between top-down and bottom-up processes and the interhemispheric competition mechanisms guiding the attentional selection and spatial allocation of visual attention. Similar to prior studies, our findings indicate that the effects of tDCS applied over the PPC on visual attention vary depending on stimulation polarity. However, our data also indicate that the polarity of the applied stimulation might have opposite effects on different attentional mechanism. Thus, we conclude that not only the interpretation of the results but also the clinical application of this type of stimulation as a potential approach for the rehabilitation of visual attention deficits requires careful consideration of the potentially differential effects on distinct attentional functions.

### Acknowledgments

This work was supported by funding from the National Institute of Health Research through the Oxford Cognitive Health Clinical Research Facility and the British Academy Postdoctoral Fellowship (M. C.). D. C. was supported by an Ambizione Fellowship of the Swiss National Science Foundation.

Reprint requests should be sent to Magdalena Chechlac, School of Psychology, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom, or via e-mail: m.chechlac.1@bham.ac.uk.

### Notes

1. We have also performed additional Bayesian paired samples  $t$  test comparing the effects of LH anodal/RH cathodal stimulation versus the RH anodal/LH cathodal stimulation using sham normalized score to index the effects of active tDCS (tDCS – sham/tDCS + sham), that is, controlling for the change induced by sham stimulation. Again, this analysis provided a very strong evidence in favor of the alternative hypothesis ( $BF_{10} = 103.575$ ), that is, that the effects of the two type of active stimulation conditions (LH anodal/RH cathodal and RH anodal/LH cathodal) on detection of left targets presented with similar distractors were indeed different.
2. Thus overall, the “classical” (ANOVA followed by post hoc tests) and Bayesian statistics converged, indicating the robustness of our conclusions about polarity-dependent effects of tDCS on the accuracy of target discrimination, but only when the target was presented in the left hemifield and with a similar distractor.

## REFERENCES

- Benwell, C. S., Learmonth, G., Miniussi, C., Harvey, M., & Thut, G. (2015). Non-linear effects of transcranial direct current stimulation as a function of individual baseline performance: Evidence from biparietal tDCS influence on lateralized attention bias. *Cortex*, *69*, 152–165.
- Bolognini, N., Fregni, F., Casati, C., Olgiati, E., & Vallar, G. (2010). Brain polarization of parietal cortex augments training-induced improvement of visual exploratory and attentional skills. *Brain Research*, *1349*, 76–89.
- Bowers, D., & Heilman, K. M. (1980). Pseudoneglect: Effects of hemispace on a tactile line bisection task. *Neuropsychologia*, *18*, 491–498.
- Bundesden, C. (1990). A theory of visual attention. *Psychological Review*, *97*, 523–547.
- Cerruti, C., & Schlaug, G. (2009). Anodal transcranial direct current stimulation of the prefrontal cortex enhances complex verbal associative thought. *Journal of Cognitive Neuroscience*, *21*, 1980–1987.
- Chi, R. P., Fregni, F., & Snyder, A. W. (2010). Visual memory improved by non-invasive brain stimulation. *Brain Research*, *1353*, 168–175.
- Constantinidis, C., Bucci, D. J., & Rugg, M. D. (2013). Cognitive functions of the posterior parietal cortex. *Frontiers in Integrative Neuroscience*, *7*, 35.
- Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., et al. (1998). A common network of functional areas for attention and eye movements. *Neuron*, *21*, 761–773.
- Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience*, *3*, 292–297.
- Corbetta, M., Kincade, J. M., & Shulman, G. L. (2002). Neural systems for visual orienting and their relationships to spatial working memory. *Journal of Cognitive Neuroscience*, *14*, 508–523.
- Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: From environment to theory of mind. *Neuron*, *58*, 306–324.
- Corbetta, M., & Shulman, G. L. (1998). Human cortical mechanisms of visual attention during orienting and search. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, *353*, 1353–1362.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*, 201–215.
- Corbetta, M., & Shulman, G. L. (2011). Spatial neglect and attention networks. *Annual Review of Neuroscience*, *34*, 569–599.
- DiQuattro, N. E., & Geng, J. J. (2011). Contextual knowledge configures attentional control networks. *Journal of Neuroscience*, *31*, 18026–18035.
- Doricchi, F., Macci, E., Silvetti, M., & Macaluso, E. (2010). Neural correlates of the spatial and expectancy components of endogenous and stimulus-driven orienting of attention in the Posner task. *Cerebral Cortex*, *20*, 1574–1585.
- Driver, J., & Mattingley, J. B. (1998). Parietal neglect and visual awareness. *Nature Neuroscience*, *1*, 17–22.
- Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, *87*, 272–300.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458.
- Filmer, H. L., Dux, P. E., & Mattingley, J. B. (2015). Dissociable effects of anodal and cathodal tDCS reveal distinct functional roles for right parietal cortex in the detection of single and competing stimuli. *Neuropsychologia*, *74*, 120–126.
- Fox, M. D., Corbetta, M., Snyder, A. Z., Vincent, J. L., & Raichle, M. E. (2006). Spontaneous neuronal activity distinguishes human dorsal and ventral attention systems. *Proceedings of the National Academy of Sciences, U.S.A.*, *103*, 10046–10051.
- Friedrich, F. J., Egly, R., Rafal, R. D., & Beck, D. (1998). Spatial attention deficits in humans: A comparison of superior parietal and temporal-parietal junction lesions. *Neuropsychology*, *12*, 193–207.
- Geng, J. J. (2014). Attentional mechanisms of distractor suppression. *Current Directions in Psychological Science*, *23*, 147–153.
- Geng, J. J., & DiQuattro, N. E. (2010). Attentional capture by a perceptually salient non-target facilitates target processing through inhibition and rapid rejection. *Journal of Vision*, *10*, 5.
- Geng, J. J., & Mangun, G. R. (2011). Right temporoparietal junction activation by a salient contextual cue facilitates target discrimination. *Neuroimage*, *54*, 594–601.
- Giglia, G., Mattaliano, P., Puma, A., Rizzo, S., Fierro, B., & Brighina, F. (2011). Neglect-like effects induced by tDCS modulation of posterior parietal cortices in healthy subjects. *Brain Stimulation*, *4*, 294–299.
- Geng, J. J., & Vossel, S. (2013). Re-evaluating the role of TPJ in attentional control: Contextual updating? *Neuroscience & Biobehavioral Reviews*, *37*, 2608–2620.
- Halligan, P. W., Fink, G. R., Marshall, J. C., & Vallar, G. (2003). Spatial cognition: Evidence from visual neglect. *Trends in Cognitive Sciences*, *7*, 125–133.
- Heilman, K. M., & Valenstein, E. (1979). Mechanisms underlying hemispatial neglect. *Annals of Neurology*, *5*, 166–170.
- Heilman, K. M., & Van Den Abell, T. (1980). Right hemisphere dominance for attention: The mechanism underlying hemispheric asymmetries of inattention (neglect). *Neurology*, *30*, 327–330.
- Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience*, *18*, 604–613.
- Hodsoll, J., Mevorach, C., & Humphreys, G. W. (2009). Driven to less distraction: rTMS of the right parietal cortex reduces attentional capture in visual search. *Cerebral Cortex*, *19*, 106–114.
- JASP version 0.8.1.2, JASP Team. 2017. Available online at: <https://jasp-stats.org/team/>, [accessed 22nd December 2017].
- Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *10*, 371–375.
- Jeffreys, H. (1961). Theory of probability. In *Oxford classic texts in the physical sciences* (3rd Ed.). Oxford: Oxford University Press.
- Jewell, G., & McCourt, M. E. (2000). Pseudoneglect: A review and meta-analysis of performance factors in line bisection tasks. *Neuropsychologia*, *38*, 93–110.
- Kincade, J. M., Abrams, R. A., Astafiev, S. V., Shulman, G. L., & Corbetta, M. (2005). An event-related functional magnetic resonance imaging study of voluntary and stimulus-driven orienting of attention. *Journal of Neuroscience*, *25*, 4593–4604.
- Kinsbourne, M. (1987). Mechanisms of unilateral neglect. *Advances in Psychology*, *45*, 69–86.
- Kinsbourne, M. (1993). Orientational bias model of unilateral neglect: Evidence from attentional gradients within hemisphere. In I. H. Robertson & J. C. Marshall (Eds.), *Brain damage, behaviour & cognition series. Unilateral neglect: Clinical and experimental studies* (pp. 63–86). Hillsdale, NJ: Erlbaum.
- Leblanc, E., Prime, D. J., & Jolicoeur, P. (2008). Tracking the location of visuospatial attention in a contingent

- capture paradigm. *Journal of Cognitive Neuroscience*, *20*, 657–671.
- Li, L. M., Leech, R., Scott, G., Malhotra, P., Seemungal, B., & Sharp, D. J. (2015). The effect of oppositional parietal transcranial direct current stimulation on lateralized brain functions. *European Journal of Neuroscience*, *42*, 2904–2914.
- Mazaheri, A., DiQuattro, N. E., Bengson, J., & Geng, J. J. (2011). Pre-stimulus activity predicts the winner of top–down vs. bottom–up attentional selection. *PLoS One*, *6*, e16243.
- McCourt, M. E., & Jewell, G. (1999). Visuospatial attention in line bisection: Stimulus modulation of pseudoneglect. *Neuropsychologia*, *37*, 843–855.
- Medina, J., Beauvais, J., Datta, A., Bikson, M., Coslett, H. B., & Hamilton, R. H. (2013). Transcranial direct current stimulation accelerates allocentric target detection. *Brain Stimulation*, *6*, 433–439.
- Mesulam, M. M. (1981). A cortical network for directed attention and unilateral neglect. *Annals of Neurology*, *10*, 309–325.
- Mevorach, C., Hodsoll, J., Allen, H., Shalev, L., & Humphreys, G. (2010). Ignoring the elephant in the room: A neural circuit to downregulate salience. *Journal of Neuroscience*, *30*, 6072–6079.
- Mevorach, C., Humphreys, G. W., & Shalev, L. (2006a). Effects of saliency, not global dominance, in patients with left parietal damage. *Neuropsychologia*, *44*, 307–319.
- Mevorach, C., Humphreys, G. W., & Shalev, L. (2006b). Opposite biases in salience-based selection for the left and right posterior parietal cortex. *Nature Neuroscience*, *9*, 740–742.
- Mevorach, C., Shalev, L., Allen, H. A., & Humphreys, G. W. (2009). The left intraparietal sulcus modulates the selection of low salient stimuli. *Journal of Cognitive Neuroscience*, *21*, 303–315.
- Miranda, P. C., Faria, P., & Hallett, M. (2009). What does the ratio of injected current to electrode area tell us about current density in the brain during tDCS? *Clinical Neurophysiology*, *120*, 1183–1187.
- Moos, K., Vossel, S., Weidner, R., Sparing, R., & Fink, G. R. (2012). Modulation of top–down control of visual attention by cathodal tDCS over right IPS. *Journal of Neuroscience*, *32*, 16360–16368.
- Mulder, M. J., & van Maanen, L. (2013). Are accuracy and reaction time affected via different processes? *PLoS One*, *8*, e80222.
- Nicholls, M. E. R., Bradshaw, J. L., & Mattingley, J. B. (1999). Free-viewing perceptual asymmetries for the judgement of brightness, numerosity and size. *Neuropsychologia*, *37*, 307–314.
- Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., et al. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*, 206–223.
- Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *Journal of Physiology*, *527*, 633–639.
- Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, *57*, 1899–1901.
- Nobre, A. C., Sebestyen, G. N., Gitelman, D. R., Mesulam, M. M., Frackowiak, R. S., & Frith, C. D. (1997). Functional localization of the system for visuospatial attention using positron emission tomography. *Brain*, *120*, 515–533.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.
- O’Shea, J., Boudrias, M.-H., Stagg, C. J., Bachtiar, V., Kischka, U., Blicher, J. U., et al. (2014). Predicting behavioural response to tDCS in chronic motor stroke. *Neuroimage*, *85*, 924–933.
- Pirulli, C., Fertonani, A., & Miniussi, C. (2013). The role of timing in the induction of neuromodulation in perceptual learning by transcranial electric stimulation. *Brain Stimulation*, *6*, 683–689.
- Poreisz, C., Boros, K., Antal, A., & Paulus, W. (2007). Safety aspects of transcranial direct current stimulation concerning healthy subjects and patients. *Brain Research Bulletin*, *72*, 208–214.
- Posner, M. I., Walker, J. A., Friedrich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orienting of attention. *Journal of Neuroscience*, *4*, 1863–1874.
- Prinzmetal, W., McCool, C., & Park, S. (2005). Attention: Reaction time and accuracy reveal different mechanisms. *Journal of Experimental Psychology: General*, *134*, 73–92.
- Proulx, M. J., & Egeth, H. E. (2006). Target-nontarget similarity modulates stimulus-driven control in visual search. *Psychonomic Bulletin & Review*, *13*, 524–529.
- Proulx, M. J., & Egeth, H. E. (2008). Biased competition and visual search: The role of luminance and size contrast. *Psychological Research*, *72*, 106–113.
- Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian *t* tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*, 225–237.
- Roy, L. B., Sparing, R., Fink, G. R., & Hesse, M. D. (2015). Modulation of attention functions by anodal tDCS on right PPC. *Neuropsychologia*, *74*, 96–107.
- Shomstein, S. (2012). Cognitive functions of the posterior parietal cortex: Top–down and bottom–up attentional control. *Frontiers in Integrative Neuroscience*, *6*, 38.
- Shulman, G. L., Pope, D. L. W., Astafiev, S. V., McAvoy, M. P., Snyder, A. Z., & Corbetta, M. (2010). Right hemisphere dominance during spatial selective attention and target detection occurs outside the dorsal frontoparietal network. *Journal of Neuroscience*, *30*, 3640–3651.
- Singh-Curry, V., & Husain, M. (2009). The functional role of the inferior parietal lobe in the dorsal and ventral stream dichotomy. *Neuropsychologia*, *47*, 1434–1448.
- Sparing, R., & Mottaghy, F. M. (2008). Noninvasive brain stimulation with transcranial magnetic or direct current stimulation (TMS/tDCS)—From insights into human memory to therapy of its dysfunction. *Methods*, *44*, 329–337.
- Sparing, R., Thimm, M., Hesse, M. D., Küst, J., Karbe, H., & Fink, G. R. (2009). Bidirectional alterations of interhemispheric parietal balance by non-invasive cortical stimulation. *Brain*, *132*, 3011–3020.
- Stagg, C. J., & Nitsche, M. A. (2011). Physiological basis of transcranial direct current stimulation. *Neuroscientist*, *17*, 37–53.
- Teo, F., Hoy, K. E., Daskalakis, Z. J., & Fitzgerald, P. B. (2011). Investigating the role of current strength in tDCS modulation of working memory performance in healthy controls. *Frontiers in Psychiatry*, *2*, 45.
- Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, *51*, 599–606.
- Theeuwes, J. (2010). Top–down and bottom–up control of visual selection. *Acta Psychologica*, *135*, 77–99.
- Vallar, G. (1998). Spatial hemineglect in humans. *Trends in Cognitive Sciences*, *2*, 87–97.
- Vandenberghe, R., Dupont, P., De Bruyn, B., Bormans, G., Michiels, J., Mortelmans, L., et al. (1996). The influence of stimulus location on the brain activation pattern in detection and orientation discrimination: A PET study of visual attention. *Brain*, *119*, 1263–1276.
- van Ede, F., de Lange, F. P., & Maris, E. (2012). Attentional cues affect accuracy and reaction time via different cognitive and neural processes. *Journal of Neuroscience*, *32*, 10408–10412.

- Vossel, S., Geng, J. J., & Fink, G. R. (2014). Dorsal and ventral attention systems: Distinct neural circuits but collaborative roles. *Neuroscientist*, *20*, 150–159.
- Vossel, S., Thiel, C. M., & Fink, G. R. (2006). Cue validity modulates the neural correlates of covert endogenous orienting of attention in parietal and frontal cortex. *Neuroimage*, *32*, 1257–1264.
- Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., et al. (2018a). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review*, *25*, 58–76.
- Wagenmakers, E.-J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Love, J., et al. (2018b). Bayesian inference for psychology. Part I: Theoretical advantages and practical ramifications. *Psychonomic Bulletin & Review*, *25*, 35–57.
- Weidner, R., Krummenacher, J., Reimann, B., Müller, H. J., & Fink, G. R. (2009). Sources of top-down control in visual search. *Journal of Cognitive Neuroscience*, *21*, 2100–2113.
- Weiss, M., & Lavidor, M. (2012). When less is more: Evidence for a facilitative cathodal tDCS effect in attentional abilities. *Journal of Cognitive Neuroscience*, *24*, 1826–1833.
- Wetzels, R., Matzke, D., Lee, M. D., Rouder, J. N., Iverson, G. J., & Wagenmakers, E.-J. (2011). Statistical evidence in experimental psychology: An empirical comparison using 855 *t* tests. *Perspectives on Psychological Science*, *6*, 291–298.
- Wolfe, J. (1998). Visual search. In H. Pashler (Ed.), *Attention*. London: University College London Press.
- Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 419–433.
- Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience*, *5*, 495–501.
- Wright, J. M., & Krekelberg, B. (2014). Transcranial direct current stimulation over posterior parietal cortex modulates visuospatial localization. *Journal of Vision*, *14*, 5.
- Yantis, S. (2000). Goal-directed and stimulus-driven determinants of attentional control. *Attention and Performance*, *18*, 73–103.
- Yantis, S. (2002). Stimulus-driven and goal-directed attentional control. In V. Cantoni, M. Marinaro, & A. Petrosino (Eds.), *Visual attention mechanisms* (pp. 125–134). Boston: Springer.
- Yantis, S., & Egeth, H. E. (1999). On the distinction between visual salience and stimulus-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 661–676.
- Zehetleitner, M., Koch, A. I., Goschy, H., & Müller, H. J. (2013). Saliency-based selection: Attentional capture by distractors less salient than the target. *PLoS One*, *8*, e52595.