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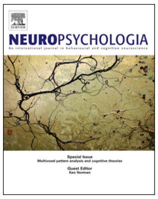

The effects of tDCS upon sustained visual attention are dependent on cognitive load

James M. Roe [1], Mathias Nesheim *,[1], Nina C. Mathiesen [1], Torgeir Moberget, Dag Alnæs, Markus H. Sneve

Department of Psychology, University of Oslo, Box 1094 Blindern, 0317 Oslo, Norway

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ABSTRACT

Transcranial Direct Current Stimulation (tDCS) modulates the excitability of neuronal responses and consequently can affect performance on a variety of cognitive tasks. However, the interaction between cognitive load and the effects of tDCS is currently not well-understood. We recorded the performance accuracy of participants on a bilateral multiple object tracking task while undergoing bilateral stimulation assumed to enhance (anodal) and decrease (cathodal) neuronal excitability. Stimulation was applied to the posterior parietal cortex (PPC), a region inferred to be at the centre of an attentional tracking network that shows load-dependent activation. 34 participants underwent three separate stimulation conditions across three days. Each subject received (1) left cathodal / right anodal PPC tDCS, (2) left anodal / right cathodal PPC tDCS, and (3) sham tDCS. The number of targets-to-be-tracked was also manipulated, giving a low (one target per visual field), medium (two targets per visual field) or high (three targets per visual field) tracking load condition. It was found that tracking performance at high attentional loads was significantly reduced in both stimulation conditions relative to sham, and this was apparent in both visual fields, regardless of the direction of polarity upon the brain's hemispheres. We interpret this as an interaction between cognitive load and tDCS, and suggest that tDCS may degrade attentional performance when cognitive networks become overtaxed and unable to compensate as a result. Systematically varying cognitive load may therefore be a fruitful direction to elucidate the effects of tDCS upon cognitive functions.

1. Introduction

Transcranial Direct Current Stimulation (tDCS) is a method that has gained considerable interest over the last decade due to its potential to modulate surface cortical excitability, and consequently performance on a wide range of cognitive tasks (Kuo and Nitsche, 2012; Utz et al., 2010). Intriguingly, tDCS has been shown to produce both short-term and long-term beneficial effects upon cognitive ability (for a review, see Kuo and Nitsche, 2012). For example, tDCS stimulation of relevant brain regions during cognitive tasks has demonstrated enhancements in visuospatial attention (Bolognini et al., 2010; Sparing et al., 2009), language acquisition (Flöel et al., 2008; Meinzer et al., 2012), and working memory performance (Fregni et al., 2005; Ohn et al., 2008; Zaehle et al., 2011), whereas beneficial long-term effects have been observed following tDCS during post-task sleep-dependent memory consolidation (Marshall et al.Born, 2004; Nitsche et al., 2010) and during motor-learning (Antal et al., 2004a). A non-invasive technique, tDCS is believed to work by inducing polarity-dependent stimulation to the outer cortical layers, exerting hyperpolarising or depolarising effects on the membrane potential of the axon. Typically, anodal stimulation will enhance excitability of the cortical area over which it is placed, whereas the cathode will reduce this potential for excitability (Nitsche et al., 2003; Nitsche and Paulus, 2000; Stagg and Nitsche, 2011). Such changes in excitability are thought to influence neuroplastic functions in the cortex that underpin learning (Nitsche and Paulus, 2000). However, interactions between the physiological effects of tDCS and ongoing processes in cognitive networks are currently poorly understood.

Although tDCS has been widely applied in the fields of learning and memory, comparatively little research has been conducted on the effects of tDCS on attentional processes (see Coffman et al., 2014; Kuo and Nitsche, 2012). Anodal stimulation of the right posterior parietal cortex (PPC) has been shown to reduce reaction times in various visual attentional tasks both during, and shortly after tDCS (Bolognini et al., 2010). In addition, separate anodal and cathodal stimulation of the PPC has been shown to respectively

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* Corresponding author.
E-mail address: omneshei@psykologi.uio.no (M. Nesheim).

[1] Authors J.M.R, M.N., and N.C.M contributed equally to this work.

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enhance and impair the attentional detection of contralaterally presented stimuli in healthy participants during a bilateral task (Sparing et al., 2009). Furthermore, the same study showed that in patients with visuospatial neglect, anodal stimulation of the PPC in the affected right hemisphere was found to reduce the attentional deficit exhibited. However, not all studies have found improved cognitive performance after anodal, and impaired performance after cathodal stimulation. Stone and Tesche (2009) found that both anodal and cathodal stimulation over the left PPC inhibited attentional switching between global and local stimuli. On the other hand, cathodal tDCS applied over the right PPC has also led to an improvement in attentional selection (Moos et al., 2012).

It is possible that such conflicting results of tDCS effects upon cognition may be partly due to widely varying task demands. In line with a proposed interaction between tDCS and cognitive load (Miniussi et al., 2013), one study found that cathodal stimulation of the human motion area (MT+) impaired motion perception during a perceptual task of low demand, yet facilitated performance during complex tasks involving more distractors (Antal et al., 2004b). Furthermore, during high attentional load, Weiss and Lavidor (2012) found that cathodal stimulation over the PPC increased processing of flankers (peripheral cues), possibly by increasing the available attentional resources that could be applied to the task. In addition, anodal stimulation over the dorsolateral prefrontal cortex (DLPFC) has led to improved spatial working memory performance only under conditions of motor task interference combined with backward memory recall (i.e. high cognitive demand; Wu et al., 2014). Finally, one other study attempted to investigate load effects of tDCS using the n-back task, although the results were not believed to be attributable to the interaction of cognitive load and tDCS (Sandrini et al., 2011), namely due to potential qualitative differences in processing strategies between task load conditions (1-back / 2-back; Harbison et al., 2011).

Crucially, then, if conflicting results of tDCS studies are indeed partly a function of varying task demands, then establishing the interaction between tDCS effects and cognitive load is of great interest. A recent theoretical account of how tDCS affects cognitive networks suggests that the constant current induced by tDCS will interact with the state of the cognitive network, which is largely determined by the task input (load, for example; Miniussi et al., 2013). Although the field has indeed begun to investigate the interaction between cognitive load and tDCS, in many cases this has been explored somewhat indirectly. We believe that (1) a ‘pure’ manipulation of cognitive load involves a manipulation of difficulty level without changing the qualitative nature of the task, and (2) that using a load level that overtaxes cognitive capacity, as well as making use of a wider range of load levels (i.e. more than two), is preferable if one’s goal is to investigate the interaction between tDCS and cognitive load.

To more directly explore this interaction, we used a multiple object tracking (MOT) task, a popular paradigm applied in the investigation of covert visual attention (Pylyshyn and Storm, 1988). During MOT, participants have to divide their attention onto several target objects in order to simultaneously track their independent motion trajectories. This places a continual demand on the visuo-attentional system, which is integral to the successful navigation of the world. Importantly, the number of objects one is capable of tracking increases when trackers are split between the left and right visual fields, indicating tracking resources in the cerebral hemispheres are largely independent (Alvarez and Cavanagh, 2005; Cavanagh and Alvarez, 2005). Temporary disruption of the PPC by low frequency repetitive Transcranial Magnetic Stimulation (TMS) has been shown to reduce tracking performance only when tracking was required in both visual fields (Battelli et al., 2009). Moreover, this effect was seen only in the visual field contralateral to the stimulation site. Contrasting this, when tracking was required only in one visual field, no disruption of performance was seen, regardless of the hemisphere disrupted. This implies that an intact hemisphere has the potential to compensate for its disrupted counterpart *only* when tracking is unilateral. It further implies that tracking resources are primarily directed towards the contralateral visual field, and therefore are less shared between the hemispheres, provided that the task is bilateral (Battelli et al., 2009). Finally, Alnæs et al. (2014) showed that the MOT task increasingly recruits resources from the brain’s system for goal-driven attention when the number of targets-to-be-tracked increases, as measured by both blood-oxygen level dependent (BOLD) responses in the brain’s dorsolateral attention network, and load-related pupil dilations, indicative of mental effort (Kahneman, 1973). We therefore reasoned that the MOT task – through allowing us to parametrically manipulate the demands for ongoing attentional processing – should allow for a direct investigation of the interaction between tDCS and cognitive load. Furthermore, to the best of our knowledge, no previous studies have investigated the effects of tDCS upon attentional tracking.

Functional magnetic resonance imaging (fMRI) research has confirmed the activation of several brain areas in a frontoparietal tracking network (see Howe et al., 2009). Of these, consistent evidence indicates that both anterior and posterior intraparietal sulcus (aIPS and pIPS, respectively) in the PPC demonstrate parametric activation in correlation with increasing demands of tracking load (Alnæs et al., 2014; Culham et al., 2001; Howe et al., 2009; Jovicich et al., 2001), thus distinguishing these regions from those underlying non-attentional support functions (e.g. the planning and suppression of eye movements). Further, in determining the interaction of the key tracking-network structures, Howe et al. (2009) inferred that the aIPS constitutes the central hub of the tracking network, documenting extensive communications with all other tracking regions, whilst also showing motion-dependent activation. Thus, given the proposed centrality of the intraparietal sulcus (IPS) in a cortical network for attentional tracking, our aim was to manipulate the excitability of neurons in the PPC, the wider domain of the IPS accessible by the reduced spatial resolution of tDCS.

In the current study, tDCS was applied bilaterally over the PPC to avoid the confound of indirectly modulating other brain regions with a reference electrode. Bilateral designs also allow for equal spreading of the electrical current through (but not restricted to) cortical areas of interest, although with opposite polarity in each hemisphere (Zaehle et al., 2011). A split visual-field MOT task was therefore deemed suitable to control for potential polarity-dependent effects upon the hemispheres that likely translate to contralateral task performance, particularly given the evidence for largely independent hemispheric tracking resources in bilateral tasks (Alvarez and Cavanagh, 2005; Battelli et al., 2009). We then parametrically varied the load of bilateral targets-to-be-tracked whilst applying stimulation over PPC – known to show increasing activation in concert with increasing load demands in the tracking task. We included three load-levels, giving a low (one target per visual field), medium (two targets per visual field) and high (three targets per visual field) condition. Importantly, the high load condition was designed to overtax attentional resources. Under the null hypothesis, the effects of tDCS should be uniform across load conditions. However, extending previous research showing task difficulty may interact with tDCS (Antal et al., 2004b; Weiss and Lavidor, 2012; Wu et al., 2014), we reasoned that our design would allow a direct investigation of load-dependent tDCS effects, and hypothesised that tDCS would exert influence over tracking performance in a load-dependent manner. More specifically, we hypothesised that when under high cognitive loads designed to overtax cognitive capacity, tracking performance would be more prone to external influence by tDCS than under lower loads.

However, against a background of conflicting research, we remained agnostic as to whether tDCS in the high load condition would be associated with increased or decreased tracking performance.

2. Method

2.1. Participants

A total of 34 participants (21 female) were recruited. All participants were within the age range 21–35 (M=24.7, SD=3.37; a predominantly student-based sample), were right handed, reported normal or corrected-to-normal vision, and had no history of neurological impairment or psychiatric diagnoses. No participants reported taking medication which could impact cognitive functioning. 2 subjects were excluded due to below-chance tracking performance while not under stimulation. Participants remained blind to the tDCS procedure applied throughout the testing period. The study received ethical approval by the local research ethics committee at the Department of Psychology, University of Oslo, and all participants gave their informed consent.

2.2. Design and procedure

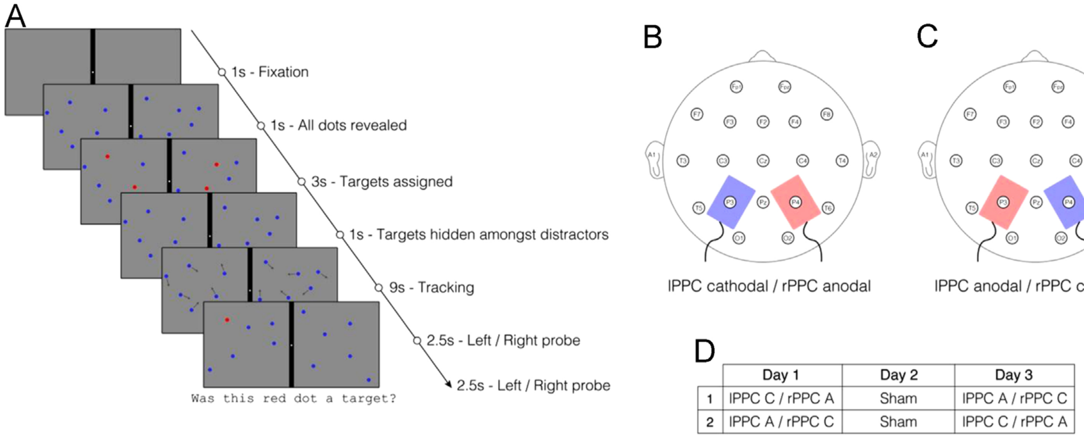
A within-subject repeated measures experimental design was employed to compare accuracy on a MOT task under tDCS stimulation to a control condition in which participants received only sham stimulation. Participants undertook 3 separate testing sessions across 3 days, where two tDCS stimulation conditions were separated by the sham condition. In order to discount any longer lasting after-effects of enhanced or diminished neuronal excitability (Nitsche and Paulus, 2001), the sham session took place at least 2 days after the first stimulation condition. A neuroConn DC-stimulator (Ilmenau, Germany) was used for tDCS-stimulation.

Half the participants received cathodal stimulation over the *left* PPC combined with anodal stimulation over the *right* PPC on day 1, sham stimulation on day 2, and anodal stimulation over the *left* PPC combined with cathodal stimulation over the *right* PPC on day 3. The other half of the participants received stimulation conditions in the opposite order. Thus stimulation configuration was counterbalanced across participants and days of the study (see Fig. 1D). Within the MOT task, the bilateral number of objects-to-track was varied to give a low (1+1 targets), medium (2+2 targets) and high (3+3 targets) attentional load condition. The experiment thus applied a 3 (stimulation) × 3 (load) design, where the accuracy of performance on the MOT task was the measure of interest.

Participants were fitted with an EEG cap (EASYCAP GmbH, Herrshing, Germany) in order to pinpoint the location of areas P3 and P4 according to the 10–20 system, corresponding to the left and right PPC, respectively (Okamoto et al., 2004). An electroconductive gel was used to reduce impedance between the tDCS electrode pads and the scalp, and the pads were placed over P3 and P4. The electrodes measured 5 × 7 cm. In stimulation conditions, a current of 1.0 mA (0.029 mA/cm^2) was delivered with a 30 s graded fade-in and fade-out at either end of the experiment. The sham stimulation condition consisted of a 30 s graded fade-in of 1 mA, followed by 30 s of stimulation at 1 mA, and a 30 s fade-out after which stimulation was terminated. This is believed to be an effective method of feigning stimulation because it gives a detectable initial sensation that is comparable to the often reported sensations of tDCS stimulation (Nitsche et al., 2008).

2.3. MOT task

MOT trials were generated using MATLAB (MathWorks, Natick, MA) and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997), and the experiment was programmed using E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). Participants were seated at an approximate viewing distance of 57 cm from a Samsung monitor measuring 52 cm × 32.5 cm. The size of the tracking display on the screen subtended 31° × 15° visual angle, and a 1° vertical midline separated this display into 2 separate tracking areas (one for each visual field) measuring 15° × 15° each. Participants were asked to fixate on a central 0.1° fixation point throughout the experiment, and to track target objects using covert attention. Fig. 1A shows the timeline of one trial. At the beginning of each trial the fixation point appeared alone on the screen for 1 s, following which 12 objects (6 per visual field frame) appeared all in blue for 1 s. The objects were circular dots subtending 0.6° in diameter. A subset of the dots (1–3 per visual field) then changed colour to red for 3 s, designating these as the targets required to track. We manipulated the bilateral load of targets



	Day 1	Day 2	Day 3
1	lPPC C / rPPC A	Sham	lPPC A / rPPC C
2	lPPC A / rPPC C	Sham	lPPC C / rPPC A

Fig. 1. (A) Timeline of an experimental trial showing a medium load (2+2) tracking trial with a left initial probe. After a 1s fixation screen, all objects appeared for 1s before target dots were assigned in red for 3s. Red targets then returned to blue, and all dots started moving within their separate visual field frames. After a 9s tracking period, a partial response was required, where one dot was probed in each visual field and the participant had to indicate whether it was a target or not. (B–D) Visualisation of the experimental design. Stimulation conditions involved simultaneous anodal/cathodal tDCS over bilateral posterior parietal cortex (PPC): P3 and P4 according to the international 10–20 system. While undergoing the bilateral multiple object tracking task participants received: (B) cathodal tDCS over the left PPC and anodal tDCS over the right PPC, and (C) anodal tDCS over the left PPC and cathodal tDCS over the right PPC. (D) Stimulation conditions were separated by a sham stimulation session, and the order of stimulation conditions (1,2) was counterbalanced across subjects (50% ran in reverse order). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

equally across visual field frames: one target in each visual field constituted the low load condition, two targets in each visual field constituted the medium tracking load, and three targets in each visual field constituted the high load condition. Following target-assignment, all dots returned to blue for 1 s. A 9 s tracking period followed, in which objects moved in smooth, straight movements at a speed of 6° per second, changing directions when coming within a lower limit of 1.6° of each other and the edges of the visual field frames. Following this, all objects stopped moving, one of the objects in one of the visual field frames was probed (turned to red) for 2.5 s, and the participant was required to indicate whether this probe was a target object or not with a forced choice 'yes' or 'no' keyboard response. The opposite visual field was then probed in the same manner. The order in which the two visual field probes appeared was counterbalanced. The target validity of the probes was also equal across all trials (50% valid). Although responses were given for both the left and the right visual field on all trials, only the first probe was utilised in the main analysis, since this is likely to more accurately reflect tracking ability. In contrast, a correct answer at the second probe probably also placed demands upon working memory that would present a confound in the data.

A total of 324 unique tracking trials were used throughout the experiment. All participants completed 36 practice MOT trials (12 for each of the 3 attentional load conditions) on each day of testing prior to receiving any tDCS stimulation, providing an assessment of learning effects over experimental days. Practice trials lasted a total of 12 min, following which the appropriate electrode configuration was applied prior to the main experimental trials. The main experiment consisted of a total of 72 tracking trials: 24 for each of the attentional load conditions. Stimulation lasted for the duration of the main experiment: a total of 24 min. Although eye-tracking data was not concurrently collected in the present tDCS experiment, we conducted a control experiment to assess whether participants were able to fixate centrally during the MOT task.

3. Results

All participants completed the protocol and were able to tolerate the stimulation comfortably. Most reported an itching sensation under the electrodes at stimulation onset, which became less noticeable as the experiment progressed. A subset of participants reported a feeling of 'hotness' under the electrodes, but this did not reach a level of discomfort so as to discontinue the experiment. One participant complained of a slight headache in the immediate aftermath, although this was following sham stimulation, which made use of established tDCS parameters to feign stimulation (Nitsche et al., 2008). Another participant reported fatigue lasting throughout the day after receiving stimulation at the first session.

3.1. Learning effects

As expected, repeated-measures ANOVA revealed that significant learning effects were evident across days in the study for both experimental orders in the practice trials, $F(1.67, 51.72)= 12.75$, $p<10^{-5}$, $\eta^2=0.3$ (Greenhouse–Geisser corrected), implying that task-based learning had taken place. This also held true during the experimental trials, $F(1.56, 48.47)=9.38$, $p=.001$, $\eta^2=0.23$ (Greenhouse–Geisser corrected). We corrected for learning effects by concatenating day 1 with day 3 from the two experimental orders, as well as day 3 with day 1 (see Fig. 1D). This yielded the constructed variable *tDCS manipulation* with three levels: *lPPC anodal/ rPPC cathodal*, *lPPC cathodal/ rPPC anodal*, and *sham*, which was the 2nd day concatenated from both experimental orders. To assess the effectiveness of counterbalancing the stimulation conditions, we performed a repeated-measures ANOVA with Greenhouse–Geisser correction on the practice trials. There was no significant effect of tDCS session upon performance accuracy in counterbalanced practice trials, $F(1.64, 50.96)=1.61$, $p=0.21$, indicating that, on a group level, the applied method of counterbalancing was sufficient in accounting for possible learning effects over the different days of the study.

3.2. tDCS effects

A repeated measures $3\times3\times2$ ANOVA was run with tDCS manipulation (left cathodal/right anodal; left anodal/right cathodal; sham), load (1+1; 2+2; 3+3 targets) and visual field of presentation for the first probe (i.e. the visual field tested immediately following tracking). As expected, there was a significant main effect of attentional load upon the overall tracking accuracy, $F(2, 62)=150.54$, $p<10^{-24}$, $\eta^2=0.83$. There was no significant main effect of tDCS stimulation upon overall tracking accuracy, $F(2, 62)=1.46$, $p=0.24$. However, our tDCS manipulation was found to significantly interact with tracking load, $F(4, 124)=6.90$, $p<10^{-5}$, $\eta^2=0.18$, indicating that the tDCS manipulation affected tracking accuracy differently across the different load conditions. There was an overall main effect of the visual field upon participant's ability to successfully track targets, $F(1, 31)=6.93$, $p=0.013$, $\eta^2=0.18$, showing a slight left visual field advantage (left M=0.78, SD=0.014; right M=0.75, SD=0.15). However, there were no significant interaction effects between visual field and tDCS manipulation, $F(2, 62)=1.87$, $p=0.16$, or between visual field and load, $F(2, 62)=1.88$, $p=0.16$, indicating that left tracking performance was higher irrespective of tDCS manipulation and load.

3.3. Load-dependent tDCS-effects

The significant interaction between load and tDCS manipulation upon tracking accuracy necessitated further analyses. Because there was no significant three-way interaction between load, tDCS manipulation, and visual field, $F(2.36, 73.22)=.01$, $p=0.94$ (Greenhouse–Geisser corrected), this indicates that tracking accuracy between the left and right visual fields did not differ across tDCS manipulation and load. We therefore averaged across visual field data prior to performing *t*-tests. 7 post-hoc tests were performed, and Bonferroni-corrected to a significance level of $p<0.0071$. Paired samples *t*-tests revealed a significant difference in accuracy scores between *lPPC cathodal/ rPPC anodal* stimulation ($M=0.59$, SD=0.13) and sham ($M=0.69$, SD=0.10) in the high load condition, $t(31)=-4.42$, $p<10^{-4}$, $d=0.78$. Similarly, a significant difference in accuracy was found between sham and *lPPC anodal/ rPPC cathodal* stimulation ($M=0.61$, SD=0.13) in the high load condition, $t(31)=-4.05$, $p<10^{-4}$, $d=0.72$. Thus, for both stimulation configurations the effect of stimulation led to a reduced performance in the high tracking load relative to sham, and accuracy in the two stimulation configurations was not significantly different ($p=0.65$; see Fig. 2). No effects of tDCS were observed on accuracy in the medium (*lPPC cathodal/ rPPC anodal* vs. sham, $p=0.41$; *lPPC anodal/ rPPC cathodal* vs. sham, $p=0.28$) or low loads (*lPPC cathodal/ rPPC anodal* vs. sham, $p=0.64$; *lPPC anodal/ rPPC cathodal* vs. sham, $p=0.78$).

3.4. Control analyses

To follow-up the lack of visual field interaction with tDCS further, we performed a repeated-measures ANOVA on tracking accuracy data averaged across active stimulation conditions only (i.e. discarding sham data). No significant interaction was seen between tDCS and visual field ($p=0.21$), also implying that tDCS did

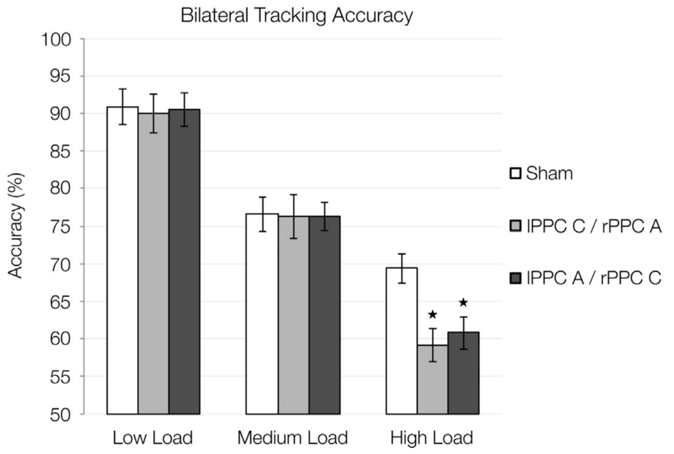


Fig. 2. Mean tracking accuracy across load conditions averaged between left and right visual fields. l/rPPC: left/right posterior parietal cortex; A: anodal; C: cathodal. Error bars represent standard error of the mean. * $p < 10^{-4}$ relative to sham (high load).

not modulate left and right visual field tracking accuracy differently. Finally, given the online stimulation design employed, we acknowledged that tDCS may need time to exert its effects upon tracking performance. After discarding the first 15 trials (5 min) from all data (including sham), no significant interaction was observed between visual field and tDCS ($p=0.07$), and the same significant interaction was observed between tDCS and load ($p=0.001$), confirming our main result.

3.5. *Control experiment*

As the present study investigated tDCS effects upon visual field tracking accuracy, it was important to assess whether any possible bias in fixation behaviour towards the left or right may have presented a confound. To this end, eye-tracking data was collected for 13 participants (4 females, mean age=28.1, SD=4.0) whilst performing the MOT task. Exclusion criteria were reliance upon and usage of glasses or contact lenses for close work. The stimuli, including viewing distance (~57 cm) and dimensions, were identical to the main experiment. Each participant completed a total of 36 trials: 12 per load condition (2, 4, and 6 targets). Stimuli were presented on a 22″ LCD Monitor (Del P2213 VGA) with a screen resolution of 1680 × 1050. Eye movement was recorded using a remote infrared eyetracking system (SMI RED®, SensoMotoric Instruments, SMI GmbH, Germany) at a sampling rate of 60 Hz, using iView X (SensoMotoric Instruments, SMI GmbH, Germany). During calibration, deviation was kept under 0.5°. Two areas of interest (AOI) were defined, covering the left and right tracking areas separately. A repeated-measures ANOVA revealed a significant main effect of load upon net dwell time (the sum of sample durations for all gaze data samples that hit the AOI) in each AOI, $F(2, 24)=4.93$, $p=0.02$. Importantly, we observed no significant main effect of hemifield, $F(1, 12)=2.97$, $p=0.11$, nor a significant hemifield * load interaction, $F(2, 24)=.079$, $p=.93$. Moreover, the average fixation deviation was found to be ~.60° from the fixation point. This is in correspondence with a recent and comparable data set (Alnæs et al., *unpublished results*), indicating that participants were indeed able to maintain a high degree of central fixation throughout the task.

4. Discussion

The main aim of this experiment was to investigate the interaction between tDCS and cognitive load upon sustained visual attention, as measured by performance accuracy in a multiple object tracking task. It was found that, under high cognitive load, tDCS of the bilateral PPC resulted in a significantly worsened attentional tracking performance relative to sham stimulation, irrespective of the bilateral configuration of electrodes. When subjects tracked just one or two targets in each visual field, no effects of tDCS were seen. This high-load detriment was observed in both visual fields; hence, visual field tracking performance was not modulated differentially by the stimulation polarity (anodal/cathodal) over the contralateral hemisphere. Thus, the effects of tDCS varied with the attentional demand placed upon subjects; only in a condition of high cognitive load did tDCS have a significant medium-to-large effect upon bilateral tracking performance, and this was in a negative direction relative to sham. Our results complement previous findings showing an interaction between task difficulty/ cognitive load and tDCS, and further extend them by investigating this interaction across a wider range of load levels whilst including a high load condition with the intention of overtaxing one's natural cognitive capacity to perform the task.

It has previously been shown that the overall attentional resources that can be allocated to a tracking task depend on the cumulative demands of each individual target object, which vary with certain task parameters (speed, object spacing etc.) (Alvarez and Franconeri, 2007). The current task made use of parameters that covered a wide range of difficulty levels, evidenced by accuracy scores during sham stimulation varying from 91% at the lowest attentional loads to 69% in the highest loads (with 50% guess-rate). Thus, the inclusion of the high load variation (3 targets in each visual field) allowed us to investigate the effects of tDCS upon attentional tracking when cognitive resources are already stretched. When bilateral tDCS was applied over the PPC, the high-load tracking accuracy of participants was reduced to a level that was just above chance performance, and this effect was not seen in the sham condition.

A recent meta-analysis of 52 tDCS studies found little evidence for an inhibitory effect of cathodal tDCS when applied during cognitive studies, which was attributed to the availability of compensatory mechanisms due to the widespread nature of neurocognitive networks (Jacobson et al., 2012). What happens, then, when cognitive networks are *unable* to compensate? It is an interesting possibility that during the low and medium load conditions employed in the present study, compensatory resources remained available in the tracking network, potentially explaining why no effect of tDCS was seen on tracking performance here. In contrast, during the high load condition, the cognitive demands of the task may have become increased to the point where the availability of compensatory resources became depleted, ultimately resulting in worse performance. This raises some intriguing questions. Perhaps studies failing to find tDCS-induced behavioural modulations may not have incorporated sufficiently demanding task conditions for tDCS to interact with ongoing cognitive processing. Indeed, we believe that an important feature of the present study is that it included an unusually demanding task condition designed to continually overtax cognitive capacity. We therefore suggest that systematically varying the load demands of a task is a potentially fruitful direction for future tDCS research, and could potentially provide new insights into compensatory principles in complex brain networks.

The present results are in line with a few previous studies showing that tDCS may exhibit differential effects during more demanding tasks. Previous research has shown that cathodal stimulation over MT+ (Antal et al., 2004b) and right PPC (Weiss and Lavidor, 2012), can improve visual perception and attention under higher cognitive load, respectively. Similarly, anodal stimulation over right DLPFC has been shown to increase one's executive ability to deal with motor interference in the most difficult tasks (backward memory recall; Wu et al., 2014). However, it is difficult to reconcile the present findings with results from unilateral stimulation designs. Indeed, our results go in the opposite direction, showing degraded performance during high cognitive loads. Since the above mentioned studies all document tDCS-induced improvements, we suggest the discrepancy could therefore have arisen as a result of the bilateral stimulation design employed in the current experiment. One can speculate that bilateral stimulation may have disturbed the optimal hemispheric balance during MOT by increasing excitability in one hemisphere while simultaneously decreasing excitability in the other. However, only when no cognitive resources were available to compensate for the imbalance (i.e. during high load), performance was reduced. This hypothesis could be tested in future studies including both unilateral and bilateral stimulation of the PPC during MOT.

The current results may also be in accordance with a few recent studies reporting that mainly low performing individuals will be affected by tDCS (Tseng et al., 2012; Hsu et al.Juan, 2014). That is, if low performers are under conditions of relatively higher cognitive load than high performers during the same task, then the interaction between individual ability and tDCS may well be compatible with an interaction between cognitive load and tDCS.

To our knowledge, only one study has previously reported an interaction effect between load and tDCS during a bilateral stimulation design (Sandrini et al., 2012). Sandrini et al. provided evidence for a double dissociation whereby left anodal / right cathodal PPC stimulation degraded performance (reaction time) in a 1-back task, while right anodal / left cathodal stimulation degraded performance during a 2-back task. However, as previous studies have shown that the relative amount of PPC activity between hemispheres is constant across load conditions during n-back tasks (Jonides et al., 1997), the results were attributed to different processing strategies interacting with tDCS. Although 2-back is more difficult than 1-back, evidence shows that they are somewhat qualitatively different (Lovett et al., 2000), and may therefore not reflect a purely parametric increase in cognitive load. Furthermore, the difference in error rate between 1-back and 2-back is often very low. No double dissociation was found in the present experiment, which we suggest was due to the qualitative similarity between load conditions in the MOT task. The MOT task in the current experiment utilised a wider range of difficulty levels, as evidenced by a wide variation in task accuracy across load conditions. Thus, we believe such an operationalisation of load is more suited to investigate the interaction between cognitive load and tDCS.

In the present study, no differential polarity effects were found upon visual field tracking performance. This is somewhat surprising, given that previous research has shown that unilateral non-invasive brain stimulation over PPC induces deficits in the contralateral visual field in attentional detection (Sparing et al., 2009) and tracking tasks (Battelli et al., 2009). However, the bilateral stimulation in the present experiment may have created a confound relating to the dominant role of the right PPC in attentional processing, indexing both visual fields (Corbetta et al., 1993; Heilman and Van Den Abell, 1980). Thus, the current design leaves open the possibility that separate anodal and cathodal stimulation could have led to different results. Future comparisons of unilateral and bilateral montages during a bilateral MOT task would help to shed more light on this issue.

Nevertheless, the current results consolidate previous correlational evidence for the role of PPC in covert attentional tracking (Howe et al., 2009), and converge with studies showing both contralesional deficits in attentional tracking in patients with right parietal lesions (Battelli et al., 2001), and induced contralateral deficits observed in healthy participants undergoing TMS over PPC (Battelli et al., 2009). Moreover, this study is the first to provide evidence for a tDCS-induced modulation of attentional tracking ability.

Since tDCS preferentially affected tracking accuracy at high attentional loads, we suggest that stimulation parameters likely interacted with the load-dependent state of neurons in the PPC. Indeed, the locations P3 and P4 (our stimulation sites) are close in proximity to the IPS within the borders of the PPC (Herwig et al., 2003), and the BOLD response exhibited in the IPS correlates positively with the attentional demands of a tracking task (Howe et al., 2009). As such, the load variations employed in the present study are likely to have elicited load-dependent variation in the activation state of neurons in the IPS, located under the stimulation area (Howe et al., 2009). Hence, tDCS exhibited an effect that was arguably dependent upon the activation state of neuronal populations in the PPC/ IPS. Crucially then, excitability manipulations brought on by tDCS may have had detrimental effects on MOT performance when neurons in the PPC were allegedly in their most active state, regardless of anodal / cathodal configuration. This is in line with a recent account of how non-invasive brain stimulation affects cognition (Miniussi et al., 2013); the noise induced by tDCS in cognitive networks will determine the behavioural outcome depending on the initial state of system, which is determined by the task input (load). The present results strengthen this hypothesis, since the state of the cognitive network was arguably modulated by the load condition. In addition, TMS studies have shown this neuronal state-dependency is a factor in determining the outcome from brain stimulation (for a review see Silvanto et al., 2008). As such, understanding the behavioural consequences of tDCS upon varyingly active neuronal states is of great interest in this field, particularly given the recent commercialisation of tDCS as a universal cognitive enhancement device aimed at the general population.

We chose a simultaneous bilateral tDCS design based on research demonstrating that the brain's hemispheres act independently of one another during a bilateral tracking task (Alvarez and Cavanagh, 2005; Battelli et al., 2009), and in light of studies demonstrating the usefulness of this approach (Fecteau et al., 2007; Mordillo-Mateos et al., 2012). Intriguingly, this experiment remained limited to a stimulation setting of 1 mA, yet found medium-large tDCS-induced effects upon cognitive performance. Because one study on attention found that higher current settings give greater modulatory effects (Moos et al., 2012), it is conceivable that boosting the current strength may have resulted in more extreme behavioural alterations than observed here, possibly also at lower loads. Future studies may benefit by altering current strength and observing the interaction with cognitive load.

In conclusion, it was found that bilateral tDCS over PPC conferred medium–to-large reductions in covert tracking accuracy at high attentional loads relative to sham, irrespective of the bilateral electrode configuration. Given the established load-dependent nature of key brain structures located under the stimulation site, we argue that this may be due to an interaction effect between the state of the cognitive network (as manipulated by cognitive load) and the excitability changes induced by tDCS. While this neuronal state-dependency hypothesis is becoming increasingly established within the field, we suggest that paradigms employing systematic manipulations of cognitive load, in addition to including sufficiently demanding task conditions, could provide useful lines of enquiry for the investigation of state-dependent effects of tDCS upon cognition.

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References

Alnæs, D., Sneve, M.H., Espeseth, T., Endestad, T., van de Pavert, S.H.P., Laeng, B., 2014. Pupil size signals mental effort deployed during multiple object tracking and predicts brain activity in the dorsal attention network and the locus coeruleus. J. Vis. 14 (4), 1. http://dx.doi.org/10.1167/14.4.1 –.

Alvarez, G.A., Cavanagh, P., 2005. Independent resources for attentional tracking in the left and right visual hemifields. Psychol. Sci. 16 (8), 637–643. http://dx.doi.org/10.1111/j.1467-9280.2005.01587.x.

Alvarez, G.A., Franconeri, S.L., 2007. How many objects can you track? Evidence for a resource-limited attentive tracking mechanism. J. Vis. 7 (4), 1–10. http://dx.doi.org/10.1167/7.13.14.

Antal, A., Nitsche, M.A., Kincses, T.Z., Kruse, W., Hoffmann, K.-P., Paulus, W., 2004a. Facilitation of visuo-motor learning by transcranial direct current stimulation of the motor and extrastriate visual areas in humans. Eur. J. Neurosci. 19 (10), 2888–2892. http://dx.doi.org/10.1111/j.1460-9568.2004.03367.x.

Antal, A., Nitsche, M.A., Kruse, W., Kincses, T.Z., Hoffmann, K.-P., Paulus, W., 2004b. Direct current stimulation over V5 enhances visuomotor coordination by improving motion perception in humans. J. Cognit. Neurosci. 16 (4), 521–527. http://dx.doi.org/10.1162/089892904323057263.

Battelli, L., Alvarez, G.A., Carlson, T., Pascual-Leone, A., 2009. The role of the parietal lobe in visual extinction studied with transcranial magnetic stimulation. J. Cognit. Neurosci. 21 (10), 1946–1955. http://dx.doi.org/10.1162/jocn.2008.21149.

Battelli, L., Cavanagh, P., Intriligator, J., Tramo, M.J., Hénaff, M.-A., Michèl, F., Barton, J.J.S., 2001. Unilateral right parietal damage leads to bilateral deficit for high-level motion. Neuron 32 (6), 985–995. http://dx.doi.org/10.1016/S0896-6273(01)00536-0.

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 Res. 1349, 76–89. http://dx.doi.org/10.1016/j.brainres.2010.06.053.

Brainard, D.H., 1997. The psychophysics toolbox. Spat. Vis. 10 (4), 433–436. http://dx.doi.org/10.1163/156856897X00357.

Cavanagh, P., Alvarez, G.A., 2005. Tracking multiple targets with multifocal attention. Trends Cognit. Sci. 9 (7), 349–354. http://dx.doi.org/10.1016/j.tics.2005.05.009.

Corbetta, M., Miezin, F.M., Shulman, G.L., Petersen, S.E., 1993. A PET study of visuospatial attention. J. Neurosci.: Off. J. Soc. Neurosci. 13 (3), 1202–1226.

Coffman, B.A., Clark, V.P., Parasuraman, R., 2014. Battery powered thought: enhancement of attention, learning, and memory in healthy adults using transcranial direct current stimulation. Neuroimage 85, 895–908. http://dx.doi.org/10.1016/j.neuroimage.2013.07.083.

Culham, J.C., Cavanagh, P., Kanwisher, N.G., 2001. Attention response functions: characterizing brain areas using fMRI activation during parametric variations of attentional load. Neuron 32 (4), 737–745. http://dx.doi.org/10.1016/S0896-6273(01)00499-8.

Fecteau, S., Pascual-Leone, A., Zald, D.H., Liguori, P., Théoret, H., Boggio, P.S., Fregni, F., 2007. Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making. J. Neurosci.: Off. J. Soc. Neurosci. 27 (23), 6212–6218. http://dx.doi.org/10.1523/JNEUROSCI.0314-07.2007.

Flöel, A., Rösser, N., Michka, O., Knecht, S., Breitenstein, C., 2008. Noninvasive brain stimulation improves language learning. J. Cognit. Neurosci. 20 (8), 1415–1422. http://dx.doi.org/10.1162/jocn.2008.20098.

Fregni, F., Boggio, P.S., Nitsche, M., Bermpohl, F., Antal, A., Feredoes, E., Paulus, W., 2005. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. Exp. Brain Res. 166 (1), 23–30. http://dx.doi.org/10.1007/s00221-005-2334-6.

Harbison, J., Atkins, S., Dougherty, M., 2011. N-back training task performance: analysis and model. Proc. Cognit. Sci. Soc. 2011.

Heilman, K.M., Van Den Abell, T., 1980. Right hemisphere dominance for attention: the mechanism underlying hemispheric asymmetries of inattention (neglect). Neurology 30 (3), 327–330. http://dx.doi.org/10.1212/WNL.30.3.327.

Herwig, U., Satrapi, P., Schönfeldt-Lecuona, C., 2003. Using the international 10–20 EEG system for positioning of transcranial magnetic stimulation. Brain Topogr. 16 (2), 95–99.

Hsu, T.Y., Tseng, P., Liang, W.K., Cheng, S.K., Juan, C.H., 2014. Transcranial direct current stimulation over right posterior parietal cortex changes prestimulus alpha oscillation in visual short-term memory task. NeuroImage 98, 306–313. http://dx.doi.org/10.1016/j.neuroimage.2014.04.069.

Howe, P.D., Horowitz, T.S., Morocz, I.A., Wolfe, J., Livingstone, M.S., 2009. Using fMRI to distinguish components of the multiple object tracking task. J. Vis. 9 (4). http://dx.doi.org/10.1167/9.4.10.

Jacobson, L., Koslowsky, M., Lavidor, M., 2012. tDCS polarity effects in motor and cognitive domains: a meta-analytical review. Exp. Brain Res. 216 (1), 1–10. http://dx.doi.org/10.1007/s00221-011-2891-9.

Jonides, J., Schumacher, E., Smith, E., Lauber, E., Awh, E., Minoshima, S., Koeppe, R., 1997. Verbal working memory load affects regional brain activation as measured by PET. J. Cognit. Neurosci. 9 (4), 462–475.

Jovicich, J., Peters, R.J., Koch, C., Braun, J., Chang, L., Ernst, T., 2001. Brain areas specific for attentional load in a motion-tracking task. J. Cognit. Neurosci. 13 (8), 1048–1058. http://dx.doi.org/10.1162/089892901753294347.

Kahneman, D., 1973. Attention and Effort. Prentice-Hall, Englewood Cliffs, NJ, p. 246.

Kuo, M.F., Nitsche, M.A., 2012. Effects of transcranial electrical stimulation on cognition. Clin. EEG Neurosci. 43 (3), 192–199. http://dx.doi.org/10.1177/1550059412444975.

Lovett, M.C., Daily, L.Z., Reder, L.M., 2000. A source activation theory of working memory: Cross-task prediction of perfomance in ACT-R. Cognit. Syst. Res. 1 (2), 99–118. http://dx.doi.org/10.1016/S1389-0417(99)00012-1.

Marshall, L., Mölle, M., Hallschmid, M., Born, J., 2004. Transcranial direct current stimulation during sleep improves declarative memory. J. Neurosci.: Off. J. Soc. Neurosci. 24 (44), 9985–9992. http://dx.doi.org/10.1523/JNEUROSCI.2725-04.2004.

Meinzer, M., Antonenko, D., Lindenberg, R., Hetzer, S., Ulm, L., Avirame, K., Flöel, A., 2012. Electrical brain stimulation improves cognitive performance by modulating functional connectivity and task-specific activation. J. Neurosci. 32 (5), 1859–1866. http://dx.doi.org/10.1523/JNEUROSCI.

Miniussi, C., Harris, J.A., Ruzzoli, M., 2013. Modelling non-invasive brain stimulation in cognitive neuroscience. Neurosci. Biobehav. Rev. 37 (8), 1702–1712.

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. J. Neurosci. 32 (46), 16360–16368. http://dx.doi.org/10.1523/JNEUROSCI.

Mordillo-Mateos, L., Turpin-Fenoll, L., Millán-Pascual, J., Núñez-Pérez, N., Panyavin, I., Gómez-Argüelles, J.M., Oliviero, A., 2012. Effects of simultaneous bilateral tDCS of the human motor cortex. Brain Stimul. 5 (3), 214–222. http://dx.doi.org/10.1016/j.brs.2011.05.001.

Nitsche, M.A., Cohen, L.G., Wassermann, E.M., Priori, A., Lang, N., Antal, A., Fregni, F., 2008. Transcranial direct current stimulation: state of the art 2008. Brain Stimul. 1 (3), 206–223. http://dx.doi.org/10.1016/j.brs.2011.05.001.

Nitsche, M.A., Fricke, K., Henschke, U., Schlitterlau, A., Liebetanz, D., Lang, N., Paulus, W., 2003. Pharmacological modulation of cortical excitability shifts induced by transcranial direct current stimulation in humans. J. Physiol. 553 (1), 293–301. http://dx.doi.org/10.1113/jphysiol.2003.049916.

Nitsche, M.A., Jakoubkova, M., Thirugnanasambandam, N., Schmalfuss, L., Hullemann, S., Sonka, K., Happe, S., 2010. Contribution of the premotor cortex to consolidation of motor sequence learning in humans during sleep. J. Neurophysiol. 104 (5), 2603–2614. http://dx.doi.org/10.1152/jn.00611.2010.

Nitsche, M.A., Paulus, W., 2000. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J. Physiol. 527 (3), 633–639. http://dx.doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x.

Nitsche, M.A., Paulus, W., 2001. Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. Neurology 57 (10), 1899–1901. http://dx.doi.org/10.1212/WNL.57.10.1899.

Ohn, S.H., Park, C.I., Yoo, W.K., Ko, M.H., Choi, K.P., Kim, G.M., Kim, Y.H., 2008. Time-dependent effect of transcranial direct current stimulation on the enhancement of working memory. Neuroreport 19 (1), 43–47. http://dx.doi.org/10.1097/WNR.0b013e3282f2adfd.

Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., Dan, I., 2004. Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10–20 system oriented for transcranial functional brain mapping. NeuroImage 21 (1), 99–111. http://dx.doi.org/10.1016/j.neuroimage.2003.08.026.

Pelli, D.G., 1997. The VideoToolbox software for visual psychophysics: transforming numbers into movies. Spat. Vis. 20 (4), 437–442. http://dx.doi.org/10.1163/156856897X00366.

Pylyshyn, Z.W., Storm, R.W., 1988. Tracking multiple independent targets: evidence for a parallel tracking mechanism. Spat. Vis. 3 (3), 179–197. http://dx.doi.org/10.1163/156856888X00122.

Sandrini, M., Fertonani, A., Cohen, L.G., Miniussi, C., 2012. Double dissociation of working memory load effects induced by bilateral parietal modulation. Neuropsychologia 50 (3), 396–402. http://dx.doi.org/10.1016/j.neuropsychologia.2011.12.011.

Silvanto, J., Muggleton, N., Walsh, V., 2008. State-dependency in brain stimulation studies of perception and cognition. Trends Cognit. Sci. 12 (12), 447–454. http://dx.doi.org/10.1016/j.tics.2008.09.004.

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 (11), 3011–3020.

Stagg, C.J., Nitsche, M.A., 2011. Physiological basis of transcranial direct current stimulation. Neuroscience 17 (1), 37–53. http://dx.doi.org/10.1177/1073858410386614.

Stone, D.B., Tesche, C.D., 2009. Transcranial direct current stimulation modulates shifts in global/local attention. Neuroreport 20 (12), 1115–1119. http://dx.doi.org/10.1097/WNR.0b013e32832e9aa2.

Tseng, P., Hsu, T.Y., Chang, C.F., Tzeng, O.J., Hung, D.L., Muggleton, N.G., Juan, C.H., 2012. Unleashing potential: transcranial direct current stimulation over the right posterior parietal cortex improves change detection in low-performing individuals. J. Neurosci. 32 (31), 10554–10561. http://dx.doi.org/10.1523/JNEUROSCI.0362-12.2012.

Utz, K.S., Dimova, V., Oppenländer, K., Kerkhoff, G., 2010. Electrified minds: transcranial direct current stimulation (tDCS) and galvanic vestibular stimulation

(GVS) as methods of non-invasive brain stimulation in neuropsychology – a review of current data and future implications. Neuropsychologia 48 (10), 2789–2810. http://dx.doi.org/10.1016/j.neuropsychologia.2010.06.002.

Weiss, M., Lavidor, M., 2012. When less is more: evidence for a facilitative cathodal tDCS effect in attentional abilities. J. Cognit. Neurosci. 24 (9), 1826–1833. http://dx.doi.org/10.1162/jocn_a_00248.

Wu, Y.J., Tseng, P., Chang, C.F., Pai, M.C., Hsu, K.S., Lin, C.C., Juan, C.H., 2014. Modulating the interference effect on spatial working memory by applying transcranial direct current stimulation over the right dorsolateral prefrontal cortex. Brain Cogn. 91, 87–94. http://dx.doi.org/10.1016/j.bandc.2014.09.002.

Zaehle, T., Sandmann, P., Thorne, J.D., Jäncke, L., Herrmann, C.S., 2011. Transcranial direct current stimulation of the prefrontal cortex modulates working memory performance: combined behavioural and electrophysiological evidence. BMC Neurosci. 12 (1), 2. http://dx.doi.org/10.1186/1471-2202-12-2.