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Title

A High-Definition tDCS and EEG study on attention and vigilance: Brain stimulation mitigates the executive but not the arousal vigilance decrement

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Abstract

Attention comprises a wide set of processes such as phasic alertness, orienting, executive control, and the executive (i.e., detecting infrequent targets) and arousal (i.e., sustaining a fast reaction) vigilance components. Importantly, the effects of transcranial direct current stimulation (tDCS) over attentional functioning have been mostly addressed by measuring these processes separately and by delivering offline tDCS with low precision over the stimulation region. In the current study, we examined the effects of online High-Definition tDCS (HD-tDCS) over the behavioral and electrophysiological functioning of attentional and vigilance components. Participants ($N = 92$) were randomly assigned to one of three stimulation groups: right dorsolateral prefrontal cortex stimulation, right posterior parietal cortex (PPC) stimulation, and sham. All of them performed – in combination with the HD-tDCS protocol – an attentional networks task (ANTI-Vea) suitable to measure the executive and arousal components of vigilance along with three typical attentional functions: phasic alertness, orienting, and executive control. In addition, EEG was registered at the baseline and at the post-stimulation period. We observed that, regardless the stimulation region, online HD-tDCS: (a) reduced phasic alertness ($p = .008$), but did not modulated the orienting and executive control functioning; and (b) mitigated the executive vigilance decrement ($p = .011$), but did not modulated arousal vigilance across time-on-task. Interestingly, only HD-tDCS over PPC reduced considerably the increment of alpha power observed across time-on-task ($p = .009$). The current study provides further evidence for both an empirical dissociation between vigilance components and the cortical regions underlying attentional processes. We highlight the advantages of using online HD-tDCS to examine the stimulation effects on attentional and vigilance functioning.

Keywords: HD-tDCS; Executive Vigilance; Arousal Vigilance; Phasic Alertness; Orienting; Executive Control.

1. Introduction

27 There is a growing interest in using transcranial direct current stimulation (tDCS) to
28 modulate attentional functioning in healthy adults (Coffman et al., 2014; Dedoncker et al.,
29 2016; Reteig et al., 2017). In particular, tDCS is a non-invasive technique that delivers a
30 small (i.e., between 0.1 and 2.0 mA) intensity of anodal (i.e., positive current) or cathodal
31 (i.e., negative current) stimulation over a target region during a period of time usually no
32 longer than ~30 min, to produce a considerable shift in neurons excitability (Fertonani and
33 Miniussi, 2017). However, although recent studies have demonstrated that specifically anodal
34 tDCS does effectively reduce attentional failures in several daily life and work activities such
35 as driving (Sakai et al., 2014), remaining vigilant in air traffic control operations (Nelson et
36 al., 2014), or during multitasking activities in military environments (Nelson et al., 2016),
37 current evidence is inconsistent, and so the specific effects of anodal tDCS on attentional
38 performance in healthy adults still remain unclear (Coffman et al., 2012; Jacoby and Lavidor,
39 2018; Nelson et al., 2014; Roy et al., 2015).

40 In particular, attentional processes seem to be supported by three independent neural
41 networks, that may interact with each other (Petersen and Posner, 2012; Posner, 2012; Posner
42 and Dehaene, 1994; Posner and Petersen, 1990). The alerting network comprises the locus
43 coeruleus along with the right parietal and prefrontal cortices, a set of regions that underlie
44 both phasic alertness (i.e., a brief increment of arousal) and vigilance (i.e., the capacity for
45 sustaining attention over long time periods) (Posner, 2008). The posterior network involves
46 the pulvinar nuclei of the thalamus, the superior colliculus, the posterior parietal cortex
47 (PPC), and the frontal eye fields, and supports the attentional orienting towards potential
48 relevant sources for stimuli location (Posner, 2016). Finally, the anterior network includes the
49 dorsolateral prefrontal cortex (DLPFC) and the anterior cingulate gyrus, underlying executive
50 control processes to adapt our behavior to long term goals (Shenhav et al., 2013).

51 Interestingly, the effects of anodal tDCS on the attentional networks functioning have
52 been particularly investigated by using offline approaches, wherein participants received
53 tDCS at rest and then performed the attentional networks test (ANT) (Coffman et al., 2012;
54 Lo et al., 2019; Roy et al., 2015). In short, the ANT is a behavioral task that combines a
55 flanker paradigm, which is suitable to assess executive control, with warning signals and
56 spatial cues preceding the response stimuli, suitable to measure phasic alertness and the
57 orienting functioning, respectively (Fan et al., 2002). However, evidence regarding the effects
58 of anodal tDCS over the behavioral performance in the ANT task is both scarce and
59 ambiguous at best. For instance, 1.5 mA of tDCS during ~20 min over the right PPC
60 significantly improved (Lo et al., 2019) or showed partial effects (Roy et al., 2015) over the
61 orienting network; improvements on phasic alertness were observed only with 2.0 mA of
62 tDCS during ~30 min over the right prefrontal cortex (Coffman et al., 2012); and no
63 modulations over the executive control network were found by tDCS over right PPC (Lo et
64 al., 2019; Roy et al., 2015), right prefrontal cortex (Coffman et al., 2012), or both left PPC
65 and DLPFC (Roy et al., 2015).

66 Regarding vigilance, some effects of tDCS have been reported as a countermeasure
67 mitigating the performance decrement across time on task (Jacoby and Lavidor, 2018;
68 McIntire et al., 2017; Nelson et al., 2014; Roe et al., 2016). Note that, importantly, vigilance
69 has been traditionally assessed by long and monotonous tasks such as the Mackworth Clock
70 Test (MCT) (Mackworth, 1948) or the Psychomotor Vigilance Test (PVT) (Basner and
71 Dinges, 2011; Lim and Dinges, 2008) which, nevertheless, seem to assess two different
72 components of this function (Oken et al., 2006; Sarter et al., 2001). To better clarify the
73 different behavioral patterns between vigilance components, in the present study we would
74 refer to them as executive and arousal vigilance, following a terminology we have recently
75 proposed (Luna et al., 2018).

76 Thus, on the one hand, the MCT measures a more executive component of vigilance,
77 which can be conceived as a cognitive ability for sustaining attention over extended periods
78 of time to monitor and detect infrequent critical signals by selecting and executing a specific
79 response over stimuli (Warm et al., 2008). In this vein, Nelson et al. (2014) found that 1.0
80 mA of 10 min online tDCS over the left DLPFC effectively helps to sustain participants'
81 target detection hits rate across time on task, in contrast to the typical decrement observed
82 with sham tDCS. On the other hand, the PVT seems to assess an arousal component of
83 vigilance, understood as the behavioral responsiveness of the arousal levels of attention for
84 sustaining a fast reaction to stimuli from environment over long time periods without
85 implementing much control over responses, a performance usually affected by sleep
86 deprivation (Drummond et al., 2005; Lim and Dinges, 2008). In this sense, after 24 hours of
87 extended wakefulness, 2.0 mA tDCS during ~30 min facilitated a fast reaction time on the
88 PVT in the following six hours, but did not reduce the percentage of lapses (i.e., responses
89 slower than 500 ms), as compared to sham tDCS (McIntire et al., 2014).

90 Note that the shifts on vigilance performance across time on task seems to correspond
91 with changes in the electrical cortical rhythms (Clayton et al., 2015). In particular, an
92 increment in the alpha band power has been positively associated with psychophysiological
93 states of decreased alertness, as sleep or mental fatigue (Oken et al., 2006). Indeed, Boksem
94 and colleagues found that the vigilance decrement observed in a signal detection task was
95 significantly accompanied by a progressive increment in lower-alpha frequencies (7.5-10 Hz)
96 in the PPC, an effect that was marginal in upper-alpha frequencies (10-12.5 Hz) (Boksem et
97 al., 2005).

98 **1.1. The current study**

99 The present research was motivated by the scarce and inconsistent evidence observed
100 in the literature regarding the precise effects of anodal tDCS on the attentional networks in
101 healthy adults. Therefore, our main goal was to further analyze whether (and how) anodal
102 tDCS effectively modulates attentional and vigilance components functioning. To this end,
103 we decided to jointly investigate the stimulation effects in two core regions of the attentional
104 networks system: the right PPC and the right DLPFC (Petersen and Posner, 2012; Posner,
105 2012). Importantly, to address the effects of anodal tDCS on several attentional and vigilance
106 components, we used a novel version of the ANT, i.e., the Attentional Networks Test for
107 Interactions and Vigilance – executive and arousal components (ANTI-Vea); a task that is
108 suitable to assess –simultaneously and in a single session–, the independence and interactions
109 of phasic alertness, orienting, and executive control, along with the executive (EV) and
110 arousal vigilance (AV) decrement across time on task (Luna et al., 2018).

111 Regarding the stimulation procedure, with the aim of increasing the precision on the
112 cortical region wherein current is delivered, we used a High-Definition tDCS (HD-tDCS)
113 protocol, which is suitable to focus transcranial stimulation by surrounding the anodal
114 electrode with a ring of cathodal ones (Datta et al., 2009; Kuo et al., 2013). Furthermore, to
115 examine whether anodal stimulation is an effective tool to modulate the vigilance decrement
116 phenomenon, our main interest relied in examining the acute effects of neurons excitability
117 during behavioral assessment, and not the long-lasting effects of stimulation related to
118 neuroplasticity mechanisms (Fertonani and Miniussi, 2017; Yavari et al., 2018). Thus, HD-
119 tDCS was administered while participants performed the ANTI-Vea task and not offline, at
120 difference to previous studies with the ANT (Coffman et al., 2012; Lo et al., 2019; Roy et al.,
121 2015) or vigilance tasks (Jacoby and Lavidor, 2018; McIntire et al., 2017, 2014). Finally, to

122 inspect whether HD-tDCS modulates the alpha band across time on task, we contrasted alpha
123 power before and after delivering HD-tDCS in the right PPC or DLPFC.

124 **2. Material and methods**

125 **2.1. Participants**

126 Ninety-two healthy volunteers from the University of Granada participated in the
127 experiment. They had normal or corrected to normal vision, were tested prior to the
128 experiment for exclusion criteria (Rossi et al., 2011), signed an informed consent, and
129 received monetary compensation (10 Euros/hour). The study was conducted according to the
130 ethical standards of the 1964 Declaration of Helsinki (last update: Seoul, 2008), and was part
131 of a larger research project positively evaluated by the University of Granada Ethical
132 Committee (536/CEIH/2018).

133 Participants were randomly assigned to one of three groups: HD-tDCS over the right
134 PPC ($n = 32$, 24 women, age: $M = 22.09$, $SD = 3.59$), HD-tDCS over the right DLPFC ($n =$
135 30 , 20 women, age: $M = 23.70$, $SD = 4.28$), and sham HD-tDCS, with half of participants
136 being sham-stimulated over the right PPC ($n = 15$, 10 women, age: $M = 23.20$, $SD = 3.23$),
137 and the other half over the right DLPFC ($n = 15$, 9 women, age: $M = 23.87$, $SD = 3.79$).

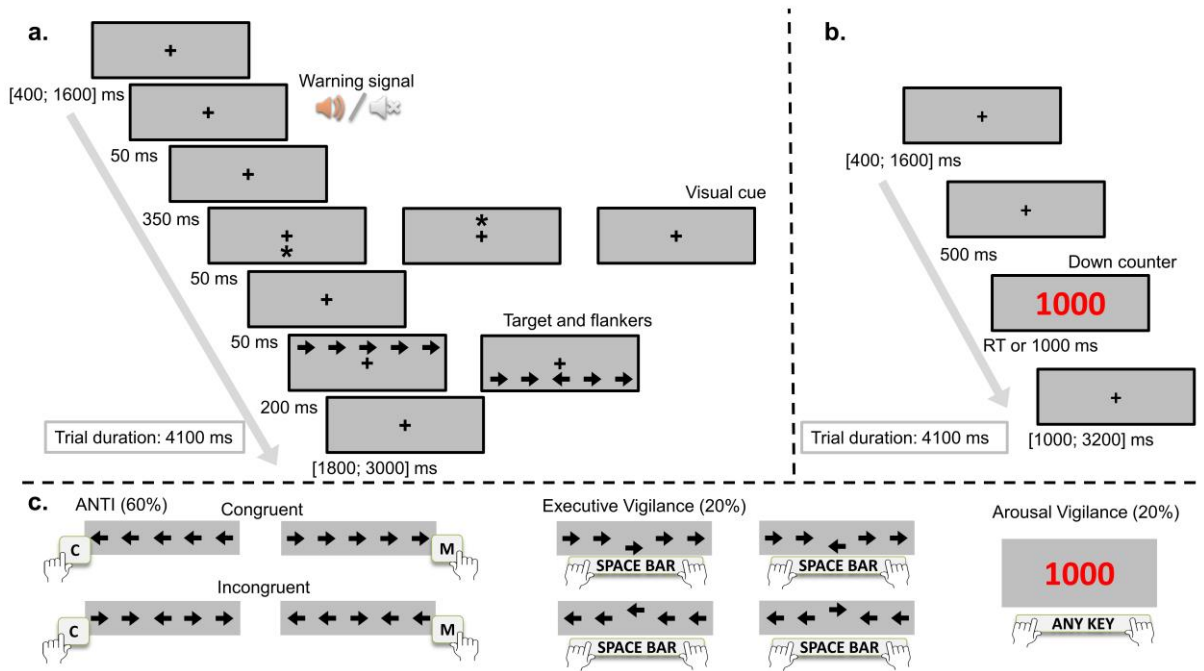
138 Using G*Power 3.1.9.4 (Faul et al., 2007), we conducted power analyses to determine
139 whether the used sample size was enough to observe a reliable modulation of vigilance
140 performance across time on task by the stimulation procedure (i.e., a within-between
141 interaction). Sensitivity analysis demonstrated that considering $\alpha = .05$ and $1 - \beta = .80$, the
142 minimum effect size detectable should be of $f = .193$, which is indeed an effect size smaller
143 than the one observed for the interaction reflecting the modulation of stimulation group over
144 the decrease of hits across blocks (i.e., $f = 0.204$ or $\eta_p^2 = .04$; see section 3.2). Thus, post hoc

145 analysis showed that given an effect size of $f = 0.204$ and $\alpha = .05$, the sample size was enough
146 to observe a within-between interaction with a power of $1 - \beta = .85$.

147 **2.2. Behavioral assessment: ANTI-Vea**

148 The task includes three different types of trials (i.e., ANTI, EV, and AV). The stimuli
149 sequence, procedure, and correct responses for each type of trials are depicted in Fig. 1, and
150 are described in detail in Luna et al. (2018b). The ANTI trials (see Fig. 1) follows the
151 procedure of the ANTI task (Callejas et al., 2004). Participants had to respond to the direction
152 pointed by a central arrow (i.e., the target), while ignoring the surrounding flanking arrows.
153 In short, to assess the executive control functioning, the target could point a congruent or
154 incongruent direction with regards to the flanking arrows. For measuring the phasic alertness
155 functioning, an auditory warning signal could anticipate the target appearance in half of these
156 trials, whereas no warning signal was presented in the other half. To assess the orienting
157 functioning, the arrows position could be predicted either by a valid (i.e., the same location)
158 or invalid spatial cue, or by no cue at all.

159 The EV trials had the same procedure as the ANTI, except that the target was
160 displaced (i.e., 8 pixels –px–) from its central position either upwards or downwards (see Fig.
161 1), and participants had to remain vigilant to detect these displaced targets, while ignoring in
162 these cases the direction the target pointed to –a task similar to the MCT (Mackworth, 1948)
163 –. Lastly, in the AV trials, no warning signal nor visual cue appeared before the response’
164 stimuli, and participants were instructed to stop a millisecond down counter as fast as
165 possible by pressing any available key from the keyboard (see Fig. 1), thus performing a task
166 similar to the PVT (Lim and Dinges, 2008).



167

168 **Fig. 1.** Stimuli and trials for the ANTI-Vea task. Top panels shows the stimuli sequence for
 169 (A) ANTI and executive vigilance trials, and (B) arousal vigilance trials. Panel (C) shows the
 170 proportion and correct responses for each ANTI, executive vigilance, and arousal vigilance
 171 trials.

172 Instructions encouraged participants to keep the gaze at every moment on the fixation
 173 point ('+'), which appeared all time in the center of the screen (see Fig. 1). Note that the three
 174 type of trials were randomly presented within each experimental block, so that participants
 175 had to keep in mind instructions to perform the three type of tasks at the same time. In the
 176 largest proportion of trials (i.e., the ANTI trials; 60%), the target and flanking arrows could
 177 appear above or below the fixation point and could be preceded by the warning signal and/or
 178 visual cue. In these cases, participants had to respond to the direction pointed by the target
 179 with the left or the right hand (see Fig. 1, panel c). The EV trials (20%) followed the same
 180 stimuli sequence than the ANTI ones, except that the target appeared largely displaced either
 181 upwards or downwards from its central position. Here, participants had to respond to the
 182 displacement with a different response key, ignoring in these cases the direction the target

183 pointed to (see Fig. 1, panel c). In the AV trials (20%), no warning signal nor visual cue was
184 presented (as in some of the ANTI and EV trials, i.e., those with no tone nor visual cue), and
185 the response' stimulus (i.e., the down counter) appeared in the center of the screen until
186 participants' response (see Fig. 1, panel c).

187 **2.3. Stimulation protocols and EEG recording**

188 **2.3.1. Apparatus.**

189 HD-tDCS procedure and EEG signal recording were controlled with a Starstim® 8
190 channels wireless system, integrated with the NIC 2.0.10 software application
191 (Neuroelectronics®, Barcelona, Spain). Five hybrid tCS/EEG PiStim (2 cm diameter,
192 containing a sintered Ag/AgCl pellet of 12 mm, and ~3.14 cm² of contact area) and three
193 standard EEG Geltrode (12 mm diameter, ~1 cm² of contact area) circular electrodes were
194 placed over a neoprene headcap with 39 positions based on the International 10-10 EEG
195 system. Electrical reference channels were connected to an EarClip electrode placed over the
196 right earlobe.

197 **2.3.2. HD-tDCS procedure.**

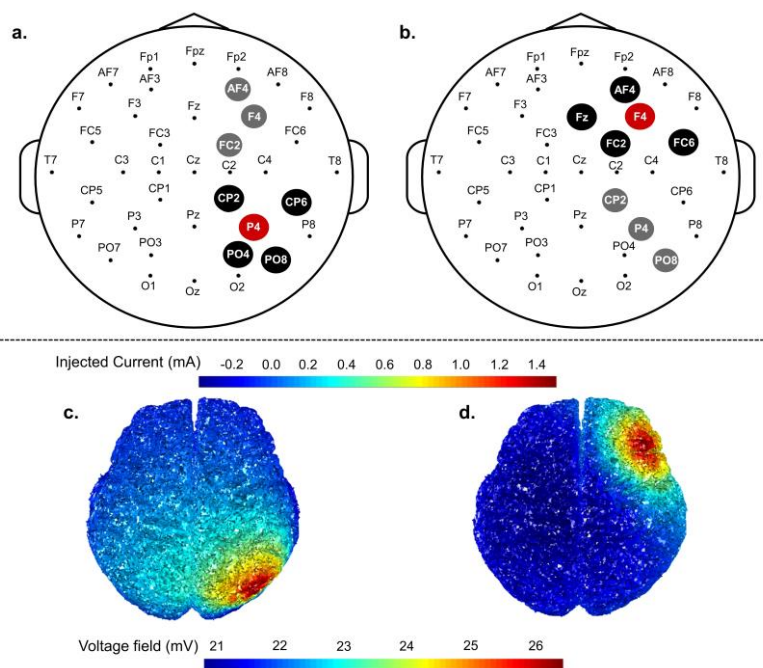
198 Electrodes were placed in one of two possible montages: right PPC or right DLPFC
199 (see Fig. 2). Anodal (1.5 mA) or sham (0 mA) HD-tDCS was used respectively depending on
200 the group. In all conditions (real/sham HD-tDCS) we used a 30 sec of ramp up/ ramp down.
201 Electrodes position, and the voltage field (simulated with ROAST; Huang et al., 2019) for the
202 stimulation protocols are depicted in Fig. 2.

203 **2.3.3. EEG data acquisition and pre-processing.**

204 In all groups, EEG signal was recorded in channels CP2, P4, PO8, AF4, F4, FC2 (see
205 Fig. 2) along the experiment, although only data from the baseline and post-stimulation block

206 were analyzed. Signal was registered with a sampling rate of 500 Hz, a bandwidth of 0 to 125
207 Hz, and a notch filter (50 Hz).

208 EEG data pre-processing was conducted with EEGLAB v14.1.1 toolbox on
209 MATLAB R2016a. Data format was first converted to the EEGLAB format with the NE
210 EEGLAB NIC plugin. To avoid ramp up and down noise effect, analyses were restricted to
211 the first 4:30 min in the baseline block and the last 4:30 min in the post-simulation block. In
212 addition, signal was decomposed using Independent Component Analysis and reconstructed
213 excluding blinks. Frequency filters were set at 0.5 Hz (high pass) and 45 Hz (low pass).
214 Lastly, mean alpha power (i.e., squared signal filtered between 7.5-12.5 Hz) was computed
215 both for the baseline and post-stimulation block.



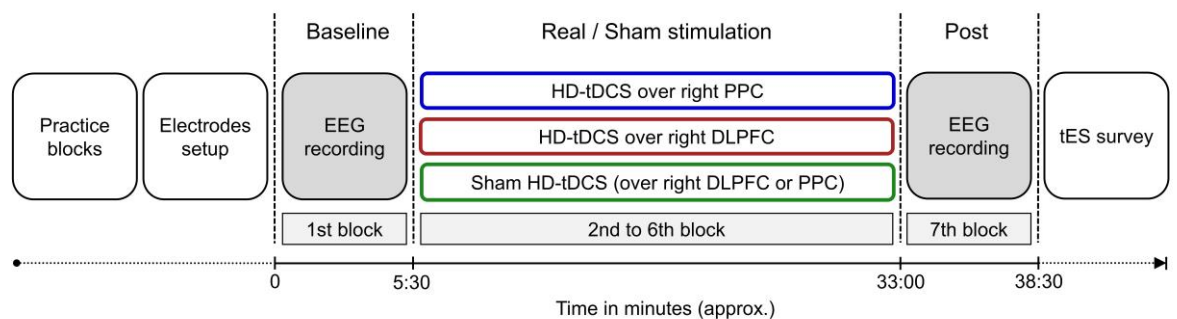
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217 **Fig. 2.** Electrodes setup and voltage field simulation. The superior panel shows the electrodes
218 setup for (a) HD-tDCS and sham procedures over the right PPC, and (b) the HD-tDCS and
219 sham procedures over the right DLPFC. Electrodes in red delivered anodal (1.5 mA) current
220 in HD-tDCS conditions, and the black electrodes were set as the return ones. Gray electrodes
221 only registered EEG signal. In addition, in the setup shown in (a), CP4, P4 and PO8 also

222 registered EEG at baseline and post stimulation periods, and in the setup shown in (b), AF4,
 223 F4, and FC2 registered EEG at baseline and post stimulation periods. The inferior panel
 224 shows the simulation of voltage field for (c) HD-tDCS in right PPC and (d) HD-tDCS in right
 225 DLPFC.

226 2.4. Procedure

227 Participants received first the usual specific instructions and practice trials of the
 228 ANTI-Vea task by Luna et al. (2018b). Then, they completed seven experimental blocks
 229 without any pause or feedback, with 80 randomly presented trials in each of them (48 ANTI,
 230 16 EV, and 16 AV). The experimental blocks were divided in three phases: baseline,
 231 real/sham stimulation, and post-stimulation (see Fig. 3). At the end of the session,
 232 participants completed the Survey of Sensations related to transcranial electrical stimulation
 233 (tES)² (Fertonani et al., 2015).



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² Anticipating results from tES, groups did not differ in the self-report of discomfort feelings: all χ^2 comparisons were not significant (all $ps > .200$). In addition, groups did not differ in the perception that discomfort feelings affected their performance [$\chi^2(4) = 9.23, p = .055$], neither in the guessing to the group they belonged to [$\chi^2(4) = 2.68, p = .612$].

235 **Fig. 3.** Session structure. Experimental blocks comprised three different periods: baseline, real
236 or sham stimulation, and post-stimulation.

237 **2.5. Statistical Analyses**

238 **2.5.1. Behavioral data.**

239 Two participants were excluded due to technical problems during data acquisition. In
240 all the analyses, the stimulation procedure was included as a between-participants factor with
241 the following groups: PPC HD-tDCS ($n = 31$), DLPFC HD-tDCS ($n = 29$), and sham HD-
242 tDCS ($n = 30$).

243 Data from the ANTI trials were analyzed only for the 2nd to 6th block (i.e., during the
244 real/sham stimulation period). In addition, trials with incorrect responses (4.37 %), or with
245 reaction times (RT) below 200 ms or above 1500 ms (1.26 %) were excluded from the RT
246 analysis. Two mixed ANOVAs were conducted, with RT or the percentage of errors as
247 dependent variable, and including warning signal (no tone/tone), visual cue (invalid/no
248 cue/valid), and congruency (congruent/incongruent) as within-participants factors.

249 To analyze the shifts of vigilance components across time on task, the EV and AV
250 measures were computed per block of trials from the 1st (i.e., baseline) to the 6th block. In
251 the EV trials, we computed the hits (i.e., correct responses on EV trials) and false alarms (FA,
252 i.e., space bar responses in the ANTI trials) rate, and non-parametric indexes of sensitivity
253 (A') and response bias (B'') (Stanislaw and Todorov, 1999). With the aim to avoid that a floor
254 effect in the FA could mask a considerable shift in the response bias (Thomson et al., 2016),
255 only some ANTI trials were used to compute FA following the method developed by Luna et
256 al. (Unpublished results). In particular, we categorized off-line the ANTI trials as a function
257 of the vertical distance between the position of the target and the closest adjacent flanker, to
258 select only those trials wherein there was a higher chance to observe a FA. Note that, in the

259 ANTI-Vea task, the target and distractors are presented with a random variability on its
260 position (i.e., ± 2 px both upwards/downwards and leftwards/rightwards), thus making more
261 difficult the detection the large displacement of the infrequent target in the EV trials (wherein
262 the target is fixed and displaced 8 px, either upwards/downwards). Therefore, the FA rate was
263 computed only considering those trials in which this distance was between 3 and 4 px, and
264 the trials wherein this distance was between 0 and 2 px were excluded from EV analyses.

265 The analysis of the EV decrement included four mixed ANOVA, with hits, FA, A',
266 and B'' as dependent variables, and blocks (1st to 6th) as a within-participant factor. For the
267 AV trials, the mean and SD of RT were included as dependent variables in the two mixed
268 ANOVA, with blocks (1st to 6th) as within-participant factor. Post-hoc analyses for
269 inspection of HD-tDCS modulations over the EV or AV performance included a one-way
270 ANOVA for the baseline data, and then comparisons to determine the significance of the
271 linear component across blocks.

272 **2.5.2. EEG data.**

273 Five participants were additionally excluded either due to technical connection issues
274 during data acquisition (three from the PPC HD-tDCS group) or EEG signal quality (two
275 from the DLPFC HD-tDCS group). Alpha power was analyzed in a mixed ANOVA with
276 group as between-participants factor, and period (baseline/post-stimulation) and region
277 (parietal – the average of CP2, P4, and PO8 data – and frontal – the average of AF4, F4, and
278 FC2 data –) as within-participant factors. Supplementary Fig. 1 presents complementary
279 analyses by channel, and full spectrograms by channel and group.

280

3. Results and Discussion

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3.1. Phasic Alertness, Orienting, and Executive Control

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The main effects usually reported with the ANTI (Callejas et al., 2004) and ANTI-Vea (Luna et al., 2018) tasks were replicated here. For warning signal (RT [$F(1, 87) = 102.43, p < .001, \eta_p^2 = .54$]; errors [$F(1, 87) = 16.15, p < .001, \eta_p^2 = .16$]), responses were faster and more accurate in the tone (RT: $M = 568$ ms, $SE = 10$; errors: $M = 3.56\%$, $SE = 0.34$) than in the no tone (RT: $M = 597$ ms, $SE = 10$; errors: $M = 5.19\%$, $SE = 0.46$) condition. Regarding the congruency effect (RT [$F(1, 87) = 301.79, p < .001, \eta_p^2 = .78$]; errors [$F(1, 87) = 20.31, p < .001, \eta_p^2 = .19$]), responses were faster and more accurate in the congruent (RT: $M = 561$ ms, $SE = 10$; errors: $M = 3.61\%$, $SE = 0.32$) than in the incongruent (RT: $M = 605$ ms, $SE = 10$; errors: $M = 5.14\%$, $SE = 0.43$) condition. Finally, the cueing effect was only observed for RT ([$F(2, 174) = 99.33, p < .001, \eta_p^2 = .53$]; errors, [$F(2, 174) = 1.95, p = .145, \eta_p^2 = .02$]), with faster responses in the valid ($M = 564$ ms, $SE = 10$), than in the no cue ($M = 587$ ms, $SE = 10$) and invalid ($M = 597$ ms, $SE = 10$) conditions.

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Additionally, the usual two-way interactions were also replicated: Visual cue \times Congruency (RT: [$F(2, 174) = 8.31, p < .001, \eta_p^2 = .09$]; errors: [$F(2, 174) = 7.23, p < .001, \eta_p^2 = .08$]), Warning signal \times Visual cue (only for RT [$F(2, 174) = 25.43, p < .001, \eta_p^2 = .23$]; errors: [$F(2, 174) = 2.11, p = .124, \eta_p^2 = .02$]), and Warning signal \times Congruency (only for RT: [$F(1, 87) = 7.58, p = .007, \eta_p^2 = .08$]; errors: $F < 1$), providing additional empirical support in favor of the effectiveness of the task to assess both the independence and interactions of the classic attentional functions in the present study (see Table 1 and 2).

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A significant main effect of group was observed for RT [$F(2, 87) = 3.71, p = .028, \eta_p^2 = .08$], but not for errors [$F(2, 87) = 1.03, p = .360, \eta_p^2 = .02$]. The PPC HD-tDCS group

303 showed slower RT ($M = 620$ ms, $SE = 17$) as compared to sham ($M = 565$ ms, $SE = 18$) and
304 DLPFC HD-tDCS groups ($M = 561$ ms, $SE = 16$). Note that this effect is unexpected, and
305 likely meaningless, as it was present even in the baseline block [$F(2, 87) = 4.37$, $p = .016$, η_p^2
306 = .09].

307 There were no modulations of HD-tDCS over visual cue (RT: $F < 1$, errors: [$F(4,$
308 $174) = 2.18$, $p = .073$, $\eta_p^2 = .05$]) nor congruency (both for RT and errors: $F_s < 1$) effects.
309 Therefore, it might be possible that online HD-tDCS does not effectively modulates
310 orienting, as reported by previous studies with offline tDCS (Lo et al., 2019; Roy et al.,
311 2015). Furthermore, the present results are consistent with previous evidence regarding
312 executive control, wherein no modulation was observed with offline tDCS (Coffman et al.,
313 2012; Lo et al., 2019; Roy et al., 2015).

314 Interestingly, during the stimulation period, HD-tDCS significantly modulated the
315 main effect of phasic alertness on errors [$F(2, 87) = 5.13$, $p = .008$, $\eta_p^2 = .11$], but not on RT
316 [$F(2, 87) = 1.87$, $p = .161$, $\eta_p^2 = .04$]. Phasic alertness (i.e., the difference between the no
317 tone and tone condition) was importantly reduced in the PCC HD-tDCS ($M = 0.59\%$, $SE =$
318 0.61) and DLPFC HD-tDCS ($M = 0.83\%$, $SE = 0.59$) groups, in contrast to the sham one (M
319 $= 3.44\%$, $SE = 0.87$). Note that a specific comparison showed a similar reduction in phasic
320 alertness with RT for the PPC (39 ms) and DLPFC (37 ms) HD-tDCS groups compared to the
321 sham one (55 ms), which was significant specifically at the no cue condition [$F(1, 87) =$
322 5.33 , $p = .023$, $\eta_p^2 = .06$], wherein the phasic alertness effect is more clearly observed
323 (Callejas et al., 2004). These results indicates a relevant modulation of phasic alertness under
324 online HD-tDCS regardless the stimulation site, in line with previous evidence concerning a
325 modulation of offline tDCS over phasic alertness (Coffman et al., 2012).

326 Lastly, HD-tDCS did not modulated neither the two-way interactions (both for RT
 327 and errors: all $F_s < 1.20$, all $p_s > .300$), nor the Warning signal \times Visual cue \times Congruency
 328 interaction (RT: [$F(4, 174) = 1.41, p = .229, \eta_p^2 = .03$], errors $F < 1$).

329 **Table 1.** Mean correct RT for warning signal, visual cue, and congruency conditions, as a
 330 function of HD-tDCS group. SE of mean is shown between parentheses.

		No tone			Tone		
		Invalid	No cue	Valid	Invalid	No cue	Valid
PPC HD-tDCS	Congruent	619 (17)	631 (21)	596 (18)	597 (15)	582 (17)	570 (17)
	Incongruent	665 (18)	659 (16)	639 (21)	650 (16)	630 (17)	606 (17)
DLPFC HD-tDCS	Congruent	554 (17)	565 (16)	535 (17)	541 (18)	521 (16)	514 (19)
	Incongruent	613 (17)	598 (15)	572 (17)	604 (16)	569 (17)	556 (16)
Sham HD-tDCS	Congruent	565 (19)	579 (19)	547 (22)	544 (22)	521 (22)	502 (16)
	Incongruent	611 (19)	622 (21)	579 (16)	601 (19)	568 (18)	552 (17)

331

332 **Table 2.** Percentage of errors for warning signal, visual cue, and congruency conditions, as a
 333 function of HD-tDCS group. SE of mean is shown between parentheses.

		No tone			Tone		
		Invalid	No cue	Valid	Invalid	No cue	Valid
PPC HD-tDCS	Congruent	3.06 (0.89)	3.06 (0.68)	6.29 (1.27)	3.06 (0.86)	2.74 (0.76)	5.16 (1.10)
	Incongruent	5.81 (1.11)	4.84 (0.75)	5.48 (1.14)	4.19 (0.90)	5.32 (1.20)	4.52 (1.12)
DLPFC HD-tDCS	Congruent	2.76 (0.84)	2.93 (0.80)	4.14 (0.83)	3.45 (0.96)	1.72 (0.57)	2.59 (0.64)
	Incongruent	6.21 (1.69)	4.48 (0.97)	4.31 (1.16)	5.69 (1.44)	3.62 (0.74)	2.76 (0.73)
Sham HD-tDCS	Congruent	4.67 (1.12)	5.00 (1.15)	6.67 (1.21)	2.50 (0.82)	2.00 (0.82)	3.00 (0.82)
	Incongruent	7.50 (1.31)	8.33 (1.73)	7.67 (1.45)	5.17 (0.94)	3.67 (0.76)	2.83 (1.04)

334

335 3.2. Executive Vigilance

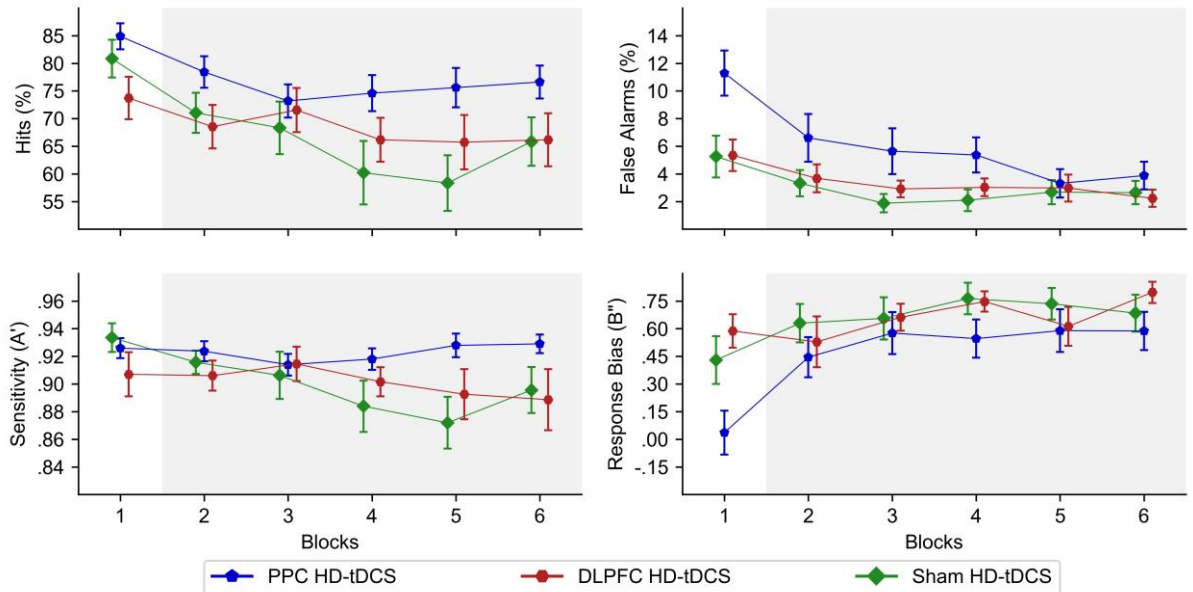
336 The main effect of group was significantly observed only for FA [$F(2, 87) = 5.33, p =$
337 $.007, \eta_p^2 = .11$], but not for hits [$F(2, 87) = 2.62, p = .078, \eta_p^2 = .06$], A' [$F(2, 87) = 1.56, p =$
338 $.216, \eta_p^2 = .03$] or B'' [$F(2, 87) = 2.69, p = .073, \eta_p^2 = .06$]. The PPC HD-tDCS group made
339 more FA ($M = 6.01\%, SE = 0.71$) than the sham ($M = 2.98\%, SE = 0.72$) and the DLPFC HD-
340 tDCS ($M = 3.36\%, SE = 0.74$) groups. Note that the difference in the FA rate between groups
341 was present even in the baseline block [$F(2, 87) = 5.76, p = .004, \eta_p^2 = .12$] (see Fig. 4), and
342 so this effect might not be due to HD-tDCS.

343 As can be seen in Fig. 4, the EV decrement was observed as previously reported with
344 the ANTI-Vea task (Luna et al., 2018). There was a significant decrement on hits [$F(5, 435)$
345 $= 12.34, p < .001, \eta_p^2 = .12$] and FA [$F(5, 435) = 9.31, p < .001, \eta_p^2 = .10$], and as
346 consequence, a relevant decrement of A' [$F(5, 435) = 2.89, p = .014, \eta_p^2 = .03$] and an
347 increment of B'' [$F(5, 435) = 7.40, p < .001, \eta_p^2 = .08$] across blocks. Note that, interestingly,
348 HD-tDCS modulated the decrement of hits [$F(10, 435) = 2.04, p = .028, \eta_p^2 = .04$] and A' [F
349 $(10, 435) = 2.04, p = .028, \eta_p^2 = .04$], but not of FA [$F(10, 435) = 1.43, p = .164, \eta_p^2 = .03$]
350 and B'' [$F(10, 435) = 1.12, p = .345, \eta_p^2 = .03$].

351 Thus, while there was no difference on hits at baseline between groups [$F(2, 87) =$
352 $3.06, p = .052, \eta_p^2 = .07$], the expected linear decrement observed in the sham group [$F(2,$
353 $87) = 24.72, p < .001, \eta_p^2 = .22$], was significantly different compared to that observed in the
354 PPC HD-tDCS [$F(1, 87) = 4.54, p = .036, \eta_p^2 = .05$] and the DLPFC HD-tDCS [$F(1, 87) =$
355 $4.02, p = .048, \eta_p^2 = .04$] groups, which did not differ from each other ($F < 1$).

356 Regarding sensitivity, as observed in the hits, groups did not differ on A' at the
357 baseline [$F(2, 87) = 1.37, p = .259, \eta_p^2 = .03$]. Moreover, the linear decrement of A' in the

358 sham HD-tDCS group [$F(1, 87) = 16.17, p < .001, \eta_p^2 = .16$] was significantly different from
 359 that observed in the two HD-tDCS groups [$F(1, 87) = 7.53, p = .007, \eta_p^2 = .08$], which did
 360 not differ from each other [$F(1, 87) = 2.15, p = .146, \eta_p^2 = .02$].



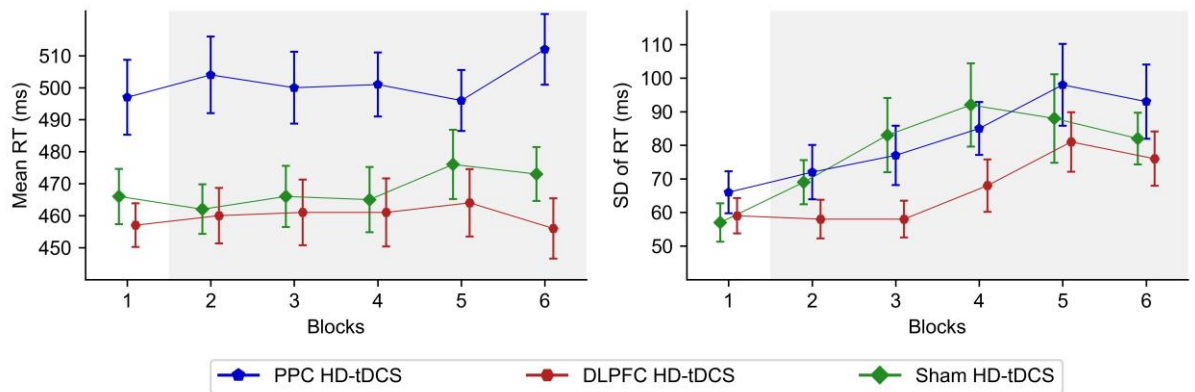
361

362 **Fig 4.** Executive vigilance decrement as a function of HD-tDCS conditions. Graphs represents
 363 the hits (superior left), FA (superior right), sensitivity (inferior left), and response bias (inferior
 364 right) per block of trials. The shadowed region at each graph denotes the real/sham stimulation
 365 period. Error bars shows SE of mean.

366 3.3. Arousal Vigilance

367 The main effect of group was found as significant for mean RT [$F(2, 87) = 6.49, p =$
 368 $.002, \eta_p^2 = .13$] but not for SD of RT [$F(2, 87) = 1.90, p = .155, \eta_p^2 = .04$]. The PPC HD-
 369 tDCS group showed slower responses ($M = 502$ ms, $SE = 9$), than the DLPFC HD-tDCS ($M =$
 370 460 ms, $SE = 9$) and the sham HD-tDCS ($M = 468$ ms, $SE = 9$) groups, a difference observed
 371 even at the baseline block [$F(2, 87) = 4.99, p = .009, \eta_p^2 = .10$] and therefore independent of
 372 stimulation.

373 As shown in Fig. 5, the AV decrement was observed as an increment in RT variability
 374 across blocks [$F(5, 435) = 6.54, p < .001, \eta_p^2 = .07$], with a significant linear component [F
 375 $(1, 87) = 21.06, p < .001, \eta_p^2 = .19$] – a pattern usually observed with the PVT (Basner and
 376 Dinges, 2011) and the ANTI-Vea (Luna et al., 2018) –, while mean RT did not change across
 377 blocks ($F < 1$). Importantly, neither mean RT nor RT variability changes across blocks were
 378 modulated by the HD-tDCS group (both F s < 1).



379
 380 **Fig 5.** Arousal vigilance decrement as a function of HD-tDCS conditions. Graphs represents
 381 the mean RT (left) and RT variability as SD of RT (right), per block of trials. The shadowed
 382 region at each graph denotes the real/sham stimulation period. Error bars shows SE of mean.

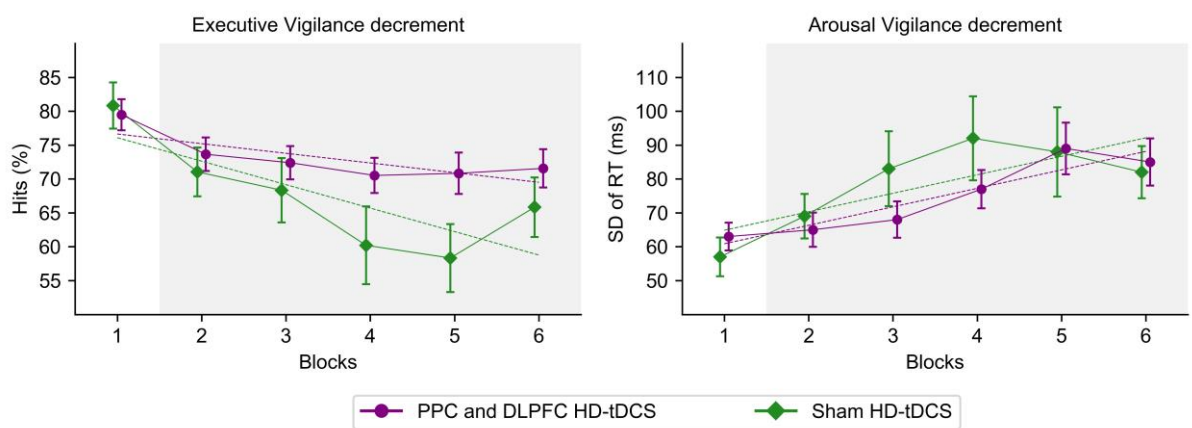
383 3.4. HD-tDCS modulates differently the EV and AV decrement

384 To further understand the effects of HD-tDCS on the vigilance components'
 385 decrement, we performed the following series of exploratory analyses. In particular, PPC and
 386 DLPFC HD-tDCS groups were collapsed in one single group and contrasted to the sham
 387 group, aiming at examining whether HD-tDCS over the two core regions of the attentional
 388 networks effectively mitigates only the EV decrement, but not the AV one.

389 For the EV component, hits showed no main effect of group [$F(1, 88) = 1.87, p =$
 390 $.174, \eta_p^2 = .02$], but it was observed a clear significant shift across blocks [$F(5, 440) = 14.92,$

391 $p < .001, \eta_p^2 = .14$] that was modulated by HD-tDCS [$F(5, 440) = 3.00, p = .011, \eta_p^2 = .03$].
 392 As depicted in Fig. 6, groups did not differ at the baseline ($F < 1$). Most important, the sham
 393 group showed a more prominent linear decrement [$F(1, 88) = 25.01, p < .001, \eta_p^2 = .22$], in
 394 contrast to the HD-tDCS group [$F(1, 88) = 8.47, p = .004, \eta_p^2 = .09$], which indeed showed
 395 no decrement at all within the stimulation period (i.e., from the 2nd to the 6th block: $F < 1$).
 396 Therefore, regardless the stimulation site, online HD-tDCS effectively mitigates the EV
 397 decrement, supporting previous evidence obtained with online tDCS protocols (Nelson et al.,
 398 2014).

399 In contrast, AV (measured as the RT variability) showed a considerable increment
 400 across blocks [$F(5, 440) = 6.20, p < .001, \eta_p^2 = .07$] with a clear linear trend [$F(1, 88) =$
 401 $18.92, p < .001, \eta_p^2 = .18$]. Nevertheless, the RT variability increment was independent of the
 402 HD-tDCS group [$F(5, 440) = 1.04, p = .392, \eta_p^2 = .01$] (see Fig. 6). Lastly, there was not a
 403 main effect of group for RT variability ($F < 1$). Thus, in contrast with previous evidence
 404 obtained with offline tDCS under sleep deprivation conditions (McIntire et al., 2014), here
 405 online HD-tDCS did not reduce the AV decrement.



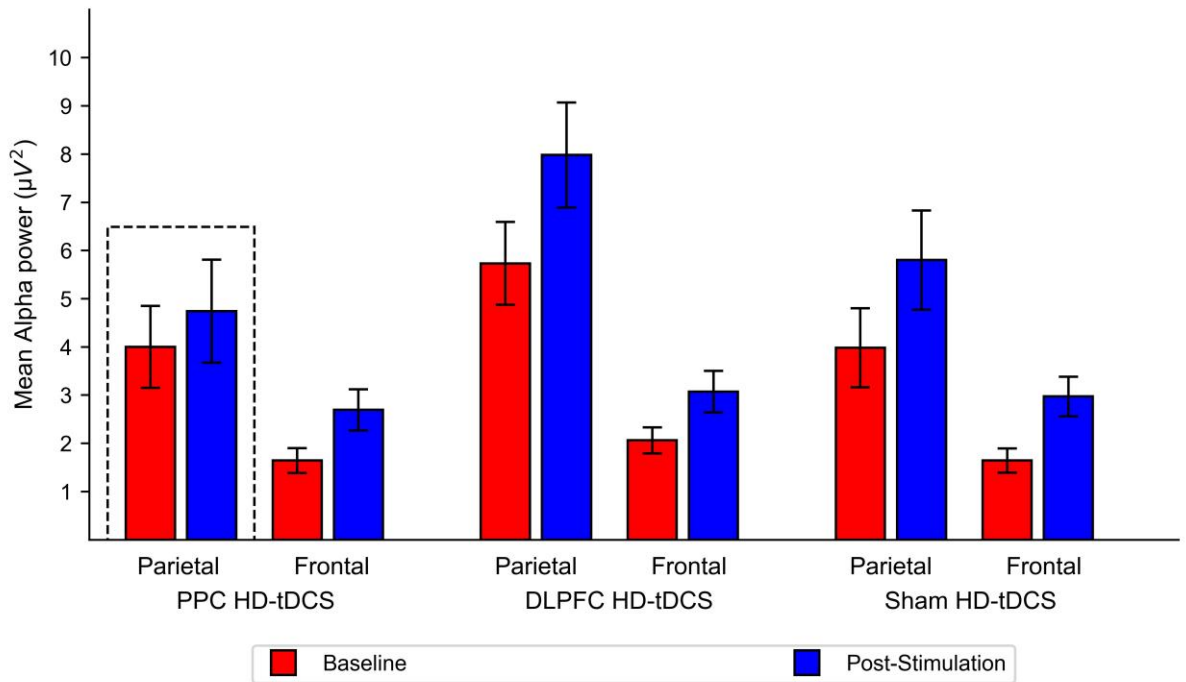
406
 407 **Fig 6.** Executive and arousal vigilance decrement as a function of HD-tDCS in the right
 408 hemisphere and sham condition. Graphs represents the hits rate (left) and SD of RT (right), per

409 block of trials. The shadowed region at each graph denotes the real/sham stimulation period.
410 Dotted line represents the linear trend for each dependent variable and group. Error bars show
411 SE of mean.

412 **3.5. HD-tDCS effects on alpha power**

413 Alpha power was not significantly different between groups [$F(1, 82) = 1.52, p =$
414 $.224, \eta_p^2 = .04$], but there were significant main effects for region [$F(1, 82) = 51.43, p < .001,$
415 $\eta_p^2 = .39$] and period [$F(1, 82) = 82.89, p < .001, \eta_p^2 = .50$] (see Fig. 7). Thus, in line with
416 previous findings with vigilance tasks (Boksem et al., 2005; Clayton et al., 2015), alpha
417 power was higher over the parietal than over the frontal region, and increased notably from
418 the beginning to the task end.

419 Most importantly, there was a significant Group \times Region \times Period interaction [$F(2,$
420 $82) = 4.95, p = .009, \eta_p^2 = .11$]. In particular, in the frontal region, alpha power increased
421 significantly between periods [$F(1, 82) = 69.25, p < .001, \eta_p^2 = .46$], with no modulation by
422 group ($F < 1$). Instead, as shown in Fig. 7, in the parietal region alpha power increased
423 differently as a function of group [$F(2, 82) = 4.27, p = .017, \eta_p^2 = .09$], with a slighter
424 increment in the PPC [$F(1, 82) = 4.00, p = .049, \eta_p^2 = .05$], than in the DLPFC and sham HD-
425 tDCS groups [$F(1, 82) = 60.52, p < .001, \eta_p^2 = .42$].



426

427 **Fig 7.** Mean alpha (7.5-12.5 Hz) power by region (parietal: CP2, P4, PO8; and frontal: AF4,
 428 FC2, FC2) as a function of period (baseline/post-stimulation) and group (PPC HD-tDCS,
 429 DLPFC HD-tDCS, sham HD-tDCS). Note that the most reduced alpha power shift between
 430 periods is observed in parietal region of the PPC HD-tDCS group (i.e., the pair of bars within
 431 the dotted line). Error bars show SE of mean.

432 Note that the modulation of PPC HD-tDCS over alpha power seems to be nevertheless
 433 independent from performance on the EV and AV components. As reported above, both the
 434 PPC and DLPFC HD-tDCS groups showed no decrement on hits within the stimulation
 435 period, whereas the reduced increment of alpha power was observed only in the PPC HD-
 436 tDCS group. Furthermore, the reduced decrement observed on hits in the two stimulation
 437 groups compared to the sham group remained significant [$F(5, 410) = 3.36, p = .006, \eta_p^2 =$
 438 $.04$] when the parietal alpha power increment was included as a covariate.

439

4. General Discussion

440 The present study aimed at examining whether anodal tDCS over the right PPC and
441 DLPFC effectively modulates the attentional networks functioning in healthy adults. To this
442 end, we assessed the attentional networks components with the ANTI-Vea, a behavioral task
443 suitable to measure within a single session the independence and interactions of the classic
444 attentional components (i.e., phasic alertness, attentional orienting, and executive control),
445 while assessing the EV and AV decrement across time on task (Luna et al., 2018).
446 Importantly, to examine the effects of anodal tDCS on the neurons excitability during the
447 performance on the ANTI-Vea task, stimulation was delivered online instead of offline
448 (Fertonani and Miniussi, 2017; Yavari et al., 2018). Furthermore, to increase the precision in
449 the region wherein current is delivered, we used a HD-tDCS procedure (Datta et al., 2009;
450 Kuo et al., 2013). Finally, we examined whether anodal HD-tDCS modulates the alpha power
451 increment across time on task, a neural mechanism usually associated with the vigilance
452 decrement phenomenon (Boksem et al., 2005; Clayton et al., 2015).

453 It is important to note that here, at difference with previous researches on attention or
454 vigilance with anodal tDCS (Coffman et al., 2012; Lo et al., 2019; McIntire et al., 2017;
455 Nelson et al., 2014; Roy et al., 2015), we assessed multiple attentional and vigilance
456 components within a single task, i.e., the ANTI-Vea (Luna et al., 2018). Although the ANTI-
457 Vea requires several different responses to multiple tasks, it must be noticed that it is indeed
458 as effective as previous versions of the attentional networks test such as the ANTI (Callejas et
459 al., 2004) and the ANTI-Vigilance (Roca et al., 2011) to assess the independence and
460 interactions of the classic attentional components (as demonstrated in the Results of the
461 present study; see section 3.1). In addition, whereas vigilance has been traditionally assessed
462 by single and monotonous behavioral tasks (Thomson et al., 2016), it is worth mentioning
463 that the ANTI-Vea is additionally suitable to assess the EV decrement as in the MCT

464 (Mackworth, 1948) and the AV decrement as in the PVT (Lim and Dinges, 2008). Therefore,
465 while a task with multiple demands might somewhat modify the dynamic of traditional
466 methods to assess attentional and vigilance components, note that our method has already
467 demonstrated to be effective in including a direct and separate measure of several attentional
468 and vigilance functions (Luna et al., 2018). In this context, we found a clear modulation of
469 online anodal HD-tDCS on two distinct components of the alerting network (i.e., phasic
470 alertness and EV, but not AV).

471 Regarding the classic attentional components, we have found that online anodal HD-
472 tDCS over the right PPC and the right DLPFC, only reduced phasic alertness but did not
473 modulated the orienting nor the executive control network. Note that the cortical regions we
474 have stimulated in the present study are specifically related to some of the brain regions
475 described for the alerting network, i.e., a brain circuit that comprises brain stem regions as the
476 locus coeruleus along with right parietal and prefrontal cortices (Petersen and Posner, 2012;
477 Posner, 2012, 2008). Importantly, by using a HD-tDCS procedure we have considerably
478 enhanced the spatial precision on the stimulated region in comparison with previous studies
479 on the attentional networks that have used the standard tDCS setup (Coffman et al., 2012; Lo
480 et al., 2019; Roy et al., 2015). Future research should examine whether anodal HD-tDCS is
481 more precise to modulate the orienting and the executive control network by stimulating
482 others cortical regions of the attentional networks system, as for instance, the frontal eye
483 fields, the anterior cingulate cortex, or the left DLPFC (Petersen and Posner, 2012).

484 Importantly, one of the main findings of the present study is to have shown that online
485 anodal HD-tDCS over the right PPC and the right DLPFC mitigated the EV decrement across
486 time on task, but did not modulated the AV one. Note that previous research aiming to
487 modulate vigilance performance by anodal tDCS has found inconsistent results, in particular
488 concerning the EV component (Jacoby and Lavidor, 2018; Nelson et al., 2014). In addition, it

489 is important to highlight that some studies have measured the EV component as the global
490 score of performing a signal detection task (Jacoby and Lavidor, 2018; Roe et al., 2016).
491 However, the vigilance decrement is a phenomenon that is observed as a progressive loss of
492 sustained attention across time on task (Hancock, 2017; Mackworth, 1948), and therefore to
493 examine the modulation of anodal tDCS over vigilance the performance should be analyzed
494 as a function of time on task. Regarding the AV component, the effects of anodal tDCS were
495 observed in previous studies particularly under sleep deprivation conditions, a state wherein
496 vigilance performance is usually hindered (McIntire et al., 2017, 2014).

497 In the present study, we examined both vigilance components with a behavioral task
498 (i.e., the ANTI-Vea) that has proved to be suitable to observe both the EV and AV decrement
499 across time on task within a single session (Luna et al., 2018). Indeed, note that in an ongoing
500 behavioral study with 617 participants, the linear decrement on hits in the EV component [F
501 (1, 589) = 155.48, $p < .001$, $\eta_p^2 = .21$] and the linear increment of RT variability in the AV
502 component [F (1, 589) = 76.40, $p < .001$, $\eta_p^2 = .11$] were consistently observed, with both the
503 standard and an online version (<https://www.ugr.es/~neurocog/ANTI/>) of the ANTI-Vea
504 (Luna et al., Unpublished results). Importantly, here we have demonstrated that anodal online
505 HD-tDCS over the right PPC and the right DLPFC are effective to moderate only the EV
506 decrement, but not the AV one.

507 Thus, whereas previous studies have reported some overlapped brain activity for the
508 EV and AV components, in the current study we provide novel evidence to support an
509 empirical dissociation at the neural level between EV and AV. For instance, previous studies
510 have found increased activity in the default mode network (i.e., a circuit of medial and
511 posterior regions strongly linked to the cognitive functioning in resting-state) associated with
512 both: (a) the AV component, when performing the PVT task after 36 hours of total sleep
513 deprivation (Drummond et al., 2005); and (b) the EV component, when performing a typical

514 signal detection task (Danckert and Merrifield, 2016). Instead, here we have observed that
515 stimulating two core regions (i.e., the right PPC and the right DLPFC) of the attentional
516 networks system while participants perform a multiple attentional and vigilance task (i.e., the
517 ANTI-Vea), mitigates particularly the EV decrement across time on task, but not the AV one.
518 Importantly, these results are in line with some recent findings that demonstrated a clear
519 dissociation of vigilance components at the physiological level (Sanchis et al., Unpublished
520 results). In a study conducted in collaboration with sport scientists, we observed that whereas
521 moderate exercise seems to stabilize the RT of responses on EV across time on task, the
522 effects of caffeine intake seems to mitigate in particular the AV decrement independently on
523 the exercise intensity (Sanchis et al., Unpublished results).

524 The current findings might help to develop new treatment alternatives in clinical
525 populations in which it is commonly observed an increment on attentional failures and a drop
526 of performance during extended periods of time. For instance, it has been reported that
527 traumatic brain injury patients (TBI) usually fail in sustaining attention for detecting
528 infrequent signals, in comparison with the performance observed in healthy adults (Dockree
529 et al., 2004; Robertson et al., 1997). Furthermore, it has been proposed that children with
530 attention-deficit hyperactivity disorder (ADHD) show an inattentive response style when
531 performing the ANT, characterized as a low accuracy on responses and a great variability in
532 performance (Adolfstottir et al., 2008). Interestingly, note that although a recent meta-
533 analysis has reported a small-to-medium effect size of anodal tDCS in modulating others
534 cognitive functions (i.e., inhibitory control and working memory) in ADHD children, in the
535 stimulation protocols analyzed in this work: (a) only one study has delivered online tDCS;
536 and (b) all of them used the standard electrodes setup (e.g., an anode and a cathode), instead
537 of delivering HD-tDCS (Salehinejad et al., 2019). Thus, future research should consider
538 whether online and anodal HD-tDCS might be a substantially more effective tool than offline

539 and standard tDCS to improve behavioral performance in clinical patients as TBI and ADHD,
540 in particular in the phasic alertness state and the ability to monitor and detect infrequent
541 signals, as we have demonstrated in the current study.

542 Regarding the effects of anodal HD-tDCS over the alpha band, it was found that the
543 increment usually observed in the alpha power during long time periods was importantly
544 reduced in the parietal region only by stimulating the right PPC. Interestingly, previous
545 research has already reported some beneficial effects of online anodal tDCS on the electrical
546 cortical activity of the stimulated region (Brosnan et al., 2018). In particular, it has been
547 observed that online anodal tDCS over the right prefrontal cortex both reduced attentional
548 lapses in a signal detection task and enhanced some EEG markers of frontal engagement and
549 early sensory processing. However, it is worth mentioning that these effects were found in a
550 sample of older adults –a population wherein vigilance performance is usually impaired
551 (Fortenbaugh et al., 2015)– that, in addition, had a low capacity to sustain attention (Brosnan
552 et al., 2018).

553 In the present research, we observed in a sample of healthy adults a clear mitigation of
554 the alpha power increment over right PPC by anodal HD-tDCS that, nevertheless, seems to be
555 independent on the performance of the vigilance components across time on task. Therefore,
556 to further determine the role of the alpha band in the vigilance decrement phenomenon, future
557 research should more deeply examine whether alpha power modulation is exclusively linked
558 to the EV decrement but not to the AV one. In this vein, future studies might consider to
559 modulate alpha power with transcranial alternating current stimulation (tACS), which is
560 indeed a suitable stimulation technique to stabilize specifically a band of electrical cortical
561 rhythms (Fertonani and Miniussi, 2017). For instance, in a recent study it has been proved
562 that if alpha power is stabilized at 10 Hz across time on task by tACS in the occipitoparietal
563 cortex while participants perform a signal detection task, then the EV decrement is mitigated

564 in both the hits and the RT of responses (Clayton et al., 2019). Moreover, future studies might
565 consider to analyze the role of others electrical cortical rhythms, in particular the delta (1-4
566 Hz) and theta (4-8 Hz) bands, which have been also associated with the AV decrement under
567 sleep deprivation conditions (Hoedlmoser et al., 2011).

568 Finally, we reckon that some results of the present study should be interpreted with
569 caution. In particular, there were some baseline differences between groups in two dependent
570 variables, i.e., the FA on EV and the mean RT on AV. However, note that, importantly, if
571 these data are corrected to compute the change on each block against baseline to eliminate
572 groups' differences at baseline, the pattern of results does not change: there is no significant
573 modulation of stimulation group neither in FA on EV nor in mean RT on AV across time on
574 task (both $F_s < 1$). To overcome this potential limitation, future studies should estimate a
575 priori the sample size (to control for substantial variability) or conduct full within-participants
576 designs (although considering associated issues such as possible learning effects).

577 To conclude, the main contributions of the present study are to have shown that online
578 anodal HD-tDCS over the right PPC and DLPFC effectively: (a) modulates phasic alertness,
579 but not the attentional orienting and executive control functioning; and (b) mitigates the EV
580 decrement, but not the AV one. Critically, the current findings further support an empirical
581 dissociation between vigilance components. Finally, PPC HD-tDCS reduced importantly
582 alpha power increment across time on task, which was however, independent of the vigilance
583 performance.

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- 598 Adolfsdottir, S., Sorensen, L., Lundervold, A.J., 2008. The attention network test: a
599 characteristic pattern of deficits in children with ADHD. *Behav. Brain Funct.* 4, 9.
600 <https://doi.org/10.1186/1744-9081-4-9>
- 601 Basner, M., Dinges, D.F., 2011. Maximizing sensitivity of the psychomotor vigilance test
602 (PVT) to sleep loss. *Sleep* 34, 581–91. <https://doi.org/10.1093/sleep/34.5.581>
- 603 Boksem, M.A.S., Meijman, T.F., Lorist, M.M., 2005. Effects of mental fatigue on attention:
604 An ERP study. *Cogn. Brain Res.* 25, 107–116.
605 <https://doi.org/10.1016/j.cogbrainres.2005.04.011>
- 606 Brosnan, M.B., Arvaneh, M., Harty, S., Maguire, T., O’Connell, R., Robertson, I.H.,
607 Dockree, P.M., 2018. Prefrontal Modulation of Visual Processing and Sustained
608 Attention in Aging, a tDCS–EEG Coregistration Approach. *J. Cogn. Neurosci.* 30,
609 1630–1645. https://doi.org/10.1162/jocn_a_01307
- 610 Callejas, A., Lupiáñez, J., Tudela, P., 2004. The three attentional networks: on their
611 independence and interactions. *Brain Cogn.* 54, 225–7.
612 <https://doi.org/10.1016/j.bandc.2004.02.012>
- 613 Clayton, M.S., Yeung, N., Cohen Kadosh, R., 2019. Electrical stimulation of alpha
614 oscillations stabilizes performance on visual attention tasks. *J. Exp. Psychol. Gen.* 148,
615 203–220. <https://doi.org/10.1037/xge0000502>
- 616 Clayton, M.S., Yeung, N., Cohen Kadosh, R., 2015. The roles of cortical oscillations in
617 sustained attention. *Trends Cogn. Sci.* 19, 188–195.
618 <https://doi.org/10.1016/j.tics.2015.02.004>

619 Coffman, B.A., Clark, V.P., Parasuraman, R., 2014. Battery powered thought: Enhancement
620 of attention, learning, and memory in healthy adults using transcranial direct current
621 stimulation. *Neuroimage* 85, 895–908.
622 <https://doi.org/10.1016/j.neuroimage.2013.07.083>

623 Coffman, B.A., Trumbo, M.C., Clark, V.P., 2012. Enhancement of object detection with
624 transcranial direct current stimulation is associated with increased attention. *BMC*
625 *Neurosci.* 13, 108. <https://doi.org/10.1186/1471-2202-13-108>

626 Danckert, J., Merrifield, C., 2016. Boredom, sustained attention and the default mode
627 network. *Exp. Brain Res.* 236, 2507–2518. <https://doi.org/10.1007/s00221-016-4617-5>

628 Datta, A., Bansal, V., Diaz, J., Patel, J., Reato, D., Bikson, M., 2009. Gyri-precise head
629 model of transcranial direct current stimulation: Improved spatial focality using a ring
630 electrode versus conventional rectangular pad. *Brain Stimul.* 2, 201-207.e1.
631 <https://doi.org/10.1016/j.brs.2009.03.005>

632 Dedoncker, J., Brunoni, A.R., Baeken, C., Vanderhasselt, M.-A., 2016. A Systematic Review
633 and Meta-Analysis of the Effects of Transcranial Direct Current Stimulation (tDCS)
634 Over the Dorsolateral Prefrontal Cortex in Healthy and Neuropsychiatric Samples:
635 Influence of Stimulation Parameters. *Brain Stimul.* 9, 501–517.
636 <https://doi.org/10.1016/j.brs.2016.04.006>

637 Dockree, P.M., Kelly, S.P., Roche, R.A.P., Hogan, M.J., Reilly, R.B., Robertson, I.H., 2004.
638 Behavioural and physiological impairments of sustained attention after traumatic brain
639 injury. *Cogn. Brain Res.* 20, 403–414. <https://doi.org/10.1016/j.cogbrainres.2004.03.019>

640 Drummond, S.P. a, Bischoff-Grethe, A., Dinges, D.F., Ayalon, L., Mednick, S.C., Meloy,
641 M.J., 2005. The neural basis of the psychomotor vigilance task. *Sleep* 28, 1059–1068.

642 <https://doi.org/10.1093/sleep/28.9.1059>

643 Fan, J., McCandliss, B.D., Sommer, T., Raz, A., Posner, M.I., 2002. Testing the efficiency
644 and independence of attentional networks. *J. Cogn. Neurosci.* 14, 340–7.
645 <https://doi.org/10.1162/089892902317361886>

646 Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: A flexible statistical
647 power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res.*
648 *Methods* 39, 175–191. <https://doi.org/10.3758/BF03193146>

649 Fertonani, A., Ferrari, C., Miniussi, C., 2015. What do you feel if I apply transcranial electric
650 stimulation? Safety, sensations and secondary induced effects. *Clin. Neurophysiol.* 126,
651 2181–2188. <https://doi.org/10.1016/j.clinph.2015.03.015>

652 Fertonani, A., Miniussi, C., 2017. Transcranial Electrical Stimulation: What We Know and
653 Do Not Know About Mechanisms. *Neurosci.* 23, 109–123.
654 <https://doi.org/10.1177/1073858416631966>

655 Fortenbaugh, F.C., Degutis, J., Germine, L., Wilmer, J.B., Grosso, M., Russo, K., Esterman,
656 M., 2015. Sustained attention across the life span in a sample of 10,000: Dissociating
657 ability and strategy. *Psychol. Sci.* 26, 1497–1510.
658 <https://doi.org/10.1177/0956797615594896>

659 Hancock, P.A., 2017. On the Nature of Vigilance. *Hum. Factors J. Hum. Factors Ergon. Soc.*
660 59, 35–43. <https://doi.org/10.1177/0018720816655240>

661 Hoedlmoser, K., Griessenberger, H., Fellingner, R., Freunberger, R., Klimesch, W., Gruber,
662 W., Schabus, M., 2011. Event-related activity and phase locking during a psychomotor
663 vigilance task over the course of sleep deprivation. *J. Sleep Res.* 20, 377–385.

664 <https://doi.org/10.1111/j.1365-2869.2010.00892.x>

665 Huang, Y., Datta, A., Bikson, M., Parra, L.C., 2019. Realistic volumetric-approach to
666 simulate transcranial electric stimulation—ROAST—a fully automated open-source
667 pipeline. *J. Neural Eng.* 16, 056006. <https://doi.org/10.1088/1741-2552/ab208d>

668 Jacoby, N., Lavidor, M., 2018. Null tDCS Effects in a Sustained Attention Task: The
669 Modulating Role of Learning. *Front. Psychol.* 9, 1–9.
670 <https://doi.org/10.3389/fpsyg.2018.00476>

671 Kuo, H.-I., Bikson, M., Datta, A., Minhas, P., Paulus, W., Kuo, M.-F., Nitsche, M.A., 2013.
672 Comparing Cortical Plasticity Induced by Conventional and High-Definition 4×1 Ring
673 tDCS: A Neurophysiological Study. *Brain Stimul.* 6, 644–648.
674 <https://doi.org/10.1016/j.brs.2012.09.010>

675 Lim, J., Dinges, D.F., 2008. Sleep Deprivation and Vigilant Attention. *Ann. N. Y. Acad. Sci.*
676 1129, 305–322. <https://doi.org/10.1196/annals.1417.002>

677 Lo, O.-Y., van Donkelaar, P., Chou, L.-S., 2019. Effects of transcranial direct current
678 stimulation over right posterior parietal cortex on attention function in healthy young
679 adults. *Eur. J. Neurosci.* 1–9. <https://doi.org/10.1111/ejn.14349>

680 Luna, F.G., Marino, J., Roca, J., Lupiáñez, J., 2018. Executive and arousal vigilance
681 decrement in the context of the attentional networks: The ANTI-Vea task. *J. Neurosci.*
682 *Methods* 306, 77–87. <https://doi.org/10.1016/j.jneumeth.2018.05.011>

683 Mackworth, N.H., 1948. The Breakdown of Vigilance during Prolonged Visual Search. *Q. J.*
684 *Exp. Psychol.* 1, 6–21. <https://doi.org/10.1080/17470214808416738>

685 McIntire, L.K., McKinley, R.A., Goodyear, C., Nelson, J., 2014. A Comparison of the Effects

686 of Transcranial Direct Current Stimulation and Caffeine on Vigilance and Cognitive
687 Performance During Extended Wakefulness. *Brain Stimul.* 7, 499–507.
688 <https://doi.org/10.1016/j.brs.2014.04.008>

689 McIntire, L.K., McKinley, R.A., Nelson, J.M., Goodyear, C., 2017. Transcranial direct
690 current stimulation versus caffeine as a fatigue countermeasure. *Brain Stimul.* 10, 1070–
691 1078. <https://doi.org/10.1016/j.brs.2017.08.005>

692 Nelson, J., McKinley, R.A., Phillips, C., McIntire, L., Goodyear, C., Kreiner, A., Monforton,
693 L., 2016. The Effects of Transcranial Direct Current Stimulation (tDCS) on Multitasking
694 Throughput Capacity. *Front. Hum. Neurosci.* 10, 1–13.
695 <https://doi.org/10.3389/fnhum.2016.00589>

696 Nelson, J.T., McKinley, R.A., Golob, E.J., Warm, J.S., Parasuraman, R., 2014. Enhancing
697 vigilance in operators with prefrontal cortex transcranial direct current stimulation
698 (tDCS). *Neuroimage* 85, 909–917. <https://doi.org/10.1016/j.neuroimage.2012.11.061>

699 Oken, B.S., Salinsky, M.C., Elsas, S.M., 2006. Vigilances, alertness, or sustained attention:
700 physiological basis and measurement. *Clin. Neurophysiol.* 117, 1885–1901.
701 <https://doi.org/10.1016/j.clinph.2006.01.017>.

702 Petersen, S.E., Posner, M.I., 2012. The Attention System of the Human Brain: 20 Years
703 After. *Annu. Rev. Neurosci.* 35, 73–89. [https://doi.org/10.1146/annurev-neuro-062111-
704 150525](https://doi.org/10.1146/annurev-neuro-062111-150525)

705 Posner, M.I., 2016. Orienting of Attention: Then and Now. *Q. J. Exp. Psychol.* 69, 1864–
706 1875. <https://doi.org/10.1080/17470218.2014.937446>

707 Posner, M.I., 2012. Imaging attention networks. *Neuroimage* 61, 450–456.

708 <https://doi.org/10.1016/j.neuroimage.2011.12.040>

709 Posner, M.I., 2008. Measuring Alertness. *Ann. N. Y. Acad. Sci.* 1129, 193–199.

710 <https://doi.org/10.1196/annals.1417.011>

711 Posner, M.I., Dehaene, S., 1994. Attentional networks. *Trends Neurosci.* 17, 75–79.

712 [https://doi.org/10.1016/0166-2236\(94\)90078-7](https://doi.org/10.1016/0166-2236(94)90078-7)

713 Posner, M.I., Petersen, S.E., 1990. The Attention System of The Human Brain. *Annu. Rev.*

714 *Neurosci.* 13, 25–42. <https://doi.org/10.1146/annurev.ne.13.030190.000325>

715 Reteig, L.C., Talsma, L.J., van Schouwenburg, M.R., Slagter, H.A., 2017. Transcranial

716 Electrical Stimulation as a Tool to Enhance Attention. *J. Cogn. Enhanc.* 1, 10–25.

717 <https://doi.org/10.1007/s41465-017-0010-y>

718 Robertson, I.H., Manly, T., Andrade, J., Baddeley, B.T., Yiend, J., 1997. “Oops!”:

719 performance correlates of everyday attentional failures in traumatic brain injured and

720 normal subjects. *Neuropsychologia* 35, 747–58. [https://doi.org/10.1016/S0028-](https://doi.org/10.1016/S0028-3932(97)00015-8)

721 [3932\(97\)00015-8](https://doi.org/10.1016/S0028-3932(97)00015-8)

722 Roca, J., Castro, C., López-Ramón, M.F., Lupiáñez, J., 2011. Measuring vigilance while

723 assessing the functioning of the three attentional networks: the ANTI-Vigilance task. *J.*

724 *Neurosci. Methods* 198, 312–24. <https://doi.org/10.1016/j.jneumeth.2011.04.014>

725 Roe, J.M., Nesheim, M., Mathiesen, N.C., Moberget, T., Alnæs, D., Sneve, M.H., 2016. The

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

727 *Neuropsychologia* 80, 1–8. <https://doi.org/10.1016/j.neuropsychologia.2015.11.005>

728 Rossi, S., Hallett, M., Rossini, P.M., Pascual-Leone, A., 2011. Screening questionnaire

729 before TMS: An update. *Clin. Neurophysiol.* 122, 1686.

730 <https://doi.org/10.1016/j.clinph.2010.12.037>

731 Roy, L.B., Sparing, R., Fink, G.R., Hesse, M.D., 2015. Modulation of attention functions by
732 anodal tDCS on right PPC. *Neuropsychologia* 74, 96–107.
733 <https://doi.org/10.1016/j.neuropsychologia.2015.02.028>

734 Sakai, H., Uchiyama, Y., Tanaka, S., Sugawara, S.K., Sadato, N., 2014. Prefrontal
735 transcranial direct current stimulation improves fundamental vehicle control abilities.
736 *Behav. Brain Res.* 273, 57–62. <https://doi.org/10.1016/j.bbr.2014.07.036>

737 Salehinejad, M.A., Wischniewski, M., Nejati, V., Vicario, C.M., Nitsche, M.A., 2019.
738 Transcranial direct current stimulation in attention-deficit hyperactivity disorder: A
739 meta-analysis of neuropsychological deficits. *PLoS One* 14, e0215095.
740 <https://doi.org/10.1371/journal.pone.0215095>

741 Sarter, M., Givens, B., Bruno, J.P., 2001. The cognitive neuroscience of sustained attention:
742 where top-down meets bottom-up. *Brain Res. Rev.* 35, 146–60.
743 [https://doi.org/10.1016/S0165-0173\(01\)00044-3](https://doi.org/10.1016/S0165-0173(01)00044-3)

744 Shenhav, A., Botvinick, M.M., Cohen, J.D., 2013. The expected value of control: an
745 integrative theory of anterior cingulate cortex function. *Neuron* 79, 217–40.
746 <https://doi.org/10.1016/j.neuron.2013.07.007>

747 Stanislaw, H., Todorov, N., 1999. Calculation of signal detection theory measures. *Behav.*
748 *Res. Methods, Instruments, Comput.* 31, 137–149. <https://doi.org/10.3758/BF03207704>

749 Thomson, D.R., Besner, D., Smilek, D., 2016. A critical examination of the evidence for
750 sensitivity loss in modern vigilance tasks. *Psychol. Rev.* 123, 70–83.
751 <https://doi.org/10.1037/rev0000021>

- 752 Warm, J.S., Parasuraman, R., Matthews, G., 2008. Vigilance Requires Hard Mental Work
753 and Is Stressful. *Hum. Factors* 50, 433–441. <https://doi.org/10.1518/001872008X312152>
- 754 Yavari, F., Jamil, A., Mosayebi Samani, M., Vidor, L.P., Nitsche, M.A., 2018. Basic and
755 functional effects of transcranial Electrical Stimulation (tES)—An introduction.
756 *Neurosci. Biobehav. Rev.* 85, 81–92. <https://doi.org/10.1016/j.neubiorev.2017.06.015>
- 757