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Beyond time and space: The effect of a lateralized sustained attention task and brain stimulation on spatial and selective attention

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ABSTRACT

The Theory of Visual Attention (TVA) provides a mathematical formalisation of the "biased competition" account of visual attention. Applying this model to individual performance in a free recall task allows the estimation of 5 independent attentional parameters: visual short-term memory (VSTM) capacity, speed of information processing, perceptual threshold of visual detection; attentional weights representing spatial distribution of attention (spatial bias), and the top-down selectivity index. While the TVA focuses on selection in space, complementary accounts of attention describe how attention is maintained over time, and how temporal processes interact with selection. A growing body of evidence indicates that different facets of attention interact and share common neural substrates. The aim of the current study was to modulate a spatial attentional bias via transfer effects, based on a mechanistic understanding of the interplay between spatial, selective and temporal aspects of attention. Specifically, we examined here: (i) whether a single administration of a lateralized sustained attention task could prime spatial orienting and lead to transferable changes in attentional weights (assigned to the left *vs* right hemi-field) and/or other attentional parameters assessed within the framework of TVA (Experiment 1); (ii) whether the effects of such spatial-priming on TVA parameters could be further enhanced by bi-parietal high frequency transcranial random noise stimulation (tRNS) (Experiment 2). Our results demonstrate that spatial attentional bias, as assessed within the TVA framework, was primed by sustaining attention towards the right hemi-field, but this spatial-priming effect did not occur when sustaining attention towards the left. Furthermore, we show that bi-parietal high-frequency tRNS combined with the rightward spatial-priming resulted in an increased attentional selectivity. To conclude, we present a novel, theory-driven method for attentional modulation providing important insights into how the spatial and temporal processes in attention interact with attentional selection.

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1. Introduction

Attention allows us to selectively prioritize the processing of either relevant or salient signals, within a limited capacity system. In contemporary cognitive sciences, attention is often described as a multifaceted system with various components and factors determining its course of operation. Prominent accounts for the heterogeneity of attention typically distinguish between the way attention is being controlled, the way it is maintained over time, and its way of operating in space (e.g., Parasuranam, 1998; Petersen & Posner, 2012; Posner & Petersen, 1990). Other common models have focused on the multiple mechanisms governing attention, including the current goal-sets, salient events, and biases derived from mnemonic representations (e.g., Corbetta & Shulman, 2002; Nobre & Mesulam, 2014).

An alternative approach to understanding and describing attention is to focus on the processes underlying its primary behavioural function, the attentional selection. Indeed, while multifaceted models of attention (e.g., Parasuranam, 1998; Posner & Petersen, 1990) propose to measure how attention is maintained over time (alertness/vigilance) and how the selection priorities are determined (control/execution), they share the view that the end goal of attention is an effective selection. One of the most influential models of attentional selection is the Biased Competition Model (Desimone & Duncan, 1995; Duncan & Humphreys, 1989) which rejects one of the key assumptions made by Posner and Petersen (1990). While the main function of the orienting network is described by Posner as controlling the spatial allocation of attention in a process resembling a serial process of shifting of a ‘spotlight’ (Posner & Petersen, 1990), the Biased Competition Model sees attention as a parallel process where perceived elements compete for a conscious representation in a limited capacity short-term memory store (Desimone & Duncan, 1995). The Biased Competition Model was formulated mathematically as part of the Theory of Visual Attention (TVA; Bundesen, 1990). TVA provides a detailed description of the factors determining selection based on a group of equations incorporating the capacity of the short-term memory supporting attention, the minimum exposure time required for stimuli to be perceived, the speed at which stimuli are processed once perceived, the attentional weights allocated to perceived elements, and the efficiency of top-down control (a detailed description of the key equations within the TVA framework is presented in the Methods section). Subsequently, TVA has been used to characterize attention in the neurologically healthy individuals (e.g., Chechlacz, Gillebert, Vangkilde, Petersen, & Humphreys, 2015; Finke et al., 2005; McAvinue, Habekost et al., 2012; McAvinue, Vangkilde et al., 2012) and in various cognitively impaired clinical populations (e.g., Bublak et al., 2005; Duncan et al., 2003; Habekost & Bundesen, 2003) to account for inter-individual differences in attention functions and dysfunctions.

TVA provides a reliable framework to account for individual differences in attention and as such TVA based assessment has been previously employed to describe changes in attention functions following different intervention based on either cognitive training or brain stimulation protocols. For example, Schubert et al. (2015) used a behavioural training paradigm based on video games and showed an enhancement in processing speed of visual stimuli at certain position in the display. In another study, the TVA framework was used to assess the effectiveness of a meditation-based intervention, and demonstrated that the affected components were unrelated to a change in attentional parameters (Jensen, Vangkilde, Frokjaer, & Hasselbalch, 2012). Finally, a recent study by Moos, Vossel, Weidner, Sparing, and Fink (2012) employed the TVA model to measure changes in attentional parameters following application of transcranial direct current stimulation (tDCS), an emerging approach for cognitive intervention in both healthy and clinical populations (for recent review see Filmer, Dux, & Mattingley, 2014; Harvey & Kerkhoff, 2015; Santarnecchi et al., 2015).

While behavioural training studies mainly target discrete attentional mechanisms, brain stimulation studies enable the targeting not just the specific attentional processes but also the underlying neural substrates of attention. Attention relies on large-scale neural networks involving cortical and subcortical structures sub-serving various components of attention (e.g., Corbetta & Shulman, 2002; Mesulam, 1981, 1990, 1999; Posner & Rothbart, 2007). There is a general consensus that the control of spatial attention is achieved by a network involving three inter-connected nodes in the posterior parietal cortex (PPC) (Lateral Intraparietal Area), the frontal cortex (Frontal Eye Field region) and the cingulate cortex (Mesulam, 1981). Multiple functional magnetic resonance imaging (fMRI) studies employing various attention orienting tasks have highlighted the key role of fronto-parietal networks in control of attention (e.g., Corbetta, Miezin, Shulman, & Petersen, 1993; Doricchi, Macci, Silvetti, & Macaluso, 2010; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005; Nobre et al., 1997; Shulman et al., 2010). And the further evidence supporting the key role of the fronto-parietal regions comes from studies demonstrating strong effects of the brain stimulation applied over the PPC and the Frontal Eye Field (FEF) (e.g., Duecker & Sack, 2015; Fierro et al., 2000; Nyffeler et al., 2008; Rushworth & Taylor, 2006; Sparing et al., 2009) on the performance in various attentional tasks. The fronto-parietal networks are functionally lateralized (the allocation of attention to each visual hemi-field is controlled by contralateral hemisphere) and asymmetrically organized, with right hemispheric dominance. The empirical evidence, supporting functional lateralization and right hemispheric dominance in attention, is based on observations in patients with hemispatial neglect syndrome characterized by a difficulty to attend, orient and respond to the items in the contralesional hemi-field following right-hemispheric damage (Corbetta & Shulman, 2011; Driver & Mattingley, 1998; Halligan, Fink, Marshall, & Vallar, 2003; Heilman & Valenstein, 1979; Heilman & Van Den Abell, 1980; Stone, Halligan, & Greenwood, 1993; Vallar, 1998; Weintraub & Mesulam, 1987). Further evidence comes from healthy individuals showing a small attentional bias towards the left hemi-field (so-called pseudoneglect) and the preferential activation of the right hemisphere leading to this striking leftward bias in orienting attention (Bowers & Heilman, 1980; Jewell & McCourt, 2000; McCourt & Jewell, 1999; Nicholls, Bradshaw, & Mattingley. 1999; Nobre et al., 2004; Shulman et al., 2010). In addition to the evidence provided by neuropsychological and functional brain imaging studies, the anatomical foundations, of the right hemispheric dominance of attention, have been linked to the structural lateralization of the fronto-parietal networks (e.g., Chechlacz, Gillebert et al., 2015; Marshall, Bergmann, & Jensen, 2015; Thiebaut de Schotten et al., 2011).

In accordance with the hypothesis of the right-hemispheric dominance of attention, researchers applying various behavioural interventions based on a perceptual adaptation have managed to modulate the attentional bias only towards the right, and failed to do so towards the left (e.g., Loftus, Vijayakumar, & Nicholls, 2009; Michel et al., 2003). Similarly, in a brain stimulation study using transcranial magnetic stimulation (TMS) applied to the right PPC, Hung, Driver, and Walsh (2005) managed to increase the attentional selectivity in the right hemifield and decrease the selectivity in the left hemifield. However, when stimulation was applied to the homologous area in the left hemisphere, no modulation was found. A similar observation was made in a follow-up study using TMS stimulation applied to the right and left frontal eye-fields (Hung, Driver, & Walsh, 2011). Furthermore, numerous other studies demonstrated that TMS applied over the right but not the left PPC could produce significant shifts in the allocation of visual attention (e.g., Cazzoli, Wurtz, Muri, Hess, & Nyffeler, 2009; Fierro et al., 2000; Hilgetag, Theoret, & Pascual-Leone, 2001; Hung et al., 2005; Sack et al., 2007; for a review see; Szczepanski & Kastner, 2009). Nevertheless, the right-hemispheric dominance in attention remains a matter of controversy, with some inconsistent findings from brain imaging studies (e.g., Doricchi et al., 2010; Shulman et al., 2010; Sommer et al., 2008) as well as with reported large inter-individual differences in anatomical lateralization and lateralized responses to brain stimulation (Cazzoli & Chechlacz, 2017; Chechlacz, Gillebert et al., 2015; Chechlacz, Humphreys, Sotiropoulos, Kennard, & Cazzoli, 2015; Szczepanski & Kastner, 2013; Thiebaut de Schotten et al., 2011).

Brain stimulation studies also support the notion of attentional biases being determined by intra-hemispheric reciprocal connectivity. For example, by applying tDCS over the parietal cortex, Sparing et al. (2009) managed to selectively alter performance in accordance with the notion of cross hemispheric competition or 'rivalry' (Kinsbourne, 1987, 1993; Reuter-Lorenz, Kinsbourne, & Moscovitch, 1990; Szczepanski, Konen, & Kastner, 2010). Specifically, they reported a selective modulation of performance according to stimulation polarity (anodal *vs* cathodal) and site (right *vs* left hemisphere), demonstrating how inhibiting one hemisphere can enhance performance in the ipsilateral hemispace (by decreasing its inhibitory effect over the contralateral brain hemisphere), and vice versa i.e., enhancing brain activity in one hemisphere can enhance performance in the contralateral hemispace (Sparing et al., 2009). In a more recent, study Giglia et al., 2011 explored whether dual tDCS (right cathodal and left anodal) stimulation applied over the PPC compared with unilateral (right cathodal) PPC stimulation would induce greater neglect-like effects in healthy individuals. Based on their findings that the dual stimulation resulted in a stronger and appearing earlier rightward bias in performance on the visuospatial task, Giglia and colleagues concluded that the greater rightward bias triggered by dual tDCS could be attributed to the modulation of the interhemispheric inhibition (as opposed to unilateral stimulation only affecting right hemisphere activity; see also Benwell, Learmonth, Miniussi, Harvey, & Thut, 2015).

In summary, the reviewed evidence suggests that a bilateral fronto-parietal network supports attention through mechanisms of intra-hemispheric competition (e.g. Szczepanski et al., 2010). However, while some studies report a modulation in attention after application of brain stimulation to both the left and the right hemisphere (e.g., Chechlacz, Humphreys et al., 2015; Dambeck et al., 2006; Sparing et al., 2009), other only noted attentional shift when stimulating the right hemisphere (e.g., Fierro et al., 2000; Loftus et al., 2009; Michel et al., 2003). These observations are somewhat conflicting, reflecting an ongoing debate on whether there is a dominance of the right hemisphere in controlling spatial attention.

By contrast, in the study of sustained attention, a right hemispheric dominance seems to be widely accepted. Sustained attention is a cognitive construct that is thought to rely on the alertness network proposed by Posner and Petersen (1990), with an emphasis on the capacity of maintaining an alerted state over time in a goal-directed manner (e.g., Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Sustained attention is sub-served by multiple cortical and sub-cortical structures, including the right PPC (e.g., Coull, Frith, Frackowiak, & Grasby, 1996; Heilman, Schwartz, & Watson, 1978; Pardo, Fox, & Raichle, 1991; Posner & Petersen, 1990; Robertson et al., 1997; Sarter, Givens, & Bruno, 2001; Shulman et al., 2010; Whitehead, 1991). This neural network seems to partially overlap with neural substrates of spatial attention, based on studies reporting an association between neglect symptoms and sustained attention (Husain & Nachev, 2007; Husain & Rorden, 2003; Robertson, 2001) and demonstrating an improvement in neglect symptoms after a training targeting sustained attention (Robertson, Tegnér, Tham, Lo, & Nimmo-Smith, 1995).

Taking into account that the sustained and the spatial attention may be sub-served by common right lateralized neural substrates within the PPC, the current study aimed to test whether sustaining attention towards one side of space could induce priming of spatial orienting, leading to transferable changes in attentional weights (assigned to the left *vs* right hemi-field) and/or other attentional parameters assessed within the framework of TVA (Experiment 1). Our approach deviates from traditional methods of modulating attention by a repetitive training protocol with test-retest of the training-task outcome as a marker of training efficiency (e.g., Robertson et al., 1995). Instead, we aimed to test whether a single administration of a relatively short task with high demands for a lateralized sustained attention could have an immediate effects of spatial-priming (priming of spatial orienting),[1] leading to a significant change in the attentional weights at the primed hemi-field and/or other attentional functions assessed in a subsequent task based on TVA

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[1] We used the term 'spatial-priming' to denote the effect of sustaining attention towards a specific hemifield in one task on spatial biases in a subsequent task. In that respect, we refer to the shared spatial characteristics of the priming-task (sustained attention task) and the following TVA paradigm. The experimental manipulation and the observed transfer effects in attention go beyond the classic definition of priming implying implicit memory effects.

framework. Subsequently, Experiment 2 aimed to test the overall effects of brain stimulation on TVA derived parameters of attention and whether the spatial-priming triggered by sustained attention task could be further enhanced by the application of brain stimulation. For the purpose of the current study, the sustained attention task used as spatial-priming was designed based on an adaptation of the Masked Conjunctive Continuous Performance Task (MCCPT), which can be used to show individuals differences in performance of young participants (Shalev, Humphreys, & Demeyere, 2016; Shalev, Humphreys, & Demeyere, 2017). Specifically, we created a variation of the MCCPT where participants were requested to monitor two lateralized visual streams presented simultaneously and by changing the frequency of the target appearing either in the left versus right visual stream, we aimed to manipulate the sustaining of attention to only one side of space. We maintained the task properties increasing the demands for sustained attention by keeping the task simple, repetitive, and non-arousing (Robertson et al., 1997). Furthermore, we employed here, a high-frequency transcranial random noise stimulation (tRNS) protocol based on its known effectiveness in inducing neuroplasticity in the brain and its frequently use to enhance the effects of behavioural training (e.g., Cappelletti et al., 2013; Fertonani, Pirulli, & Miniussi, 2011). Finally, the TVA framework (Bundesen, 1990) was chosen to measure the effects of spatial-priming (sustained attention task) and/or brain stimulation due to high sensitivity, reliability and validity of this model in estimating discrete attentional parameters (Bundesen, Habekost, & Kyllingsbaek, 2005; Dyrholm, Kyllingsbaek, Espeseth, & Bundesen, 2011; Finke et al., 2005; Habekost, 2015; Habekost, Petersen & Vangkilde, 2014).

2. Experiment 1: lateralized sustained attention task and the modulation of spatial biases

2.1. Method

2.1.1. *Participants*

Sixty naive volunteers participated in this experiment (32 female; mean ± SD age = 25.7 ± 4.9). Participants were recruited through an online research participation system managed by the University of Oxford. Exclusion criteria included any previous history of neurological or psychiatric disorders. Both left- and right-handed participants were recruited for the study, and the hand dominance was assessed according to Edinburgh handedness inventory (Oldfield, 1971; mean handness score ± SD = 80.8 ± 22.69; one participant was classified as left-handed and one as ambidextrous). All participants had either normal or corrected-to-normal vision. All study participants provided written informed consent, in compliance with relevant protocols approved by the University of Oxford Central University Research Ethics Committee. The experimental procedures were conducted in accordance with the latest version of the Declaration of Helsinki. Participants were compensated for their time by a payment of £20 for the whole study, inclusive of travel expenses.

2.1.2. *Apparatus*

A PC with Intel i7 processor and a dedicated 2 GB AMD video card was used for displaying stimuli and recording data. The sustained attention task (modified MCCPT) was generated using NBS presentation software (Neurobehavioral systems, Albany, CA), and the CombiTVA paradigm (TVA-based task) was generated using E-prime 2 Professional software (Psychology Software Tools, Inc.). The stimuli were presented on a ViewSonic V3D245 LED monitor, with screen resolution of 1080 × 1920 and a screen refresh rate set at 100 Hz allowing display times varied in gaps of 10 msec. All stimuli were preloaded to memory using the presentation software, to guarantee minimal temporal noise.

2.1.3. *General procedure*

Sixty participants were divided into four experimental groups: Right Spatial-priming (15 participants; 6 female; mean ± SD age = 24.0 ± 4.6), Left Spatial-priming (15 participants; 8 female; mean ± SD age = 25.9 ± 4.8), Neutral Spatial-priming (i.e., active control group; 15 participants; 8 female; mean ± SD age = 26.3 ± 4.7), and CombiTVA Control (i.e., static control group, 15 participants; 10 female; mean ± SD age = 26.8 ± 5.6). All participants were invited to the lab on two consecutive days at the same time during the day. On the first day, all participants performed the CombiTVA task (see below for details) to assess their baseline attentional bias and other attentional functions based on TVA framework. On the following day, participants in the Right Spatial-priming, the Left Spatial-priming and the Neutral Spatial-priming groups first performed different versions of the sustained attention task (see below for details), immediately followed by assessment using the CombiTVA task. While, the participants in the CombiTVA control group were only assessed on the CombiTVA task without any priming of spatial orienting.

2.1.4. *Sustained attention (spatial-priming) task*

2.1.4.1. Stimuli. Two coloured visual masks (*Mask*), acting as placeholders comprised of four superimposed figures in different colours (square, triangle, circle and hexagon) appeared 10° visual angles to the right and left sides of a cantered fixation point (See Fig. 1). The total size of each Mask occupied 3° visual angles. In order to avoid habituation effects, we generated minor movements to each Mask. The movement was generated by alternating every few milliseconds between two mask-images, one of which had thicker outlines for the superimposed figures. The masks disappeared only when they were replaced by either a target or a distractor shapes for 80 msec; the masks then reappeared immediately, generating pre- and post-masking of each target or distractor.

The target shape was a red circle, and distractor stimuli were either similar in colour to the target (red hexagon and red triangle), similar in shape (blue circle and red circle), or completely different (yellow and blue hexagon). All distractor types appeared in an equal distribution, both when appearing concurrently with a target and when appearing with another distractor. All distractors and target shapes were circumscribed in an invisible square of 3° visual angles. The inter stimulus interval was jittered between 1000 and 5000 msec (See Fig. 1 for a schematic outline of the experimental

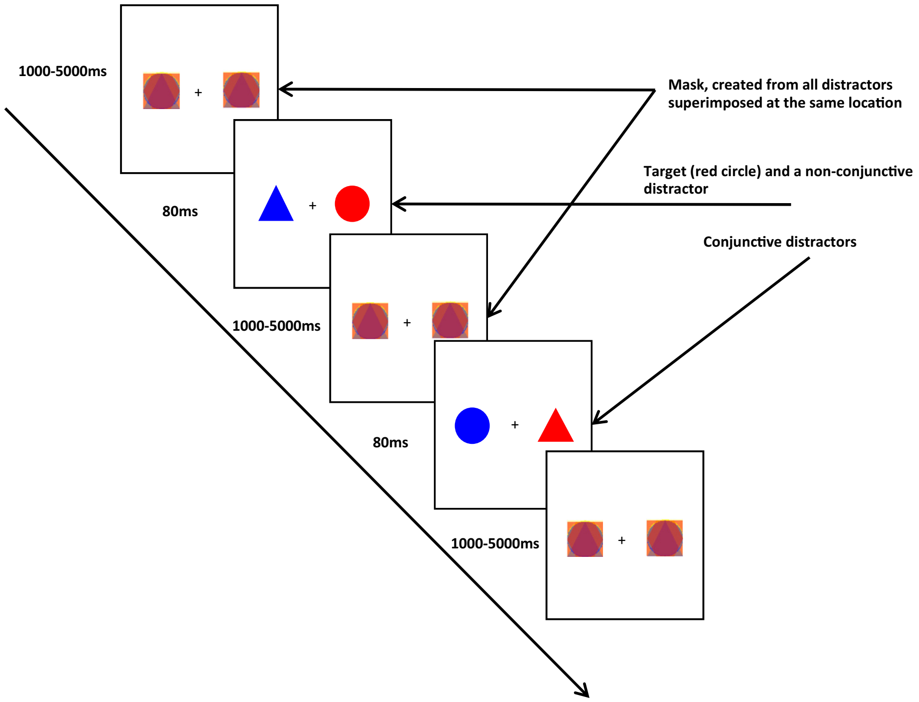

Fig. 1 – A schematic outline of the sustained attention (spatial-priming) task.

procedure). Participants were told that the static shapes (the mask) appearing at the two sides of the screen (the left and the right hemi-field), would be replaced every few seconds by another shape for a short time. Their task was to press the spacebar as fast as possible whenever they saw a *red circle* in one of the two locations (i.e., the left or the right hemi-field). They were instructed to do nothing when they saw any other coloured shape.

Participants assigned to the Right Spatial-priming, the Left Spatial-priming and the Neutral Spatial-priming groups performed different versions of the sustained attention task with respect to the frequency of targets appearing within the left or the right hemi-field. For the Right Spatial-priming group, 80% of the target-trials were on the right side; for the Left Spatial-priming group, 80% of the trials were on the left; for the Neutral Spatial-priming group, the targets were equally distributed between the two sides.

2.1.4.2. Procedure. The task started with a short practice block (15 trials), and the experimenter monitored subjects' response at this stage to ensure the instructions were clear. After finishing the practice session, the participants performed three experimental blocks each lasting 180 trials with a short break in-between. The whole procedure lasted approximately 40 min. The task was comprised of 540 trials, with targets appearing on 180 trials (33% target) and distractors on 360 trials (66%). For the Right Spatial-priming group, 40 targets appeared on the left side, and 140 on the right; for the Left Spatial-priming group, 40 targets appeared on the right side, and 140 on the left; for the Neutral Spatial-priming group, equal numbers of target appeared on the right and the left side (i.e., 90 right and 90 left targets).

2.1.5. *CombiTVA paradigm (TVA-based task)*

2.1.5.1. Stimuli. In order to assess TVA derived attentional parameters, we employed the CombiTVA paradigm (Vangkilde, Bundesen, & Coull, 2011). Traditionally, an assessment based on the TVA framework (Bundesen, 1990) uses two types of tasks i.e., a partial report task assessing attentional control and a whole report task assessing attentional capacity. The CombiTVA paradigm employed in the current study implements both full and partial report tasks, which are intermixed on different trials (Vangkilde et al., 2011). On each trial, a centred red fixation-cross appeared at the centre of the screen for 1000 msec, followed by a blank screen appearing for 100 msec, followed by the stimulus display. The stimulus display could be of one of two random conditions: a *whole report*, where either two or six red letters appeared on the screen; or a *partial report*, where four blue letters and two red letters appeared on the screen. The letters were presented around an invisible centred circle in six fixed placeholders equally distributed on the perimeter ($r = 7.5°$ visual angles). The stimulus display presented random letters from a set of 20 capital letters (ABDEFGHJKLMNOPRSTVXZ) with font size corresponding to $2.7° \times 2.3°$ of visual angles. The display appeared for one of six fixed durations of 10, 20, 50, 80, 140 or 200 msec (randomly assigned and equally distributed), and followed by a masking noise on each of the fixed placeholders lasting 500 msec. Following the mask presentation, the participants were presented with a response display for unlimited time, and were prompt to recall, as many red letters as they could, using the computer keyboard, and pressing 'Enter' when done. The response display appeared for an unlimited time. See Fig. 2 for a schematic outline of the experimental procedure, adopted from Chechlacz, Gillebert et al. (2015).

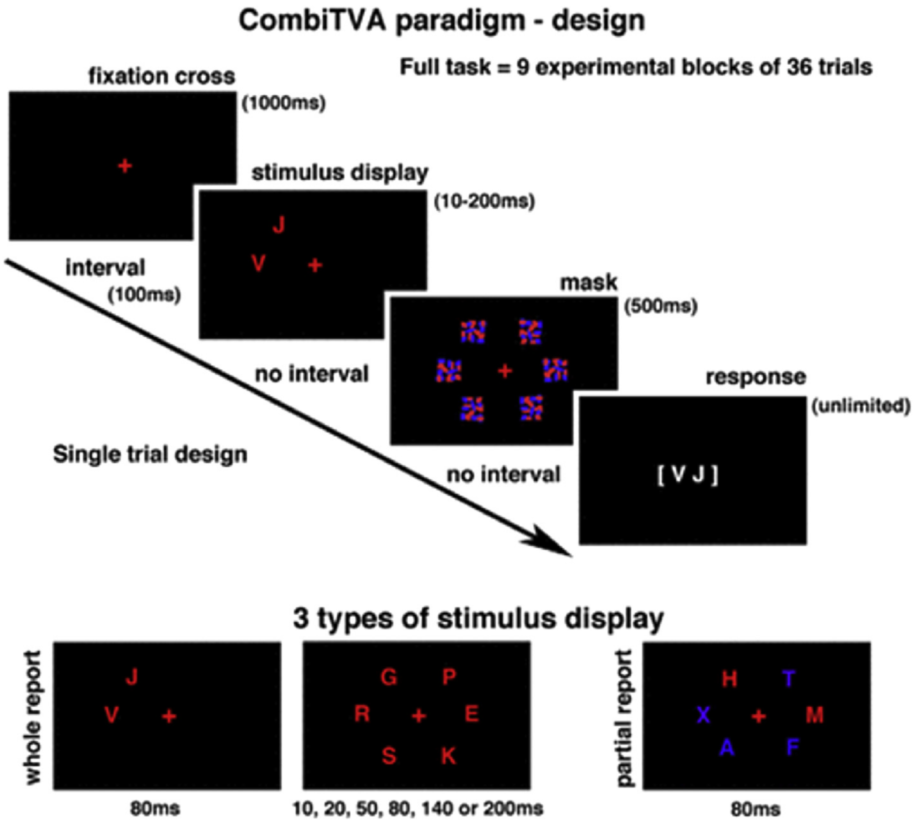

Fig. 2 – CombiTVA experimental outline, from Chechlacz, Gillebert et al. (2015).

2.1.5.2. Procedure. The task started with a short practice block (24 trials), and the experimenter monitored subjects' responses at this stage to ensure the instructions were clear. Following the practice session, participants performed nine experimental blocks consisting of 36 trials each. The exposure times of the stimulus displays, as well as the different conditions and the stimuli letters were all randomly distributed. The participants were told that their reaction speed was not being monitored, and they should report all the red letters they were "fairly certain" of having seen and to refrain from pure guessing. Following each experimental block, the participants were informed of their accuracy rate. They were asked to try to maintain an accuracy range of 80%–90%; they were told that if their accuracy was higher, they should try to lower their decision criteria; conversely, if their accuracy was lower, it meant they were guessing too many letters and they should try to be more accurate. The whole procedure lasted approximately 45 min.

2.1.5.3. Estimation of TVA parameters. Our analysis procedure relied on a set of variables extracted based on the TVA framework (Bundesen, 1990). The TVA model represents a mathematical formalization of the "biased competition" account of visual attention, where visual categorizations ascribing features to objects compete to be encoded into a limited capacity visual short-term memory (VSTM). The categorization of a visual element is accomplished once it has been encoded to VSTM. This race model is normally described by two main equations: the rate equation and the weight equation. The rate equation describe the rate $\upsilon(x,i)$ at which a particular visual categorization 'x belongs to i' is encoded into Visual Short Term Memory VSTM. The rate is determined as a product of three terms: $\eta(x,i)$ which represents the strength of the sensory evidence in favour of categorizing x as belonging to category i; β_i which represents the perceptual decision bias associated with category i; and $\frac{W_x}{\sum_{z\in S}W_z}$ which determines the relative attentional weight of object x divided by the sum of all the attentional weights of all objects within the visual field (S). All together comprise the rate equation

$$\upsilon(x,i)=\eta(x,i)\beta_i\left\{\frac{W_x}{\sum_{z\in S}W_z}\right\}$$

The sum of all rate values (υ) across the visual field defines the overall processing speed (C), formally:

$$C=\sum_{x\in S}\upsilon(x)=\sum_{x\in S}\sum_{i\in R}\upsilon(x,i)$$

A second key equation is the Weight Equation which describes the theoretical weights given to the perceived elements according to their pertinence value π_j. The pertinence value is defined by the momentary importance of attending a perceived element x belonging to a category j, where R is the set of all categories $\eta(x,j)$. The Weight Equation is

$$W_x=\sum_{j\in R}\eta(x,j)\pi_j.$$

Finally, we used in our study a partial report paradigm where participants were requested to attend and reports targets while ignoring irrelevant distractors (defined by a colour feature). Under the assumption that every target on a given display has approximately the same weight, and every distractor have the same weight (different from targets), we determine the α value which defines the efficiency of top-down control

$$\alpha = \frac{W_{distractor}}{W_{target}}$$

Based on this proposed set of equations we calculate 5 parameters described in the Statistical Analysis section.

2.1.6. *Statistical analysis*

The analysis of the performance on the sustained attention task is restricted to examining group differences (Right Spatial-priming, Left Spatial-priming and Neutral Spatial-priming) in the accuracy on trails with target appearing on the right, target appearing on the left, and trials with no target. To estimate whether the sustained attention task procedure influenced attention parameters estimated based on TVA framework, we compared the performance in the CombiTVA paradigm pre- and post-spatial-priming by the sustained attention task. The CombiTVA paradigm allows the extraction of multiple independent theoretical parameters representing different aspects of attention (Vangkilde et al., 2011). The calculation of the theoretical attentional parameters is based on a maximum-likelihood fitting procedure introduced by Kyllingsbaek (2006) to model the observations based on the TVA-framework. The fitting algorithm output includes five theoretical parameters: (1) Parameter K is an estimation of the visual short term memory capacity, measured in number of letters that can be stored; (2) Parameter t0 is the perceptual threshold, defined as the longest exposure duration that does not evoke conscious perception, measured in seconds; (3) Parameter C is the visual processing speed, or processing rate, measured in number of letters processed per second. The three parameters: K, t0 and C, can be visualized when plotting the number of correctly identified letters as a function of the exposure duration, as illustrated in Fig. 3, adopted from Habekost (2015).

The other two parameters are (4). The spatial bias parameter ω_{index} which represents the ratio between the sum of the attentional weight assigned to items on the left, and the overall sum of all attentional weights. The parameter ranges between 0 and 1, with a value of .5 indicating symmetrical attentional weighting; a value closer to 0 indicates an attentional bias to the right, and a value higher than .5 indicates an attentional bias to the left side of the visual field. (5). The top-down selectivity index α, defined as the ratio between the attentional weights allocated to a distractor and to a target. The resulting α value range between 0 and 1, with the lowest score indicating perfect selectivity (no attentional weight given to irrelevant distractor). For a detailed overview of the attentional parameters and their correlates, see Habekost (2015). As the attentional weight score (ω_{index}) and the attentional selectivity index (α) are measured on ratio scales with arbitrary values, we used a log transformation to all those data and report the transformed values (a similar approach, of normalizing the raw values was used by Moos et al., 2012). In our new calculated score, the lower the raw score, the lower the transformed value (the transformed values are on a negative scale as they are based on a ratio smaller than 1).

In the presented here experiment, our main analysis focused on whether there was change in the attentional weight index (transformed ω_{index}) pre- and post-spatial-priming by the sustained attention task. We hypothesized that we would observe a significant shift towards the right only in participants in the Right Spatial-priming group. However, we also analysed the other parameters (K, t0, C and transformed α) to explore any other effects of the sustained attention task on attention functions. We compared the estimated parameters in four groups: Right Spatial-priming, Left Spatial-priming, Neutral Spatial-priming and CombiTVA control (no Spatial-priming) at the two time points. Before analysing the data, we removed one outlier participant from the Right Spatial-priming group who exceeded 3SD from the group transformed ω_{index} average. The data extraction and fitting procedures were performed using Matlab (Ver. 2015a; MathWorks, Inc., Natick, MA) and the LibTVA (Dyrholm et al., 2011; Kyllingsbaek, 2006). The statistical analysis was

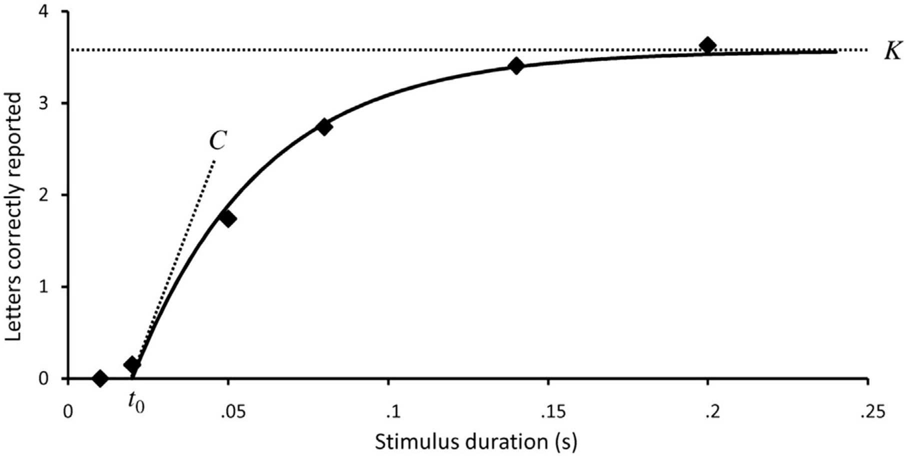

Fig. 3 – A plot describing the probability of detecting a single target as a function of exposure time, fitted to an exponential function based on the TVA framework (Habekost, 2015).

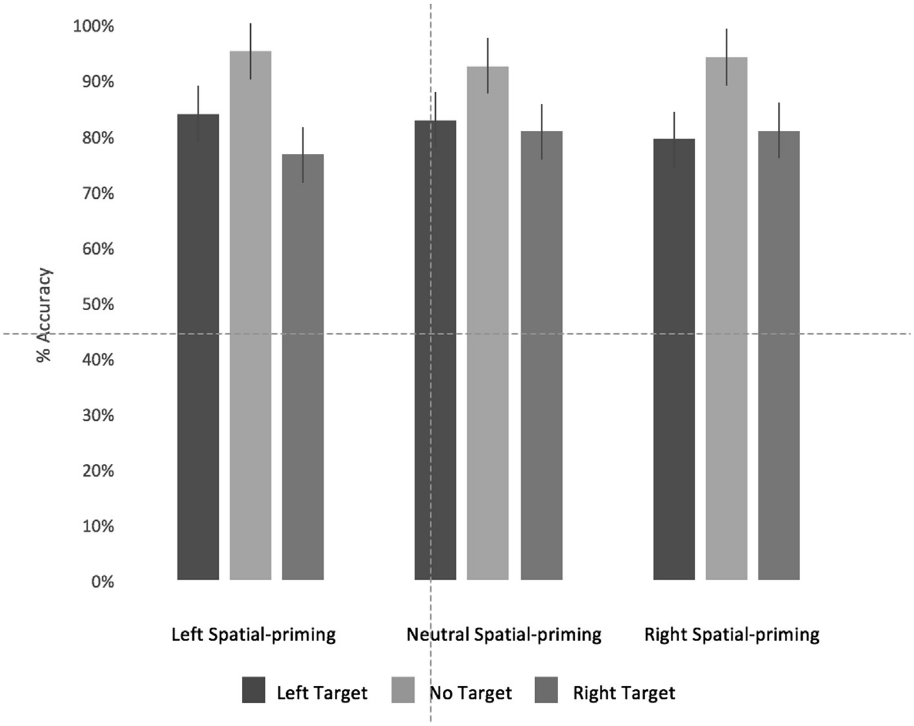

Fig. 4 – Accuracy rate in the spatial-priming (sustained attention) task for each experimental group, when target is presented either on right or left, or not presented.

performed using SPSS (Ver 24; IBM Corp, 2016) and the Bayes Factor R Package (Version 0.9.12-2).

2.2. *Results*

We first calculated mean accuracy in the performance of the sustained attention task (across three experimental groups: Right Spatial-priming, Left Spatial-priming and Neutral Spatial-priming) separately for all three different trial types/target conditions (target appearing on the right, target appearing on the left, and no target). We ran a 3 × 3 repeated measures AVNOVA with the target condition as a within-subjects factor (Left-Target, No-Target, Right-Target) and the experimental group as a between-subjects factor (Right Spatial-priming, Left Spatial-priming and Neutral Spatial-priming). There were no interactions between the factors, suggesting that the overall performance pattern did not differ between groups when performing the different versions of the sustained attention task ($p > .4$). There were also no group differences ($p > .8$). The only significant effect we observed was for target condition, due to a higher accuracy in trials when no target is observed ($F(82,2) = 26.126$, $p < .001$, partial $\eta^2 = .389$). To further verify that the only significant effect was a result of a higher performance in the lack of any target, we repeated the ANOVA procedure comparing only the lateralized target conditions (Left-Target/Right-Target) and the three groups. In this secondary analysis, there were no significant differences (all p's $> .2$). For a detailed description of the performance, see Fig. 4.

Presented below Table 1 described the TVA-based attentional parameters, derived from the performance on the CombiTVA paradigm, estimated separately for all experimental groups during the two TVA assessment sessions.

As our main analysis, we carried out a mixed-model repeated measures ANOVA with the CombiTVA session number as a within-subjects factor (First/Second), the experimental group as a between-subjects factor (CombiTVA Control/Right Spatial-priming/Left Spatial-priming/Neutral Spatial-priming) and the transformed ω_{index} as the dependent measure. Our analysis revealed a significant main effect of session ($F(55,1) = 4.084$, $p = .048$, partial $\eta^2 = .069$) and a significant interaction between Group and Session ($F(55,3) = 3.220$, $p = .03$, partial $\eta^2 = .149$). There were no between-group differences ($p > .9$). A post-hoc analysis revealed that the source of the reported interaction was a significant difference in the transformed ω_{index} between sessions only in the Right Spatial-priming group, with a greater bias towards the left in the first session (transformed $\omega_{\text{index}} = -.32$) comparing to the second session (transformed $\omega_{\text{index}} = -.35$) ($t(13) = 2.573$, $p = .023$; 95% CI [.004; .048]; Cohen's $d = .68$).

There were no significant differences in any of the other groups when comparing the attentional bias across sessions (all p's $> .18$), and no between-group differences when comparing the mean attentional bias ($p > .89$). In order to further investigate the change in ω between the two sessions in each group, and to examine whether there was stronger evidence in support of the alternative versus the null hypothesis (no significant change), we repeated the post-hoc analysis procedure with a series of paired-sample Bayesian T Tests (Rouder, Speckman, Sun, Morey, & Iverson, 2009). The statistical test was based on the Bayes Factor R Package (Version 0.9.12-2, by R Moray[2]). We set the Prior Scale to a

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[2] Downloaded from https://www.rdocumentation.org/packages/BayesFactor/versions/0.9.12-2.

Table 1 – Descriptive statistics of mean group performance (and SD) of each of the estimated TVA parameters in four experimental groups.

Group	TVA parameters	CombiTVA session 1 (first day/before spatial-priming)	CombiTVA session 2 (second day/after spatial-priming)
Right Spatial-priming	Transformed ω_{index}	−.32 (.05)	−.35 (.07)
	K	3.61 (.90)	3.75 (.69)
	t0	15.39 (13.22)	12.58 (5.87)
	C	64.54 (21.72)	79.63 (29.06)
	Transformed α	−.27 (.16)	−.26 (.19)
Left Spatial-priming	Transformed ω_{index}	−.32 (.08)	−.34 (.09)
	K	3.43 (.70)	3.46 (.81)
	t0	15.27 (5.45)	17.38 (9.12)
	C	59.99 (18.84)	67.66 (22.93)
	Transformed α	−.19 (.17)	−.27 (.17)
Neutral Spatial-priming	Transformed ω_{index}	−.33 (.05)	−.33 (.06)
	K	3.34 (.67)	3.23 (.77)
	t0	12.12 (8.69)	17.42 (12.09)
	C	55.25 (20.68)	66.42 (24.78)
	Transformed α	−.23 (.17)	−.17 (.22)
CombiTVA control (no spatial-priming)	Transformed ω_{index}	−.33 (.06)	−.32 (.06)
	K	3.06 (.67)	3.31 (.57)
	t0	16.05 (10.73)	18.27 (10.46)
	C	56.85 (26.73)	68.97 (23.10)
	Transformed α	−.22 (.15)	−.25 (.13)

Table 2 – Bayes Factors obtained in four post-hoc comparisons, comparing the transformed Bias Score between two sessions.

Group	Bayes Factor
Right Spatial-priming	2.878
Left Spatial-priming	.587
Neutral Spatial-priming	.269
CombiTVA Control (no spatial-priming)	.487

medium effect size (.7071) and report the Bayes Factor for each comparison between the first and second session (Table 2).

The Bayes Factors obtained in the Bayesian post-hoc *t*-tests comparing session 1 and 2 in the Left Spatial-priming, Neutral Spatial-priming, and CombiTVA Control groups can be interpreted as a lack of evidence in support of the alternative hypothesis, thus suggesting that there was no change in ω between the sessions in those three groups. A further interpretation of the Bayes factors, following Jeffreys (1961) and Wetzels et al. (2011), would suggest that there was moderate evidence in favour of the null hypothesis in the Neutral Spatial-priming condition (Bayes factor .1–.3) and therefore it is likely that the participants' behaviour did not change between conditions. However, the Bayes Factors obtained in the Left Spatial-priming and CombiTVA Control groups would only suggest weak evidence in favour of the null hypothesis (Bayes Factor .3–1). The only Bayes Factor which was found to be greater than 1 was in the Right Spatial-priming group, but this only indicates weak evidence in favour of the alternative hypothesis (change in ω between session 1 and 2), namely that the observed data are 2.878 times more likely to have occurred under the alternative hypothesis than under the null hypothesis. As this result only approached the cutoff of moderate evidence (Bayes Factor 3–10) in favour of the alternative hypothesis, in order to further verify whether the task reliably changed the attentional bias, we aimed to provide additional evidence by means of a replication in the next experiment performed in an independent sample (Experiment 2).

Fig. 5 illustrates the effect of the spatial-priming task for all individual participants plotted as the direction of change in performance (in TVA parameter ω) in all experimental groups (presented as raw scores).

Subsequently, we repeated three more separate ANOVA procedures with all the other attentional parameters derived from the CombiTVA paradigm as the dependent variable (K, t0, C and transformed α). There was a significant main effect of increased processing speed (C parameter) between the two sessions ($F(3,55) = 24.359$, $p < .001$, partial $\eta^2 = .307$). This observation is in line with previous reports of a general increase in processing speed between TVA sessions (Habekost, Petersen, & Vangkilde, 2014). To test whether this change is simply attributable to our procedure (repeated CombiTVA testing on two consecutive days using same behavioural paradigm), we carried out a post-hoc comparison of processing speed estimated based on the performance of the CombiTVA control group during the first and the second session. There was a significant difference between the sessions ($t(14) = 2.519$, $p = .024$, 95% CI[−22.4; .−1.80]. Therefore, we can attribute this change to an overall practice effect in performing the CombiTVA task. Memory capacity (K), perceptual threshold (t0) and selectivity (transformed α) did not differ between sessions (all p's > .1).

2.3. *Interim discussion*

Our findings demonstrated a transfer effect between two different tasks and stimuli sets. Interestingly this effect was observed only in conjunction with the application of the spatial-priming protocol based on the right-lateralized sustained-

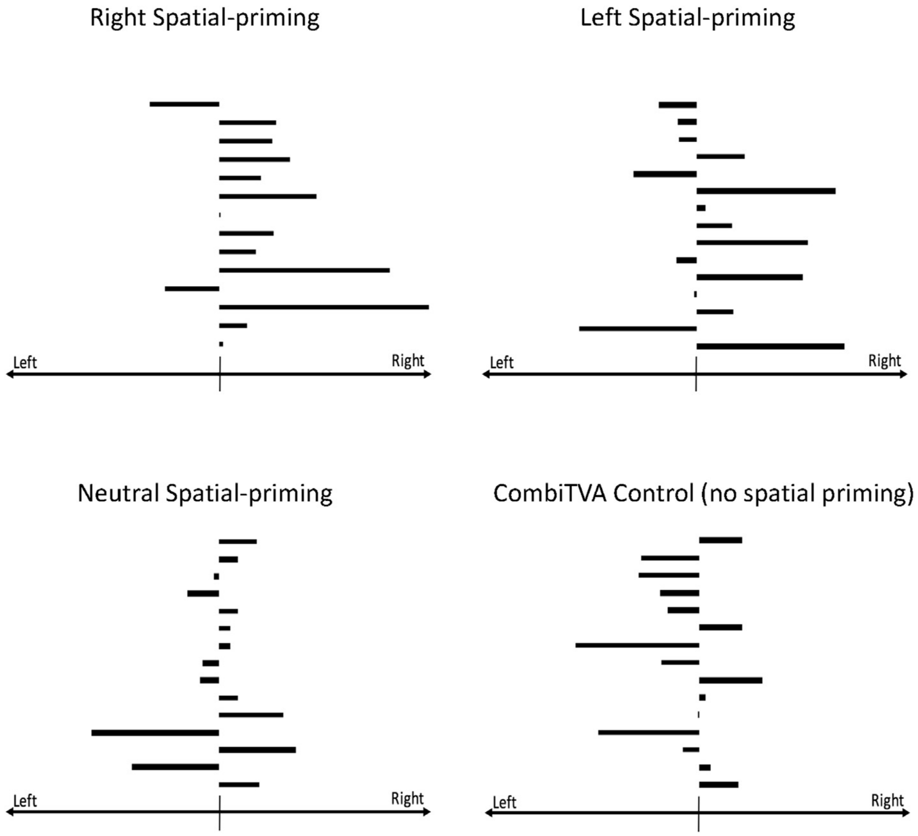

Fig. 5 – Raw values of change in the attentional bias (ω parameter) plotted for individual participants in each experimental group.

attention task (Right Spatial-priming), which resulted in a shift in the attentional bias towards the right visual hemi-field. Our results can be explained in view of the right hemispheric dominance in control of attention. We suggest that by biasing the right visual hemi-field we enhance the allocation of spatial attention toward this side of space predominantly controlled by the non-dominant left hemisphere and/or this effect results from the fact that the allocation of spatial attention toward the right side of space is controlled both by the left and the right hemisphere (According to Heilman's model; Heilman & Van Den Abell, 1980). In other words, our Right Modulation protocol either changed the balance between the hemispheres by triggering increased activation of the non-dominant left hemisphere when we trained our participants to sustain attention to the right hemifield and/or biased both hemispheres towards the right side of space. By contrast the left-lateralized sustained-attention task (Left Spatial-priming) failed to trigger attentional shift towards the left visual hemi-filed as the allocation of attention toward the left is already biased by the preferential activation of the dominant hemisphere. Our findings are consistent with previous studies showing that prism adaptation can improve perception only towards the right (e.g., Loftus et al., 2009; Michel et al., 2003). But importantly here we demonstrate that the right bias effect can be triggered by the transfer between attention tasks with different stimuli sets, rather than a perceptual manipulation as in prior prism adaptation studies. Furthermore, in light of evidence that the attentional parameters derived from the TVA based task are independent of the sustained attention performance (McAvinue, Habekost et al., 2012; McAvinue, Vangkilde et al., 2012), the transfer effects appear to reflect a mechanistic change in hemispheric dominance as opposed to a generic effect of task practice.

Another parameter that changed between tasks is the processing speed, although the presence of the same effect even in the CombiTVA control group (no modulation) suggests that this was clearly a result of a generalized training effect (practice effect in task performance).

In Experiment 2, we aimed to examine whether combining the lateralized sustained attention (spatial-priming) task with brain stimulation targeting bilateral PPC could further enhance this effect, and/or also impact the non-spatial parameters of attention. Due to the relatively low spatial selectivity of employed here bi-parietal stimulation, we were unable to precisely manipulate discrete neuro-substrates of attention. Instead, our experimental protocol relied on the overall function of the PPC in attentional control (for review see Beck & Kastner, 2014) and thus we were unable to precisely foresee the effects on discrete attentional mechanisms. Nevertheless, based on prior findings (e.g., Benwell et al., 2015; Fierro et al., 2000; Giglia et al., 2011; Hung et al., 2005; Moos et al., 2012; Sparing et al., 2009) we anticipated that the attentional weight index (ω_{index}) and the attentional selection (the top-down selectivity index α) estimated based on the Bundesen's (1990) TVA could be affected by the stimulation applied over the PPC.

3. Experiment 2: spatial-priming protocol combined with brain stimulation

3.1. *Method*

3.1.1. *Participants*

Forty-five naive volunteers participated in this experiment (30 female; mean ± SD age = 25.4 ± 4.2). They were recruited through an online research participation system at the University of Oxford. Exclusion criteria included any previous history of neurological or psychiatric disorders, and contraindications to transcranial current stimulation (Poreisz, Boros, Antal, & Paulus, 2007). Both left- and right-handed participants were recruited for the study, and the hand dominance was assessed according to Edinburgh handedness inventory (Oldfield, 1971; mean handness score ± SD = 60.2 ± 54.68; six participants classified as left-handed and one as ambidextrous). All participants had either normal or corrected-to-normal vision. All study participants provided written informed consent, in compliance with relevant protocols approved by the University of Oxford Central University Research Ethics Committee. The experimental procedures were conducted in accordance with the latest version of the Declaration of Helsinki. Participants were compensated for their time (payment of £25 for the whole study, inclusive of travel expenses).

3.1.2. *Apparatus*

We used the same set up as in Experiment 1. Additionally, we also employed transcranial current stimulation (see tRNS section for full details).

3.1.3. *General procedure*

Participants were divided into three experimental groups: Right Spatial-priming with bi-parietal tRNS (15 participants), Right Spatial-priming with sham stimulation (15 participants), tRNS control with bi-parietal tRNS but with no spatial-priming (15 participants). All participants were invited to the lab on two consecutive days at the same time during the day. On the first day, all participants performed the CombiTVA task to assess their baseline attentional bias and other attentional functions based on TVA framework. On the second day, the two spatial-priming groups performed the Right version of the sustained attention task (with 80% of the right target-trials) while either bi-parietal tRNS (tRNS Right Spatial-priming group) or sham stimulation (sham Right Spatial-priming group) was applied (see below for details). The tRNS control group was given bi-parietal tRNS without the spatial-priming task. Participants in all three experimental groups were assessed on the CombiTVA task immediately following either tNRS or sham stimulation.

3.1.4. *Behavioural paradigm*

We used the same task design as in Experiment 1, please note that in Experiment 2 we only used Right version of the task i.e., with 80% of the right target-trials.

3.1.5. *tRNS*

The high-frequency tRNS was administered by means of a battery-driven, constant current stimulation (neuroConn DC-STIMULATOR PLUS, GmbH, Ilmenau, Germany), using 5 × 5 cm rubber electrodes placed in saline soaked sponges. The saline was used to reduce the risk of skin irritation and the electrodes were secured using an elastic strap to ensure electrical contact with the scalp. 1 mA tRNS, with a frequency of alternating current ranging from 100 to 640 Hz at random, was applied bilaterally over the left and right PPC (P3 and P4, respectively) with the placement of the electrodes determined according to the 10–20 EEG system (Jasper, 1958). The tRNS stimulation lasted 1200 sec (20 min), while sham stimulation lasted only 30s. Both the 1200s and 30s tRNS stimulation was flanked by a gradual 15s up and 15s down current ramp. The start of the experimental task was always triggered following the short practice and the subsequent immediate onset of either the sham or the real tRNS stimulation. The sustained attention task outlasted the 20 min stimulation.

3.1.6. *Statistical analysis*

We repeated the same statistical procedure as in Experiment 1 with the CombiTVA session number as a within-subject ANOVA factor (First/Second), only in this experiment the group factor consisted of three experimental groups (tRNS Right Spatial-priming, sham Right Spatial-priming, tRNS control). The dependent variables were the five parameters extracted based on the TVA computational model: transformed ω_{index}, K, t0, C and transformed α.

3.2. *Results*

For the two groups who performed the spatial-priming task (tRNS Right Spatial-priming and sham Right Spatial-priming), we calculated the mean accuracy in the right-lateralized sustained attention task, separately for each experimental condition (target appearing on the right, target appearing on the left, and no target). We next ran a 3 × 2 repeated measures AVNOVA with the target condition as a within-subjects factor (Left-Target, No-Target, Right-Target) and the experimental group as a between-subjects factor (tRNS Right Spatial-priming and sham Right Spatial-priming). There were no interactions between the factors, suggesting that the performance pattern on the spatial-priming task did not differ between groups ($p > .8$). There were also no overall group differences ($p > .6$). As in Experiment 1, we found a main effect for target condition, due to a higher accuracy in trials when no target is observed ($F(56,2) = 21.944$, $p < .001$, partial $\eta^2 = .439$).

As a supplementary analysis, we performed a second ANOVA with the Block Number as another within-subject factor to explore if the application of brain stimulation triggered changes in the accuracy rate in the performance on the lateralized sustained-attention (spatial-priming) task. Specifically, we carried out a 3 × 3 × 2 repeated measures ANOVA with two within-subjects factors: Target Condition (Left-Target, No-Target, Right-Target) and Block Number factor (First, Second, Third); and Experimental Group as a between-subjects factor (tRNS Right Spatial-priming and sham Right Spatial-priming). There were no interactions or main effects (all p's > .2) except for the Target Condition, as in the primary analysis.

Table 3 describes the means and SDs of all five attentional parameters derived based on the performance in the

Table 3 – Descriptive statistics of mean group performance (and SD) of each of the estimated TVA parameters in three experimental groups.

Group	TVA Parameters	CombiTVA session 1 (first day/prior spatial-priming & stimulation)	CombiTVA session 2 (second day/after spatial-priming & stimulation)
tRNS Right	Transformed ω_{index}	−.33 (.06)	−.35 (.05)
Spatial-priming	K	3.55 (.58)	3.56 (.61)
	t0	11.57 (7.59)	10.85 (7.50)
	C	68.65 (23.97)	73.64 (27.07)
	Transformed α	−.22 (.12)	−.34 (.13)
sham Right	Transformed ω_{index}	−.32 (.05)	−.35 (.07)
Spatial-priming	K	3.67 (.69)	3.81 (.74)
	t0	10.10 (5.49)	12.10 (7.25)
	C	69.22 (24.71)	71.85 (24.52)
	Transformed α	−.28(.16)	−.29(.18)
tRNS Control	Transformed ω_{index}	−.32 (.04)	−.32 (.06)
(no spatial-priming)	K	3.56 (.70)	3.70 (.62)
	t0	11.23 (7.33)	11.30 (7.41)
	C	62.26 (21.92)	73.13 (23.74)
	Transformed α	−.26 (.17)	−.28 (.18)

CombiTVA task in two sessions calculated separately for every experimental conditions.

As our main analysis we carried out a 2 × 3 mixed measures ANOVA with CombiTVA session number as a within-subject factor (session 1/session 2), the experimental group as a between-subject factor (tRNS Right Spatial-priming/tRNS Control/sham Right Spatial-priming) and ω_{index} index as the dependent variable. Our analysis revealed a significant main effect for session number ($F(42,1) = 7.235$, $p = .01$, partial $\eta^2 = .145$), no group differences ($p > .7$) and no interaction ($p > .1$). We next analysed the simple effects of change in bias direction separately in each of the three experimental groups. Strikingly, the significant difference between session 1 and 2 was only observed in the two groups that received the spatial-priming protocol i.e., in the tRNS Right Spatial-priming group ($t(14) = 2.284$, $p = .038$, 95% CI[.001; .039]; Cohen's $d = .58$) and in the sham Right Spatial-priming group ($t(14) = 2.401$, $p = .031$, 95% CI[.002; .046]; Cohen's $d = .61$). There was no significant change in attentional weights in the tRNS control group ($p > .9$).

As in Experiment 1, we repeated the analysis of the simple effects with a series of Bayesian T Tests (Rouder et al., 2009). We set the Prior Scale to a medium effect size (.7071) and report the Bayes Factor for each comparison between the first and the second session (Table 4). The group who did not undergo the spatial-priming protocol (tRNS control) had a Bayes Factor smaller than one, indicating a lack of evidence in the support of the alternative hypothesis and suggesting that there was no change in ω between the two sessions. A further interpretation in accordance with Jeffreys (1961) and Wetzels et al. (2011), would indeed suggest that there was moderate evidence in favour of the null hypothesis (no change) in the tRNS control group (Bayes Factor .1–.3). Both spatial-priming groups (tRNS Right Spatial-priming and sham Right Spatial-priming) had Bayes Factors larger than one, suggesting that the alternative hypothesis (change in ω between session 1 and 2) is favoured. However, an interpretation in accordance with Jeffreys (1961) and Wetzels et al. (2011), would indicate only weak evidence (Bayes Factor 1–3) in favour of the alternative hypothesis, namely that the observed data are approximately 2 times more likely to have occurred under the alternative hypothesis than under the null hypothesis in tRNS Right Spatial-priming and sham Right Spatial-priming groups (see Table 4). Although, this evidence could only be considered as weak (Bayes Factor 1–3), the findings observed in these two groups provide two independent replications of the effect demonstrated in Experiment 1 and therefore support a potential robustness of the observed change in attentional weights.

Table 4 – Bayes Factors obtained in three post-hoc comparisons, comparing the transformed Bias Score between two sessions.

Group	Bayes Factor
tRNS Control	.263
tRNS Right Spatial-priming	1.884
sham Right Spatial-priming	2.245

As an additional verification for the change in the attentional weights, we carried a set of comparisons including participants in all three experimental groups who underwent the right sustained attention protocol (one group in Experiment 1/Right Spatial-priming Group, and two groups in Experiment 2/tRNS Right Spatial-priming and sham Right Spatial-priming). We first carried two Bayesian ANOVA tests to see whether the groups differed in their attentional weights on either the first or the second CombiTVA sessions, with the experimental group as a between-subjects factor, and the ω_{index} index as the dependant variable. We set the prior scale to a medium effect size (.7071), and found evidence in favour of the null hypothesis, suggesting a similar bias among the three groups (BF = .102). A similar result was obtained for the second session (BF = .108). After establishing that there were no group differences on each session, we grouped all the observations and carried a Bayesian repeated measures *t*-test, with the session number as a within-subjects factor, and the attentional weights (ω_{index}) as the dependant variable (now including 45 participants). The results demonstrate very strong evidence in favour of the alternative hypothesis, namely a significant change in the ω_{index} following the right spatial-priming protocol (BF = 32.745).

Subsequently, we carried out a 2 × 3 mixed measures ANOVA with session number as a within-subject factor (session 1/session 2), the experimental group as a between-subject factor (tRNS Right Spatial-priming/tRNS Control/sham Right Spatial-priming) and the theoretical attentional selectivity parameter (α) as the dependent variable. Our analysis revealed a significant main effect for session number ($F(42,1) = 8.351$, $p = .006$, partial $\eta^2 = .166$) and a significant interaction between Group and Session ($F(42,2) = 4.317$, $p = .02$, partial $\eta^2 = .171$). A post-hoc analysis revealed that the source of the interaction was a significant difference in α between sessions only in the tRNS Right Spatial-priming group, with a greater α in the first session (transformed $\alpha = -.22$) as compared to the second session (transformed $\alpha = -.34$) (a lower score stands for a better selectivity) ($t(14) = 4.250$, $p = .001$; 95% CI[.063; .193]; Cohen's $d = 1.09$). There were no significant between sessions differences in α in any of the other groups (all p's > .38). Finally we performed a follow up analysis with three Bayesian T Tests for each group, comparing the transformed α between the two session. The results (Table 5) confirmed that 1 mA tRNS applied over the PPC significantly increased selectivity but only when combined with the sustained attention (spatial-priming) task. The Bayes Factors suggest that while in both tRNS control and sham Right Spatial-priming groups, there was substantial evidence in favour of the null hypothesis (e.g., selectivity did not differ between sessions), the evidence in the tRNS Right Spatial-priming group provide very strong evidence (following Wetzels et al., 2011) for increased selectivity when combining tRNS and the spatial-priming task.

Finally, we repeated the ANOVA analysis entering one of the three parameters: C, t0 and K as dependent variable. Similarly to the earlier findings i.e., Experiment 1, there was a significant main effect of session on the processing speed parameter (C), with a lower processing speed in the first session (66.71 items per second) compared to the second session (74.19 items per second) ($F(42,1) = 14.277$, $p < .001$, partial $\eta^2 = .145$). In addition, we found a significant main effect of session on the memory capacity K ($F(42,1) = 5.288$, $p = .027$, partial $\eta^2 = .112$) showing overall improved capacity over the second session. While we did not observe such change in our first experiment, a similar effect of increased capacity between repeated sessions has been reported previously (Habekost et al., 2014). There were no other interactions or main effects in any other condition (all p's > .2).

4. General discussion

Our results suggest that attentional bias (weights assigned to the left versus right hemi-field, here measures by ω_{index}) can be modulated by spatial-priming invoked by sustaining attention towards the right hemi-field, but this effect does not occur when sustaining attention towards the left visual field. Interestingly, when combined with a bi-parietal high-frequency random noise stimulation (high-frequency tRNS), the rightward sustained attention task did not further increase the shift in attentional bias triggered by the spatial-priming task alone, but instead resulted in the increased capacity of filtering irrelevant distractors (selectivity).

Table 5 – Bayes Factors obtained in three post-hoc comparisons, comparing the transformed α parameter between two sessions.

Group	Bayes Factor
tRNS Control	.269
tRNS Right Spatial-priming	46.489
sham Right Spatial-priming	.273

Experiment 1 supports the notion of the right-hemispheric dominance in visual attention (Corbetta & Shulman, 2002; Kinsbourne, 1987, 1993; Mesulam, 1981). Consequently, the enhanced bias towards the right, but not the left visual hemi-filed triggered by the sustained attention task, can be explained as a result of inherently lower contralateral activity of the left hemisphere, which perhaps might be easier to modulate/increase. On the other hand, the failure to modulate the attentional bias towards the left hemi-field can be explained by the inherently higher activity within the dominant right hemisphere, which might be more difficult to further enhance. Previous studies seeking to modulate the lateral biases, by using a perceptual adaptation, have reported similar outcomes i.e., have shown successful shifts in pseudoneglect only towards the right but not the left visual field (e.g., Loftus et al., 2009; Michel et al., 2003). The interesting and novel finding presented here is that we were able to modulate attentional bias by means of the sustained attention task and thus this modulation was a result of transfer effect between two different attentional tasks, rather than a perceptual manipulation (e.g., Loftus et al., 2009) or direct modulation of brain activity (e.g., Giglia et al., 2011). Importantly, this task transfer effect was stable and we were able to reliable replicate this finding in Experiment 2. We would like to emphasize that our approach differed from more traditional methods of manipulating attention by a repetitive training protocols, which employ test-retest of the training-task outcome as a measure of training efficiency (e.g., Robertson et al., 1995). In contrast, we aimed here to test whether a single administration of a relatively short task with high demands for a lateralized sustained attention (left or right visual hemi-field) can have an immediate transferable effect of spatial priming on attentional weights (assigned to the left *vs* right hemi-field) and/or other attentional functions. Thus, we assessed the efficiency of our task by the change in TVA parameters and have not done any test-retest comparison of performance in the task itself. Furthermore, we have neither hypothesized that we would observe improvement (effect of training) in the sustained attention task itself nor that the change in attentional parameters measured by TVA framework would result from/require improvement in the sustained attention task itself.

As stated above, the observed change in the TVA attentional bias parameter was a result of a lateralized sustained attention task. Such design was chosen based on previous reports of an overlap between the brain mechanisms supporting sustained and spatial attention (e.g., Husain & Nachev, 2007; Husain & Rorden, 2003; Robertson, 2001). Accordingly, we propose that combining the requirements to sustain attention while focussing on a specific hemi-field may have contributed to this striking effect. It should be noted that the task employed here required not only the maintenance of attention over time, but also the capacity of distinguishing targets from distractors with conjunctive features (Shalev et al., 2017). This way, we ensured that individuals had to rely on attentional selection, by attending and combining the relevant aspects of the visual stimuli to identify the targets.

In Experiment 2, we aimed to examine whether bi-parietal tRNS could potentially further enhance the observed effect and/or affect other attentional parameters as well as to check whether we could replicate the main finding from Experiment 1. When combining the right lateralized sustained attention (spatial-priming) task with tRNS, we observed an increase in the theoretical parameter representing selectivity, measuring the individual capacity of selecting the relevant stimuli over irrelevant distractors. By applying a Bayesian approach, we demonstrated the strength of our protocol, when either tRNS alone or the sustained attention task alone (sustained attention task and sham stimulation) were applied, we found a substantial evidence in favour of the null hypothesis, namely that selectivity was not affected at all by these manipulations. Strikingly, the Bayes Factor calculated when comparing sessions in the group who underwent the combined protocols (tRNS and sustained attention task) highlighted a very strong evidence in favour of a change. These findings can be further interpreted as suggesting that there was a unique value in combining tRNS with sustained attention task, and that when applied alone these manipulations were ineffective in altering selectivity.

Our observation is in line with the contemporary view of the role of the parietal cortex in charge of attentional control and not just spatial allocation of attention (e.g., Corbetta et al., 1993; Doricchi et al., 2010; Kincade et al., 2005; Nobre et al., 1997; Shulman et al., 2010; for review see Beck & Kastner, 2014), and further supported by a previous study showing a modulation in the TVA parameter of attentional selectivity after parietal stimulation (Moos et al., 2012). Although, it should be noted that in our study the change in selectivity was triggered only when stimulation was combined with sustained attention task and not by stimulation alone as in the study by Moos and colleagues. This discrepancy is likely attributable to either the use of a different method of brain stimulation likely operating via somewhat distinct neural mechanism (bi-parietal tRNS in our study, as opposed to cathodal tDCS over the right PPC in Moos et al., 2012; for a recent review contrasting different transcranial current stimulation methods see Santarnecchi et al., 2015) or differences in study design. Strikingly, a recent study has shown that the introduction of random noise in the neural system (by using high-frequency tRNS) contributes to overall amplified signal detectability by increasing action potentials across the visual cortex (van der Groen & Wenderoth, 2016). In our study, the increased excitability in the parietal cortex triggered by tRNS stimulation targeting the parietal cortex combined with sustained attention task affected both the attentional selectivity and spatial attention. Importantly, prior evidence has suggested that neural enhancement triggered by tRNS is transferable when the trained and non-trained cognitive domains share common neural substrates (e.g., Cappelletti et al., 2013).

The successful manipulation of selectivity observed only when lateralized sustained attention task was combined with tRNS is worth further consideration. Potentially, it was the requirement for selective attention in our protocol (the task required to distinguish a target from conjunctive distractors, and therefore had a clear requirement for selection) that contributed to the improvement in selection. Therefore, the effects of sustained attention task could be understood in line of our protocol targeting both selectivity and spatial attention, and thus consequently affecting the two corresponding TVA derived parameters. But then we need to speculate why the sustained attention task applied alone (i.e., without brain stimulation) failed to alter selectivity and affected only the attentional weights. A potential explanation perhaps lays in the nature of the parameters in question, while selectivity had improved, the attentional weights had shifted. The results of Experiment 1 demonstrate how attention can be modulated to be spatially biased to one hemi-field over the other (the right *vs* the left hemi-field). In other words, our lateralized sustained attention task affected the balance of the intra-hemisphere competition, rather than the overall attentional capacity. Subsequently, the improvement, which is reflected in reporting an overall higher proportion of targets compared with distractors, was only obtained when brain stimulation was combined with lateralized sustained attention task but not by the task alone.

Lastly, it should be noted that the reported here findings are consistent with prior studies showing only very small or no effects of stimulation alone as compared to the effects of stimulation combined with cognitive training (e.g., Antal, Terney, Poreisz, & Paulus, 2007; Cappelletti et al., 2013; Filmer, Varghese, Hawkins, Mattingley, & Dux, 2017).

In summary, our study indicated that attentional bias can be shifted towards the right hemi-field by a lateralized sustained attention task. When repeating the same paradigm combined with bi-parietal tRNS, attentional selectivity was also enhanced. Several prior studies indicate that combining tRNS with cognitive training can improve behavioural performance and such effect can be maintained over time after application of repetitive protocols with multiple sessions spread over several days (e.g., Cappelletti et al., 2013; Fertonani et al., 2011; Popescu et al., 2016). This is of particular interests as it has been suggested that repetitive high-frequency tRNS combined with cognitive training not only increases the activity of the neuronal populations sub-serving the trained cognitive function but also facilitates brain plasticity (Cappelletti et al., 2013; Cohen Kadosh, Levy, O'Shea, Shea, & Savulescu, 2012; Fertonani et al., 2011; Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). It would be therefore interesting to explore in the future whether the observed here changes in spatial bias and selectivity could be maintained over time and whether such lasting affect could be observed after a single session or require multiple task combined with stimulation sessions. Furthermore, it would be worth investigating whether increased amount of the spatial-priming (multiple session) could enhance the observed effects i.e., changes in the spatial bias and/or selectivity. Future work could also investigate the clinical applicability of such protocols in rehabilitation of visuospatial disorders, in particular if the effect is found to be long lasting (see Harvey & Kerkhoff, 2015).

While in our study we applied a bilateral stimulation while participants performed a right-lateralized task, future studies may try to explore whether the effect of enhanced selectivity can be obtained also when combining stimulation with a bilateral (neutral), or perhaps a left-lateralized task. Such approach could address an interesting question, of whether there could be an effect of modulating the left hemisphere on the selectivity without a change in spatial bias, and to answer the question whether the observed here change in selectivity was merely the result of performing an attentional selection over time and was completely independent from targeting the rightward attentional shift. Alternatively, it would be interesting to explore whether attention could be biased towards the left hemi-field by a different protocol alone or combined with brain stimulation, perhaps by a repetitive training protocol conducted over the period of not one but several sessions better suited to trigger changes in the activity/ neuroplasticity within the dominant right hemisphere.

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