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Transcranial Electrical Stimulation as a Tool to Enhance Attention

L. C. Reteig^{1,2,3} · L. J. Talsma^{1,2} · M. R. van Schouwenburg^{1,2} · H. A. Slagter^{1,2}

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Abstract Attention is a fundamental cognitive process—without it, we would be helplessly adrift in an overload of sensory input. There is considerable interest in techniques that can be used to enhance attention, including transcranial electrical stimulation (tES). We present an overview of 52 studies that have paired attention tasks with tES, mostly in the form of transcranial direct current stimulation (tDCS). In particular, we discuss four aspects of attention that have been most extensively targeted to date: visual search, spatial orienting (e.g., Posner cueing tasks), spatial bias (e.g., line bisection tasks), and sustained attention. Some promising results have been reported in each of these domains. However, drawing general conclusions about the efficacy of tES is at present hampered by a large diversity in study design and inconsistent findings. We highlight some pitfalls and opportunities and suggest how these may be addressed in future research aiming to use tES as a tool to enhance or test theoretical hypotheses about attention.

Keywords transcranial direct current stimulation (tDCS) · transcranial alternating current stimulation (tACS) · Cognition · Cognitive enhancement · Spatial attention · Neglect · Sustained attention

✉ L. C. Reteig
l.c.reteig@uva.nl

¹ Department of Psychology, University of Amsterdam, Nieuwe Achtergracht 129-B, 1018 WS Amsterdam, The Netherlands

² Amsterdam Brain and Cognition, University of Amsterdam, Nieuwe Achtergracht 129-B, 1018 WS Amsterdam, The Netherlands

³ PO Box 15915, 1001 NK Amsterdam, The Netherlands

Introduction

Attention—the ability to prioritize processing of goal-relevant information—underpins many of our daily behaviors. Attentional disturbances lie at the core of many psychiatric and neurological disorders, such as ADHD and hemineglect. It is therefore not surprising that attention has been a primary focus of cognitive enhancement techniques, ranging from pharmacological stimulants (Koelega 1993) to video games (Green and Bavelier 2012) and meditation training (Lutz et al. 2008).

The recent rediscovery of transcranial electrical stimulation (tES) has added another technique to the arsenal. tES comprises a family of methods in which a weak current is run between electrodes placed on the skin, partly passing through the skull and changing the excitability of the underlying brain tissue.

In transcranial direct current stimulation (tDCS)—the most widely used form of tES—the current flows in one direction: from the (positive) anode to the (negative) cathode. tDCS has been used to enhance a number of cognitive abilities (Cohen Kadosh 2014; Coffman et al. 2014; Mancuso et al. 2016; but see Horvath et al. 2015a).

While the neurophysiological mechanisms of tDCS remain to be fully uncovered (for reviews, see Stagg and Nitsche 2011, and Medeiros et al. 2012), its effects during stimulation are generally attributed to changes in the resting membrane potential of neurons. Anodal stimulation typically depolarizes the resting membrane potential, bringing neurons closer to their firing threshold, while cathodal stimulation generally decreases neuronal excitability (Nitsche et al. 2008). This finding is backed up by *in vitro* (Terzuolo and Bullock 1956), animal (Bindman et al. 1964), and human motor-evoked potential studies (Nitsche and Paulus 2000, 2001).

However, the anode-excitation and cathode-inhibition dichotomy is dependent on many factors and does not necessarily extrapolate to all cases (Bestmann et al. 2015; Jacobson et al. 2012; Parkin et al. 2015). Even very low-level factors can influence the precise neurophysiological effects of tDCS. For example, individual differences in the cortical folding pattern lead to differences in local current density (Opitz et al. 2015) and the orientation of neurons with respect to the electric field (Radman et al. 2009).

The effects of tDCS are not confined to the stimulation period, but can outlast it for minutes to hours, or even months after multiple stimulation sessions (Snowball et al. 2013), probably by promoting neural plasticity. These aftereffects appear to involve many different stages and effectors, but glutamate and GABA concentrations might play a central role (Stagg and Nitsche 2011). Anodal tDCS has been associated with increases in glutamate (Clark et al. 2011; Hone-Blanchet et al. 2016), while cathodal tDCS has been linked to decreases in both glutamate and GABA levels (Stagg et al. 2009). Because the immediate and aftereffects of tDCS involve such different neural mechanisms, studies that apply *online* stimulation (during a cognitive task) are not necessarily comparable to *offline* studies (where tDCS is applied before the task).

Instead of applying direct current, the polarity of the electrodes (anode or cathode) can also be switched at a certain frequency. This method, known as transcranial alternating current stimulation (tACS), effectively injects an oscillatory current into the brain that might entrain endogenous neural oscillations (Herrmann et al. 2013). As oscillations play an important role in cognitive processes (Buzsáki and Draguhn 2004; Siegel and Donner 2010), including attention (Buschman and Miller 2007; Womelsdorf and Fries 2007), tACS may offer a more specific means to affect attention. Finally, transcranial random noise stimulation (tRNS) applies a whole spectrum of frequencies at once (e.g., 0.1–640 Hz). tRNS is believed to enhance excitability and promote neuroplasticity under both electrodes (Antal and Herrmann 2016; Terney et al. 2008).

We aim to provide a comprehensive overview of studies conducted to date that used tES to modulate attention. After a systematic search and screening of the results, we included 52 studies. Details on our search query, inclusion criteria, and excluded studies are available on the Open Science Framework <https://osf.io/kqvap/>. A summary of the methods and results of the included studies is presented in the next sections and in Tables 1, 2, 3, and 4, clustered by the most frequently used types of tasks: visual search, spatial orienting, spatial bias, and sustained attention. Each of these tasks taps into distinct attentional processes that are relevant in different real-life situations. Our selection also included six studies that did not fit into one of these four categories (Table 5).

As our overview reveals, there is tremendous variability in design and stimulation parameters between studies, and in study outcome, hampering integration and interpretation of

different results. The scope of this review did not allow an extensive discussion of each study or differences between them. To remain as comprehensive as possible, we chose to catalogue the details of each study in the tables and to summarize the main conclusions in the body text. We hope that this way our review will prove useful to a broad audience—those looking for the gist as well as those interested in fine details, perhaps while preparing to set up a new experiment of their own. To this end, we also provide more general recommendations for future research in the “Discussion” section.

Visual Search

Whether you are looking for a particular pair of socks or crossing a busy intersection, the process of scanning the visual field is ubiquitous in daily life and therefore an interesting target for cognitive enhancement. We included 13 studies that examined the effects of tES on visual search (Table 1).

In visual search tasks, participants look for a target item among an array of distractors (Wolfe 1998). This involves keeping a template of the target online and shifting spatial attention across the visual field, while constantly filtering out distracting information. Faster reaction times on these tasks indicate more efficient visual search. Visual search performance is supported by an extensive network of brain areas, centered on the right posterior parietal cortex and frontal eye field (Reynolds and Chelazzi 2004).

Ball et al. (2013) investigated the effect of anodal and cathodal tDCS on both of these areas. They observed no effects of anodal tDCS, but cathodal stimulation to the right posterior parietal cortex increased reaction times, a finding later replicated by the same group (Ellison et al. 2014). Interestingly, an earlier study did find that anodal stimulation over the parietal cortex decreased search time (Bolognini et al. 2010a). As the studies differ in many design choices, it is difficult to tell what may account for these inconsistent results.

More recent studies suggest that stimulation effects on visual search depend on target location and distractor type. For example, whereas anodal tDCS may improve performance for targets contralateral to the stimulated hemisphere, it may worsen performance for ipsilateral targets (Reinhart and Woodman 2015). In another study, the effect of tDCS was contingent on the presence of a salient distractor: tDCS increased distractor resistance but did not improve visual search in general (Cosman et al. 2015).

Two other studies also observed effects specific to distractor processing. One study found that cathodal tDCS to the right parietal cortex increased the effect of task-irrelevant flanker stimuli on performance, specifically for difficult searches (Weiss and Lavidor 2012). Another study was unable to replicate this result, but found that in fact anodal tDCS decreased the flanker effect for easy searches (Kajimura and

Table 1 Studies using visual search tasks

Reference	<i>n</i>	Design	Stimulation	Size	Dosage	Timing	Task	Findings
Ball et al. (2013)	35	Between-group	rFEF (A, C), rPPC (A, C), left forehead (ref)	35 cm ²	1 mA, 15 min	Online	Visual search	Cathodal tDCS of rPPC increased reaction time
Ellison et al. (2014)	20	Within-subject	Right PPC (C), left forehead (ref)	35 cm ²	1.5 mA, 15 min	Offline	Visual search	Cathodal tDCS of rPPC increased reaction time
Bolognini et al. (2010a)	20, 12	Between-group	P3 (A) or P4 (A), contralateral shoulder (ref)	35 cm ²	2 mA, 30 min	Online, offline	Visual search	Left and particularly right anodal tDCS decreased reaction time
Reinhardt and Woodman (2015)	18, 18, 18	Within-subject	FCz (A), P2 (A), right cheek (ref)	19, 52 cm ²	2 mA, 20 min	Offline	Cued visual search	Parietal stimulation decreased (increased) reaction time to contralateral (ipsilateral) targets
Cosman et al. (2015)	18	Within-subject	F3 and F4 (A, C), contralateral cheeks (ref)	20, 50 cm ²	1 mA, 20 min	Offline	Visual search with distractor	No overall effect; anodal tDCS decreased negative effect of distractors on reaction time
Weiss and Lavidor (2012)	30, 20	Between-group	P4 (A, C), left forehead (ref)	16, 35 cm ²	1.5 mA, 15 min	Online	Visual search with flankers	No overall effect; cathodal tDCS increased flanker effect under high attentional load
Kajimura and Nomura (2015)	73	Between-group	P4 (A, C), AF7 (ref)	35 cm ²	1.5 mA, 20 min	Offline	Visual search with flankers	No overall effect; anodal tDCS decreased flanker effect under low attentional load
Kajimura et al. (2016)	52	Between-group	P4 (A, C), AF7 (ref)	35 cm ²	1.5 mA, 20 min	Offline	Visual search with flankers	No effects on accuracy (flanker effect not present in behavioral data)
Clark et al. (2012)	63, 12	Between-group	Near F10 (A), P4 (A), upper left arm (ref)	11 cm ²	2 mA, 30 min	Online	Concealed object detection	Anodal tDCS to frontal cortex increased accuracy after training more than sham; factor of 2 difference after 1-h retest
Coffman et al. (2012)	55	Between-group	Near F10 (A), upper left arm (ref)	11 cm ²	2 mA, 30 min	Online	Concealed object detection	Extension of Clark et al. (2012): effect replicated and stronger for repeated images with objects present
Falcone et al. (2012)	37	Between-group	Near F10 (A), upper left arm (ref)	11 cm ²	2 mA, 30 min	Online	Concealed object detection	Extension of Clark et al. (2012): effect replicated and retained for 24 h
Callan et al. (2016)	28	Between-group	P4 (A), left shoulder (ref)	38 cm ²	1 mA, 30 min	Online	Visual search	No difference in accuracy between anodal and sham conditions
Müller et al. (2015)	24	Between-group	Oz, Cz (alpha)	35 cm ²	Avg 0.76 mA, 20 min	Offline	Visual search	5 sessions of tACS improved accuracy for conjunction searches only

Studies are presented in order of appearance in the body text; studies not cited in the bottom section of the table (in alphabetical order). All studies were sham controlled. A anodal, C cathodal, *ref* location of tDCS electrode that was not of interest, FEF frontal eye field, PPC posterior parietal cortex, *Online* task performed during stimulation, *Offline* task performed after stimulation, *Dosage* zero-to-peak amplitude

Nomura 2015). These inconsistencies could be due to a difference in stimulation timing—Weiss and Lavidor (2012) applied online tDCS; Kajimura and Nomura (2015) stimulated offline—but otherwise these two studies used highly similar tasks and stimulation protocols.

The largest and most consistent effects of tDCS on visual search processes hail from a series of studies by Clark and colleagues. They found that learning to detect concealed threatening objects embedded in naturalistic scenes was greatly enhanced by anodal tDCS over the right inferior frontal cortex—up to a factor of 2 compared to sham stimulation (Clark et al. 2012). Subsequent studies replicated this effect (Coffman et al. 2012) and showed it is retained for at least 24 h (Falcone et al. 2012).

In conclusion, anodal tDCS over the right parietal cortex may speed up visual search, while cathodal stimulation may slow it down. However, results are inconsistent, may differ per hemifield, and appear restricted to particular aspects of visual search (e.g., salient distractors). Anodal stimulation over the right inferior frontal cortex has consistently shown to speed up object detection. Perhaps this success can be attributed to the challenging nature of the task: tES effects might be greatest for difficult tasks with plenty of room for improvement (e.g., Jones and Berryhill 2012). Because this task is more complex than the typical visual search paradigm, it could also be that tDCS affected other processes such as threat detection or scene perception, and not those underlying visual search per se.

Spatial Orienting

A second aspect of attention implicit in visual search is visuospatial orienting: the ability to allocate spatial attention to relevant parts of the visual field. Visuospatial orienting can be driven by a target stimulus itself (*stimulus-driven orienting*) or by spatial cues that prompt automatic (*exogenous*) or voluntary (*endogenous*) orienting towards or away from the upcoming target. In total, we identified 12 studies that evaluated tES effects on spatial orienting (Table 2).

Stimulus-Driven Orienting

The effects of tES on stimulus-driven orienting can be studied by stimulating the parietal cortex ipsi- or contralateral to a target stimulus. The assumption is that increasing the excitability of the contralateral hemisphere with anodal tDCS might shift attention towards the relevant visual field—thus improving accuracy or reaction times for target detection—while ipsilateral stimulation should have the opposite effect.

To test this, Bolognini et al. (2010b) briefly presented target stimuli either to the left or right part of the visual field concurrent with anodal tDCS to the right parietal cortex. Indeed,

they report a decrease in reaction time for targets presented in the left (contralateral), but not the right hemifield (ipsilateral). Likewise, contralateral target detection was also found to improve with anodal stimulation in another study (Sparing et al. 2009). However, Filmer et al. (2015) found diminished performance for both contralateral and bilateral stimuli following anodal tDCS. This discrepancy in findings is unexpected as the design of the latter two studies is quite similar, although both did employ fairly low-dosage stimulation.

Cathodal stimulation over the parietal cortex increased performance for ipsilateral targets (Sparing et al. 2009), but decreased performance for contralateral targets and also bilateral stimuli (Filmer et al. 2015; Sparing et al. 2009). Possibly, the representation of the ipsilateral stimulus is enhanced by cathodal stimulation, captures attention, and biases awareness to just that one stimulus.

Interestingly, tES might not affect orienting similarly in everyone. Learmonth et al. (2015) found no group effects of stimulation, but splitting their sample according to baseline performance revealed a weak impairment with anodal tDCS: both accuracy and reaction time worsened, but only in participants with already low baseline task performance.

To summarize, although some studies report unilateral modulations in the expected direction, the overall findings of studies were not consistent. Stimulation did not necessarily improve attention, but sometimes also led to decrements in one or both hemifields. Future studies could examine whether enhancing the excitability of both hemispheres at once with tRNS or two anodes is more effective and might circumvent these impairments.

Endogenous and Exogenous Orienting

Spatial cueing tasks, such as the classical Posner paradigm, can chart how spatial attention prior to stimulus presentation facilitates performance (Chica et al. 2014; Posner 1980). In the endogenous (or top-down) variant, attention is willfully directed to the left or right hemifield following a central cue. In exogenous (or bottom-up) orienting, attention is automatically drawn to a location in the left or right hemifield with a peripheral cue. On trials with valid cues, a target is presented at the cued location; on trials with invalid cues, the target is presented at the uncued location. While endogenous orienting is associated with activity in a more dorsal frontoparietal network, a mostly right-lateralized network of ventral frontal and parietal areas underpins exogenous orienting (Corbetta and Shulman 2002).

tDCS studies with Posner tasks have yielded markedly different results. Anodal tDCS to the right parietal cortex improved performance, but surprisingly for both valid and invalid endogenous cues (Bolognini et al. 2010a). A more recent study in which both hemispheres received opposite polarity stimulation did not identify any significant effect on

Table 2 Studies using spatial orienting tasks, with and without spatial cues

Reference	<i>n</i>	Design	Stimulation	Size	Dosage	Timing	Task	Findings
Stimulus-driven (no cues)								
Bolognini et al. (2010b)	48	Between-group	P4 (A), O2 (A), left shoulder (ref)	35 cm ²	2 mA, 15 min	Offline	Audiovisual target detection	Only right parietal tDCS decreased reaction time for contralateral targets
Sparing et al. (2009)	20	Within-subject	P3 (A, C) or P4 (A, C); Cz (ref)	25, 35 cm ²	1 mA, 10 min	Offline	Uni/bilateral target detection	Anodal tDCS facilitates contralateral target detection, cathodal diminishes contralateral/bilateral and increases ipsilateral performance
Filmer et al. (2015)	28	Within-subject	P3 (A, C) or P4 (A, C); Cz (ref)	25 cm ²	0.7 mA, 9 min	Offline	Uni/bilateral target detection	Right anodal tDCS decreased contralateral performance; anodal and cathodal decreased bilateral performance
Learmonth et al. (2015)	20	Within-subject	P3 (A) or P4 (A); contralateral forehead (ref)	25, 35 cm ²	1 mA, 15 min	Online	Target detection	Left anodal tDCS worsened accuracy and reaction time in both hemifields, but only for poor performers
Medina et al. (2013)	18	Within-subject	CP3 (A, C), CP4 (C, A)	25 cm ²	1.5 mA, 20 min	Online	Allocentric/egocentric detection	Concurrent right anodal/left cathodal tDCS speeded reaction times to stimuli with left gaps compared to right (allocentric effect)
Brignani et al. (2013)	96	Between-group	PO7 or PO8, Cz (6, 10, 25 Hz)	16, 35 cm ²	0.5 mA, 15 min	Online	Detection and discrimination	Improvements in detection performance occurring in sham condition were not present for 6 or 10 Hz tACS
Exo-/endogenous orienting (with cues)								
Bolognini et al. (2010a)	20	Between-group	P3 (A) or P4 (A); contralateral shoulder (ref)	35 cm ²	2 mA, 30 min	Online (different tasks)	Target detection, endogenous Posner	Right anodal tDCS decreased reaction times for valid, invalid, and no cue conditions
Li et al. (2015a)	18	Within-subject	P3 (A, C), P4 (C, A)	25 cm ²	2 mA, 30 min	Online	Endogenous Posner	No effect on reaction time
Roy et al. (2015)	24	Within-subject	F3 (A), left forehead (ref); P3 (A) or P4 (A), Cz (ref)	25, 35 cm ²	1.5 mA, 20 min	Offline	Attention network test	Right PPC stimulation increased reaction time after invalid trials (enhanced spatial orienting)
Coffman et al. (2012)	19	Between-group	Near F10 (A), left upper arm (ref)	11 cm ²	2 mA, 30 min	Online (different tasks)	Attention network test	Frontal anodal tDCS only improved alerting compared to sham, not orienting
Hopfinger et al. (2016)	23	Within-subject	P6, Cz (10, 40 Hz)	25, 35 cm ²	1 mA	Online	Endogenous and exogenous Posner	Gamma tACS decreased reaction time to invalidly cued targets (endogenous)
Laczó et al. (2012)	20	Within-subject	O1, Cz (40, 60, 80 Hz)	16, 28 cm ²	1.5 mA, 45 min	Online	Peripheral spatial cueing	60 Hz tACS lowered contrast thresholds, but no interaction with spatial cues

Studies are presented in order of appearance in the body text; studies not cited in the bottom section of the table (in alphabetical order). All studies were sham controlled
A anodal, C cathodal, *ref*/location of tDCS electrode that was not of interest, *IPS* intraparietal sulcus, *Online* task performed during stimulation, *Offline* task performed after stimulation, *Dosage* zero-to-peak amplitude

Table 3 Studies using spatial bias tasks, in healthy controls or neglect patients

Reference	n	Design	Stimulation	Size	Dosage	Timing	Task	Findings
Pseudoneglect (healthy controls)								
Lofus and Nicholls (2012)	30	Within-subject	P3 (A, C) or P4 (A, C), Cz (ref)	35 cm ²	1 mA, 20 min	Offline	Greyscales	Anodal tDCS of the left PPC abolished pseudoneglect (rightward shift in bias)
Giglia et al. (2011)	11	Within-subject	P5 (A), P6 (C); P6 (C), left forehead (ref)	16 cm ²	1 mA, 15 min	Online	Landmark task	Right cathodal and particularly left anodal + right cathodal tDCS abolished pseudoneglect
Benwell et al. (2015)	38	Within-subject	P5 (A, C), P6 (C, A)	16 cm ²	1 or 2 mA, 20 min	Online	Landmark task	Left anodal + right cathodal tDCS shifted bias rightward; low performers responded to 2 mA stimulation only; high performers to 1 mA only
Wright and Krekelberg (2014)	12	Within-subject	P3 (A), P4 (C)	ca. 50 cm ²	1 mA, 15 min	Online or offline	Centroid localization	Left anodal + right cathodal tDCS produced more rightward mislocalization compared to the opposite montage
Picazio et al. (2015)	13	Within-subject	Left cerebellum (A, C); left shoulder (ref)	25 cm ²	2 mA, 20 min	Offline	Landmark task	Cathodal tDCS to the left cerebellum abolished pseudoneglect, but only in combination with music listening
de Tommaso et al. (2014)	20	Within-subject	P3 (A), right forehead (ref)	35 cm ²	2 mA, 20 min	Offline	Line bisection, landmark	Stimulation decreased rightward errors in the landmark task, but only in men
Hemispacial neglect (patients)								
Sparing et al. (2009)	10	Within-subject	P3 (A, C), P4 (A), Cz (ref)	25, 35 cm ²	1 mA, 10 min	Offline	Test of Attentional Performance (neglect subtest), line bisection	No effect on neglect subtest. One session of anodal tDCS of the right or cathodal tDCS of the left hemisphere flipped rightward bias to left. Patients with small lesions showed a larger bias shift
Smit et al. (2015)	5	Within-subject	P3 (C), P4 (A)	–	2 mA, 20 min	Offline	Behavioral Inattention Test	No significant effects after 5 sessions
Brem, Fried, et al. (2014a, b)	1	Within-subject	P3 (C), P4 (A)	35 cm ²	1 mA, 20 min	Online	Test of Attentional Performance (incl. Posner), Behavioral Inattention Test (incl. line bisection)	1 stimulation session already decreased reaction time, mostly towards invalid left hemifield targets. Effect was retained 3 months later after 6 sessions in total
Ladavas et al. (2015)	30	Between-group	P5 (A/C) or P6 (A/C), contralateral forehead (ref)	35 cm ²	2 mA, 20 min	Online	Behavioral Inattention Test	Group with 10 sessions of right anodal tDCS improved more than sham when paired with prism adaptation training; the left cathodal group did not improve
Yi et al. (2016)	30	Between-group	P3 (C), P4 (A), Cz (ref)	25 cm ²	2 mA, 30 min	Offline	Motor-free visual perception, line bisection, star cancellation	15 sessions of both right anodal and left cathodal tDCS produced greater improvement on all tests than sham
Bang and Bong (2015)	12	Between-group	P3 (C), P4 (A), contralateral foreheads (ref)	35 cm ²	1 mA, 20 min	Offline	Motor-free visual perception, line bisection	15 sessions of tDCS paired with feedback training improved scores on all tests more than just feedback training
Ko et al. (2008)	15	Within-subject	P4 (A), left forehead (ref)	25 cm ²	2 mA, 20 min	Offline	Figure cancellation, line bisection	1 stimulation session decreased line bisection errors

Table 3 (continued)

Reference	<i>n</i>	Design	Stimulation	Size	Dosage	Timing	Task	Findings
Sunwoo et al. (2013)	10	Within-subject	P3 (C), P4 (A), contralateral foreheads (ref); P4 (A), right forehead (ref)	25 cm ²	1 mA, 20 min	Offline	Line bisection, star cancellation	1 session of right anodal and right anodal + left cathodal tDCS improved line bisection (latter more effective)
Turgut et al. (2016)	32	Between-group	P3 or P4 (C), P4 or P3 (A)	–	1.5–2 mA, 20 min	Online	Body orientation, clock drawing, apple cancellation, line bisection	8 sessions of tDCS paired with optokinetic training improved body orientation and clock drawing test (right lesions only) more than standard treatment

Studies are presented in order of appearance in the body text; studies not cited in the body text appear in the bottom section of the table (in alphabetical order). All studies were sham controlled, except Turgut et al. (2016) and Bang and Bong (2015)

A anodal, C cathodal, ref location of tDCS electrode that was not of interest, Online task performed during stimulation, Offline task performed after stimulation, Dosage zero-to-peak amplitude

performance (Li et al. 2015a). Using a more comprehensive version of Posner's paradigm that also measures alerting and executive attention—the attention network test (Fan et al. 2002)—Roy et al. (2015) found that anodal tDCS to the right parietal cortex decreased performance after invalid exogenous cues. Stimulation over the right inferior frontal cortex did not seem to affect orienting in the attention network test (Coffman et al. 2012), although here, participants did not perform the test until 1.5 h after stimulation offset.

Two studies so far have paired tACS with a spatial cueing task. Laczó et al. (2012) found that while 60 Hz (gamma-band) tACS over the visual cortex improved contrast perception, this effect was not modulated by exogenous spatial cues. A recent study found no effect on exogenous cues, but gamma tACS over the right parietal cortex did decrease reaction times following invalid, endogenous cues (Hopfinger et al. 2016).

In conclusion, whether preceded by a spatial cue or not, anodal tDCS to the right parietal cortex did not consistently enhance processing of left visual field stimuli. Several studies even found performance decreases (Filmer et al. 2015; Learmonth et al. 2015). Not a single study reported a benefit to the endogenous control of attention. Future studies should aim to replicate these (null) findings and explore different nodes of the top-down (e.g., the frontal eye fields) or bottom-up (e.g., the temporoparietal junction) attention networks (Corbetta and Shulman 2002).

Spatial Bias

A closely related line of studies has used tES to modify spatial biases in attention, both in the healthy and diseased brains. These studies capitalize on the finding that attention is not symmetrically distributed over the visual field. Most people exhibit *pseudoneglect*: they overemphasize features in the left versus the right hemifield (Jewell and McCourt 2000). This bias likely occurs because the right hemisphere is slightly more active than the left at rest, thus shifting attention towards the left visual hemifield. Spatial biases can be quantified with line bisection tests (Bowers and Heilman 1980), in which people typically bisect the line slightly towards the left. In contrast to the naturally occurring *pseudoneglect*, *hemispacial neglect* is a much more extreme bias that can occur in stroke patients. We identified 15 studies examining the effect of tDCS on both of these biases, which have produced relatively consistent results (Table 3).

Pseudoneglect

Loftus and Nicholls (2012) demonstrated that *pseudoneglect* can be reversed with anodal tDCS over the left parietal cortex.

Table 4 Studies using sustained attention tasks

Reference	<i>n</i>	Design	Stimulation	Size	Dosage	Timing	Task	Findings
Nelson et al. (2014)	19	Between-group	F3 (A, C), F4 (C, A)	35 cm ²	1 mA, 10 min	Online	Air traffic controller simulation	Both montages prevented time-on-task performance decline that occurred in sham group, when stimulation was started after 10 min (early group); not 30 (late group)
McIntire et al. (2014)	30	Between-group	F3 (A), right upper arm (ref)	10 cm ²	2 mA, 30 min	Offline	Mackworth Clock Test, Psychomotor Vigilance Task	When sleep deprived for 22 h, performance in tDCS group remained stable throughout the night compared to sham (accuracy in Mackworth and reaction time on PVT)
Li, Leech, et al. (2015a, b)	18	Within-subject	P3 (A), P4 (C)	25 cm ²	2 mA, 30 min	Online (CRT; RVP immediately after)	Choice Reaction Time, Rapid Visual Processing	Right anodal + left cathodal stimulation increased reaction time on CRT, only for short interval trials in the final block. Effect only present when compared to opposite montage, not sham
Axelrod et al. (2015)	45	Between-group	F3 (A), right forehead (ref); Oz (A), Cz (ref)	16, 35 cm ²	1 mA, 20 min	Online	Sustained Attention to Response Task	No effects on accuracy or reaction time, but frontal tDCS did increase mind wandering
Nieratschker et al. (2015)	41	Within-subject	F3 (C), right forehead (ref)	35 cm ²	1 mA, 20 min	Online	Parametric go/no-go	Cathodal tDCS decreased performance at medium task difficulty (response inhibition), only for Val/Val allele carriers of the COMT gene. No effects on reaction time
Plewania et al. (2013)	46	Within-subject	F3 (A), left forehead (ref)	35 cm ²	1 mA, 20 min	Online	Parametric go/no-go	Anodal tDCS decreased performance at highest task difficulty (set shifting), only for Met/Met allele carriers of the COMT gene. No effects on reaction time
Hsu et al. (2015)	39	Within-subject	F3 (A), Fp2 (ref)	45 cm ²	1 mA, 10 min	Offline	NeuroRacer [go/no-go task only]	No effects on accuracy (d') for the go/no-go task only, but tDCS did reduce multitasking costs
Miller et al. (2015)	8	Within-subject	AFz (A), under chin (ref)	35 cm ²	1 mA, 15 min	Offline	Go/no-go	No effects on accuracy or reaction time
Mauri et al. (2015)	14	Within-subject	FPz, Oz (100–640 Hz)	23 cm ²	2 mA, 81 bursts of 900 ms	Online	Continuous Performance Test	Stimulation decreased reaction time

All studies were sham controlled. Studies are presented in order of appearance in the body text; studies not cited in the body text appear in the bottom section of the table (in alphabetical order) A anodal, C cathodal, ref location of tDCS electrode that was not of interest, Online task performed during stimulation, Offline task performed after stimulation

Table 5 Studies using other attention paradigms (not discussed in the body text)

Reference	<i>n</i>	Design	Stimulation	Size	Dosage	Timing	Task	Findings
Bardi et al. (2013)	9, 12	Within-subject	P3 (A, C), P4 (C, A)	9 cm ²	1.5 mA, 20 min	Online	Local/global + salience	In exp. 1 (conditions blocked), right anodal/left cathodal stimulation increased inverse efficiency in local task and for salient targets. In exp. 2 (conditions varied trial-by-trial), the opposite montage produced the local effect, but no effect on saliency
Blumberg et al. (2015)	48	Between-group	CP4 (A), left upper arm (ref); F3 (A), right upper arm (ref)	11 cm ²	2 mA, 30 min	Online	Multiple object tracking	Anodal tDCS to the anterior intraparietal sulcus (CP4) improved high load MOT performance
London and Slagter (2015)	34	Within-subject	F3 (A, C), right forehead (ref)	35 cm ²	1 mA, 20 min	Online	Attentional blink	Anodal tDCS decreased attentional blink in low baseline performers; increased attentional blink in high baseline performers
Moos et al. (2012)	20	Within-subject	Right IPS (A, C); left forehead (ref)	36, 95 cm ²	1 or 2 mA, 20 min	Offline	Target partial report	2 mA cathodal reduced alpha parameter of Theory of Visual Attention model (in both hemifields), reflecting enhanced top-down control
Roe et al. (2016)	32	Within-subject	P3 (A, C), P4 (C, A)	35 cm ²	1.5 mA, 24 min	Online	Multiple object tracking	tDCS with both montages decreased high load MOT performance
Stone and Tesche (2009)	14	Within-subject	P3 (A, C), right lower arm (ref)	25 cm ²	2 mA, 20 min	Online	Local/global	No effect on local/global contrast feature discrimination. Anodal tDCS decreased performance on local-to-global switch trials after stimulation; cathodal tDCS decreased performance on all switch trials during stimulation

All studies were sham controlled, except London and Slagter (2015)

A anodal, C cathodal, *ref* location of tDCS electrode that was not of interest, *Online* task performed during stimulation, *Offline* task performed after stimulation

Presumably, tDCS increased the activity of the left parietal cortex beyond that of the right, causing a rightward shift in spatial bias. Similarly, Giglia et al. (2011) report a rightward shift for right cathodal tDCS (although note that Loftus and Nicholls (2012) did not find this). They furthermore observed that a “dual” montage with one electrode on each posterior parietal cortex (anode left; cathode right) was even more effective.

This dual montage effect was replicated with a larger sample, although the overall effect size was fairly small (Benwell et al. 2015). An exploratory analysis revealed that the effect was strongly modulated by individual differences: those who performed well at baseline responded only to weaker current intensity (1 mA); those who did poorly at baseline responded only to 2 mA tDCS. This pattern makes sense: those with a large bias to begin with likely had a more active right hemisphere at baseline, so higher intensity stimulation would be needed to tip the scales.

In conclusion, anodal tDCS to the left and cathodal tDCS to the right parietal cortex appear to shift spatial bias rightwards, though the effect could be subject to individual differences, which were also present in the other three studies (Table 3).

Hemispatial Neglect

Hemispatial neglect occurs most frequently following lesions of the right ventral parietal cortex (Vallar and Perani 1986). Neglect patients have difficulty to voluntarily orient attention to the visual hemifield contralateral to the lesion (Heilman et al. 2012) and thus exhibit a spatial bias to the ipsilateral hemifield (most often right). This bias is related to hypoactivity of the ipsilateral (right) parietal cortex and hyperactivity of the contralateral (left) parietal cortex (Corbetta et al. 2005). tES might be uniquely suitable to restore this interhemispheric imbalance by either increasing excitability of the lesioned hemisphere and/or inhibiting the non-lesioned hemisphere.

Nine studies have investigated this prospect to date, with promising results (Table 3). For example, Sparing et al. (2009) administered anodal tDCS to the right parietal cortex or cathodal tDCS to the left parietal cortex in neglect patients with right hemisphere lesions. Both protocols abolished the rightward bias in line bisection and produced a small leftward bias. Seven of the other studies also report some improvement after parietal tDCS, many on line bisection tasks.

Notably, one study did not find any effect of tDCS (Smit et al. 2015). Possibly this is due to their low sample size ($n = 5$)—a problem that plagues all these studies—or because their patients were in the later, chronic stage of stroke, when recovery is more difficult. Still, the null result by Smit et al. (2015) carries some weight, as their study was relatively well-designed: it included multiple patients, was sham-controlled,

and had multiple (five) stimulation sessions—only two other studies fit all these criteria (Làdavias et al. 2015; Yi et al. 2016).

Although promising, these initial results should therefore be interpreted with some caution. Moreover, follow-up tests are crucial to assess whether the stimulation effects have any long-term clinical value. Only Brem et al. (2014b) had a 3-month follow-up, but treated just a single patient. Still, the current findings warrant a large-scale clinical trial to determine the efficacy of tDCS for treatment of hemispatial neglect.

Sustained Attention

The final aspect of attention that multiple tES studies have targeted is sustained attention. In sustained attention paradigms, participants continuously monitor a stimulus stream for targets. Typically, after prolonged time-on-task, performance declines rapidly—the so-called vigilance decrement (Mackworth 1948; Parasuraman 1979). Finding ways to counter the vigilance decrement is especially pertinent given that these tasks mirror many real-life situations, such as air traffic control, surveillance, and quality control.

We found nine studies that examined effects of tES on sustained attention (Table 4). Nelson et al. (2014) report that the vigilance decrement could be prevented by applying bilateral tDCS to the dorsolateral prefrontal cortex early into a vigilance task. Prefrontal tDCS may also counter the effects of sleep deprivation on vigilance, to the same or greater extent than caffeine (McIntire et al. 2014). When bilateral stimulation was applied to parietal cortex, Li et al. (2015a) found that tDCS only affected performance on the final block of a reaction time task, but this effect reflected slower instead of faster reaction times.

Other studies that were not geared towards time-on-task effects have reported mixed results. For example, prefrontal tDCS did not affect performance on a sustained attention to response task, but did increase mind wandering (Axelrod et al. 2015). Two other studies employing a go/no-go task found that tDCS negatively affected performance, but only when increased demand was placed on inhibitory control (Nieratschker et al. 2015) and set shifting abilities (Plewnia et al. 2013). However, these effects were restricted to carriers of particular subtypes of the COMT gene, involved in regulation of dopamine levels. Still, this lends some support to the idea that tDCS effects are most apparent at higher levels of task difficulty. Similarly, Hsu et al. (2015) only found effects in a multitasking context, not when participants were performing a single task. These findings collectively suggest that prefrontal tDCS primarily affects higher-order processes involved in sustained attention, and not simple target detection per se.

In conclusion, while most studies found no or restricted effects on sustained attention, two studies report that prefrontal tDCS specifically offsets the vigilance decrement, suggesting that its effects may only become apparent after prolonged task performance. If replicated, it may be interesting for future studies to investigate the cognitive mechanisms at work: does tDCS allow fatigued individuals to tap into additional attentional resources, or do they simply become more motivated or less prone to mind wandering?

Discussion

Each of the four aspects of attention reviewed here harbors both promising results and many inconsistencies, such that compelling conclusions cannot be drawn at this point. Anodal stimulation to the right parietal and frontal cortex might speed up learning and reaction time in visual search, but robust results were only reported by one group for one particular visual search task (Clark et al. 2012; Coffman et al. 2012; Falcone et al. 2012). For spatial attention, parietal tDCS may enhance visuospatial processing, but many studies also reported null results or even performance decrements. Prefrontal tDCS may improve sustained attention by counteracting the performance decrements normally observed after prolonged time-on-task (Nelson et al. 2014; McIntire et al. 2014), but this effect remains to be replicated independently, and tDCS did not produce consistent effects in other sustained attention tasks. The most exciting and consistent results may be those showing that tDCS can shift spatial biases and thereby ameliorate symptoms in hemispatial neglect patients. However, even this field is not without its contradictory results, and it remains to be seen whether this effect stands up to well-controlled and larger clinical trials.

We proceed to discuss several factors that may contribute to the diversity in observed results. We also offer recommendations for future studies that may help resolve these inconsistencies and shed more definitive light on the ability to use tES to enhance attention. As effects of tES on other domains also appear less robust than initially thought (e.g., Horvath et al. 2015b; López-Alonso et al. 2014, 2015; Mancuso et al. 2016), our recommendations may also be of value to tES researchers in fields other than attention.

The large variability in stimulation parameters is one important factor that may explain the lack of consistent results—we rarely came across two studies that used the same protocol (Tables 1, 2, 3, 4, and 5). Electrode montage and stimulation intensity, duration, timing, and polarity alone offer a daunting number of degrees of freedom, and all of these parameters can greatly affect the outcome of stimulation. For instance, varying stimulation duration (Monte-Silva et al. 2013) or current intensity (Batsikadze et al. 2013) may completely flip the effect of tDCS between excitation and inhibition. Even the

order of sham and real tES sessions could potentially affect the outcome: tES may interact with practice-related improvements in task performance, for example, such that tES effects are less pronounced in later sessions. This remains a factor even if session order is counterbalanced between subjects.

Mostly, this review highlights a dire need for studies that more systematically explore the parameter space and for a mechanistic understanding of the neurophysiological effects of tES. To determine promising parameter combinations, direct replications are essential. Preregistration may also facilitate progress in the field, as a recent meta-analysis of tDCS and working memory found some evidence for selective reporting of positive results (Mancuso et al. 2016).

Future studies should also make an effort to increase power: some studies had particularly low sample sizes (fewer than 10 participants per group) or trial counts (fewer than 10 min of task performance), which do little to mitigate within- and between-subject variability. Indeed, several studies underlined that individual differences may shape the outcome of stimulation. Many factors could play a role here, ranging from differences in head and brain anatomy to gender and genetics (see Li et al. (2015b) and Krause and Cohen Kadosh (2014) for reviews). Differences in baseline brain state and cortical excitation/inhibition balance seem especially relevant (Krause et al. 2013), as they could explain why in some studies the effects of stimulation were contingent on baseline task performance (e.g., Learmonth et al. 2015; Benwell et al. 2015; London and Slagter 2015).

Recent studies have shown that even the influence of stimulation on motor-evoked potentials—the primary proof of tDCS efficacy in humans—is subject to high inter- (López-Alonso et al. 2014; Strube et al. 2016; Wiethoff et al. 2014) and intraindividual variability (Dyke et al. 2016; Horvath et al. 2015b; López-Alonso et al. 2015). The ultimate solution may be to tailor stimulation dosage and placement of electrodes to individual brains, but this requires sophisticated computational modeling efforts that are only just getting under way (Berker et al. 2013; Bikson et al. 2012).

Understanding the factors that drive tES responsiveness is absolutely crucial to the aim of cognitive enhancement. One cannot meaningfully speak of enhancement when a substantial portion of individuals shows no response or even a detriment. Potential costs to cognitive enhancement are often overlooked, but are a real possibility: enhancement of one cognitive function could be paired with a decline in another function (Brem et al. 2014a; Iuculano and Cohen Kadosh 2013; Sarkar et al. 2014), as the brain networks underlying cognitive functions do not operate in isolation (Wokke et al. 2015).

In the diseased brain, this principle may be exploited to return network function to the normal state. For instance, in hemispatial neglect, tDCS studies may restore the balance

between the overactive, non-lesioned hemisphere and the overinhibited, lesioned hemisphere. However, in the healthy brain, boosting one network function with tES may incur a cost to another network function. For example, while cathodal parietal tDCS enhanced attention to ipsilateral stimuli, it worsened performance for contralateral and bilateral stimuli (Filmer et al. 2015; Sparing et al. 2009). Similarly, an improved ability to focus attention in a top-down manner (e.g., on the road when driving) may hamper bottom-up attention to unexpected, albeit potentially relevant stimuli (e.g., a child next to the road).

To evaluate such costs, including control tasks that probe other cognitive abilities is essential (Parkin et al. 2015; Wokke et al. 2015). This is particularly important for multiple session tES studies, where both enhancements and costs may be larger and potentially longer lasting. Future research in this direction is imperative, as virtually nothing is known about the long-term effects of repeated tES on attention processes in the healthy brain, nor about its potential adverse effects.

Another important avenue for future research is to combine tES with neuroimaging techniques (Bergmann et al. 2016). Concurrent applications of tES with fMRI or M/EEG measurements are technically challenging but allow for more insight into the neurophysiology of tES and the relationship between baseline activity and tES effects. Moreover, neuroimaging may greatly inform the choice of stimulation parameters. Clark et al. (2012) determined the stimulation site based on a prior fMRI study, which may have contributed to the large and consistent effects they found. Similarly, prior M/EEG studies may aid in picking the most optimal stimulation frequency (van Driel et al. 2015). Future studies combining tACS with M/EEG are also necessary to determine if tACS—by synchronizing endogenous neural oscillations—may be particularly effective for enhancing attention.

Is transcranial electrical stimulation an effective tool to enhance attention? At present, it is too early to say. Although the initial findings are encouraging, they require replication and further study. However, the interest from society at large in tES is considerable and has grossly outpaced the state of the field. Informal surveys suggest that enhancement is the most common incentive for the growing use of tES at home, and that attention tops the list of enhancement purposes (Jwa 2015). A recent open letter signed by many leading tES experts commands utmost caution and highlights a long list of unknowns that preclude practical applications of tES for enhancement (Wurzman et al. 2016). We can only underscore that statement on the basis of this review and hope that our overview of current studies and recommendations for future research will help to determine the efficacy of tES for enhancing attention.

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