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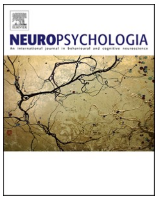

A High-Definition tDCS and EEG study on attention and vigilance: Brain stimulation mitigates the executive but not the arousal vigilance decrement

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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.

1. Introduction

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

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attentional performance in healthy adults still remain unclear (Coffman et al., 2012; Jacoby and Lavidor, 2018; Nelson et al., 2014; Roy et al., 2015).

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

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

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

Thus, on the one hand, the MCT measures a more executive component of vigilance, which can be conceived as a cognitive ability for sustaining attention over extended periods of time to monitor and detect infrequent critical signals by selecting and executing a specific response over stimuli (Warm et al., 2008). In this vein, Nelson et al. (2014) found that 1.0 mA of 10 min online tDCS over the left DLPFC effectively helps to sustain participants' target detection hits rate across time-on-task, in contrast to the typical decrement observed with sham tDCS. On the other hand, the PVT seems to assess an arousal component of vigilance, understood as the behavioral responsiveness of the arousal levels of attention for sustaining a fast reaction to stimuli from environment over long time periods without implementing much control over responses, a performance usually affected by sleep deprivation (Drummond et al., 2005; Lim and Dinges, 2008). In this sense, after 24 h of extended wakefulness, 2.0 mA tDCS during ~30 min facilitated a fast reaction time on the PVT in the following 6 h, but did not reduce the percentage of lapses (i.e., responses slower than 500 ms), as compared to sham tDCS (McIntire et al., 2014).

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

1.1. *The current study*

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

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

2. Material and methods

2.1. *Participants*

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

Participants were randomly assigned to one of three groups: HD-tDCS over the right PPC (n = 32, 24 women, age: M = 22.09, SD = 3.59), HD-tDCS over the right DLPFC (n = 30, 20 women, age: M = 23.70, SD = 4.28), and sham HD-tDCS, with half of participants being sham-stimulated over the right PPC (n = 15, 10 women, age: M = 23.20,

$SD = 3.23$), and the other half over the right DLPFC ($n = 15$, 9 women, age: $M = 23.87$, $SD = 3.79$).

Using G*Power 3.1.9.4 (Faul et al., 2007), we conducted power analyses to determine whether the used sample size was enough to observe a reliable modulation of vigilance performance across time-on-task by the stimulation procedure (i.e., a within-between interaction). Sensitivity analysis demonstrated that considering $\alpha = 0.05$ and $1 - \beta = 0.80$, the minimum effect size detectable should be of $f = 0.193$, which is indeed an effect size smaller than the one observed for the interaction reflecting the modulation of stimulation group over the decrease of hits across blocks (i.e., $f = 0.204$ or $\eta_p^2 = 0.04$; see section 3.2). Thus, post hoc analysis showed that given an effect size of $f = 0.204$ and $\alpha = 0.05$, the sample size was enough to observe a within-between interaction with a power of $1 - \beta = 0.85$.

2.2. Behavioral assessment: ANTI-Vea

The behavioral task was designed and run with E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). The task includes three different types of trials (i.e., ANTI, EV, and AV). The stimuli sequence, procedure, and correct responses for each type of trials are depicted in Fig. 1, and are described in detail in Luna et al. (2018). The ANTI trials (see Fig. 1) follows the procedure of the ANTI task (Callejas et al., 2004). Participants had to respond to the direction pointed by a central arrow (i.e., the target), while ignoring the surrounding flanking arrows. In short, to assess the executive control functioning, the target could point a congruent or incongruent direction with regards to the flanking arrows. For measuring the phasic alertness functioning, an auditory warning signal could anticipate the target appearance in half of these trials, whereas no warning signal was presented in the other half. To assess the orienting functioning, the arrows position could be predicted either by a valid (i.e., the same location) or invalid spatial cue, or by no cue at all.

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

Instructions encouraged participants to keep the gaze at every moment on the fixation point ('+'), which appeared all time in the center of the screen (see Fig. 1). Note that the three type of trials were randomly presented within each experimental block, so that participants had to keep in mind instructions to perform the three type of tasks at the same time. In the largest proportion of trials (i.e., the ANTI trials; 60%), the target and flanking arrows could appear above or below the fixation point and could be preceded by the warning signal and/or visual cue. In these cases, participants had to respond to the direction pointed by the target with the left or the right hand (see Fig. 1, panel c). The EV trials (20%) followed the same stimuli sequence than the ANTI ones, except that the target appeared largely displaced either upwards or downwards from its central position. Here, participants had to respond to the displacement with a different response key, ignoring in these cases the direction the target pointed to (see Fig. 1, panel c). In the AV trials (20%), no warning signal nor visual cue was presented (as in some of the ANTI and EV trials, i.e., those with no tone nor visual cue), and the response' stimulus (i.e., the down counter) appeared in the center of the screen until participants' response (see Fig. 1, panel c).

2.3. Stimulation protocols and EEG recording

2.3.1. Apparatus

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

2.3.2. HD-tDCS procedure

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

2.3.3. EEG data acquisition and pre-processing

In all groups, EEG signal was recorded in channels CP2, P4, PO8, AF4, F4, FC2 (see Fig. 2) along the experiment, although only data from the baseline and post-stimulation block were analyzed. Signal was registered with a sampling rate of 500 Hz, a bandwidth of 0–125 Hz, and a notch filter (50 Hz).

EEG data pre-processing was conducted with EEGLAB v14.1.1 toolbox (Delorme and Makeig, 2004) on MATLAB R2016a (The MathWorks, Inc.). Data format was first converted to the EEGLAB format with the NE EEGLAB NIC plugin. To avoid ramp up and down noise effect, analyses were restricted to the first 4:30 min in the baseline block and the last 4:30 min in the post-simulation block. In addition, signal was decomposed using Independent Component Analysis and reconstructed excluding blinks. Frequency filters were set at 0.5 Hz (high pass) and 45 Hz (low pass). Lastly, mean alpha power (i.e., squared signal filtered between 7.5 and 12.5 Hz) was computed both for the baseline and post-stimulation block.

2.4. Procedure

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

2.5. Statistical analyses

2.5.1. Behavioral data

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

Data from the ANTI trials were analyzed only for the 2nd to 6th block

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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 [χ^2 (4) = 9.23, $p = .055$], neither in the guessing to the group they belonged to [χ^2 (4) = 2.68, $p = .612$].

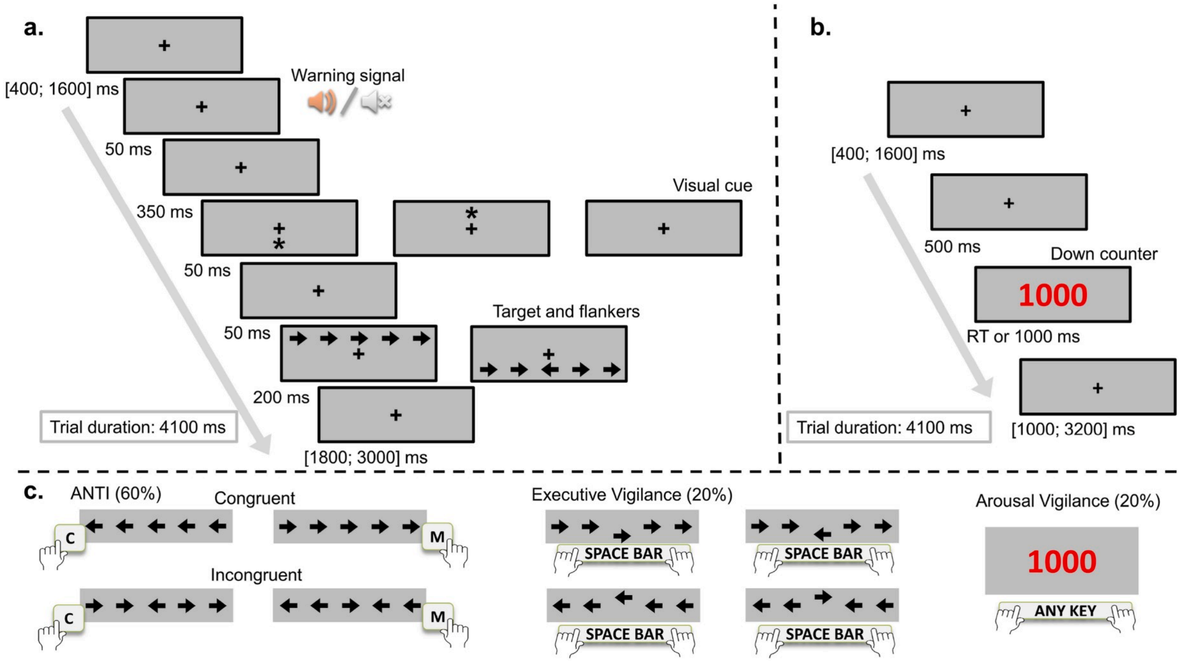

Fig. 1. Stimuli and trials for the ANTI-Vea task. Top panels shows the stimuli sequence for (A) ANTI and executive vigilance trials, and (B) arousal vigilance trials. Panel (C) shows the proportion and correct responses for each ANTI, executive vigilance, and arousal vigilance trials.

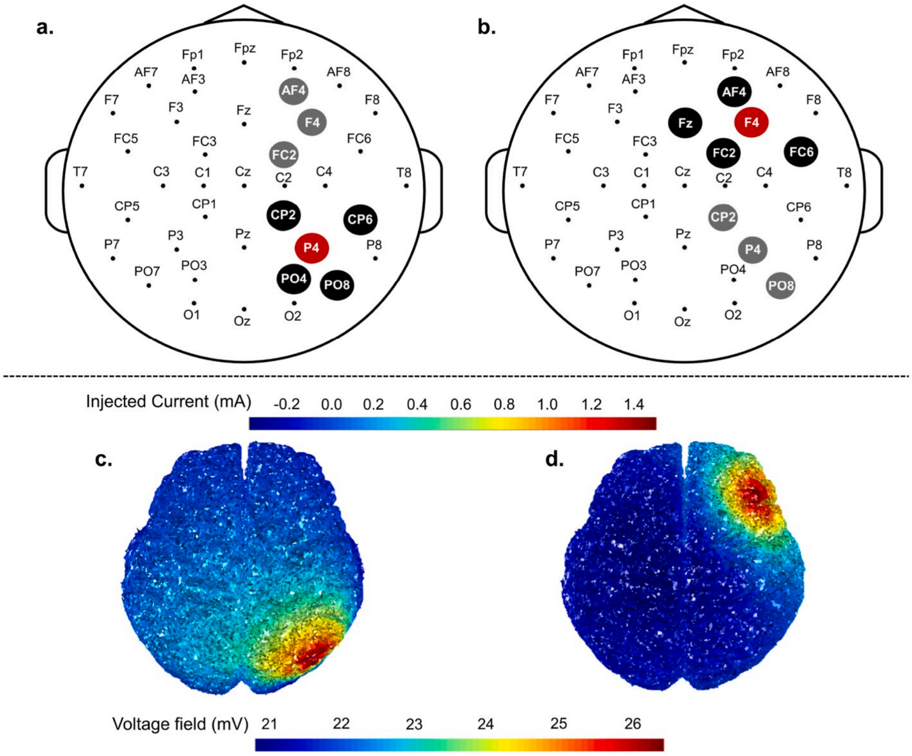

Fig. 2. Electrodes setup and voltage field simulation. The superior panel shows the electrodes setup for (a) HD-tDCS and sham montages over the right PPC, and (b) the HD-tDCS and sham montages over the right DLPFC. Electrodes in red delivered anodal (1.5 mA) current in HD-tDCS conditions, and the black electrodes were set as the return ones. Gray electrodes only registered EEG signal. In addition, in the setup shown in (a), CP4, P4 and PO8 also registered EEG at baseline and post-stimulation periods, and in the setup shown in (b), AF4, F4, and FC2 registered EEG at baseline and post-stimulation periods. The inferior panel shows the simulation of voltage field for (c) HD-tDCS in right PPC and (d) HD-tDCS in right DLPFC. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(i.e., during the real/sham stimulation period). In addition, trials with incorrect responses (4.37%), or with reaction times (RT) below 200 ms or above 1500 ms (1.26%) were excluded from the RT analysis. Two mixed ANOVAs were conducted, with RT or the percentage of errors as dependent variable, and including warning signal (no tone/tone), visual cue (invalid/no cue/valid), and congruency (congruent/incongruent) as within-participants factors.

To analyze the shifts of vigilance components across time-on-task, the EV and AV measures were computed per block of trials from the 1st (i.e., baseline) to the 6th block. In the EV trials, we computed the hits (i.e., correct responses on EV trials) and false alarms (FA, i.e., space bar responses in the ANTI trials) rate, and non-parametric indexes of

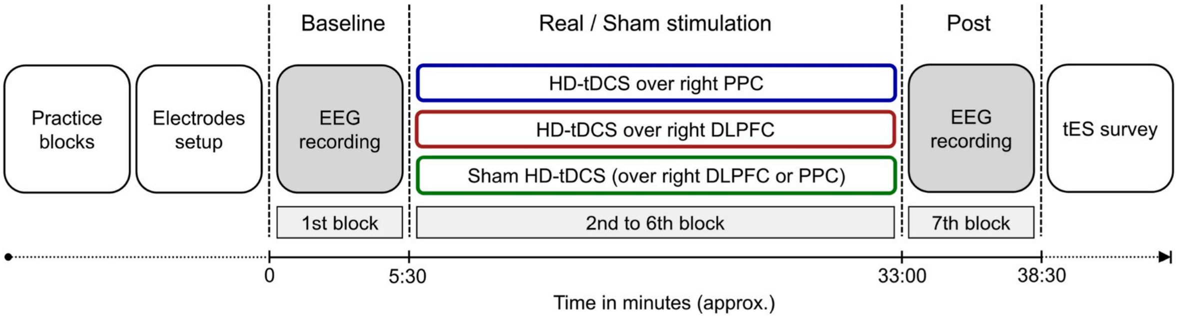

Fig. 3. Session structure. Experimental blocks comprised three different periods: baseline, real or sham stimulation, and post-stimulation.

sensitivity (A′) and response bias (B″) (Stanislaw and Todorov, 1999). With the aim to avoid that a floor effect in FA could masks a considerable shift in the response bias (Thomson et al., 2016), only some ANTI trials were used to compute FA following the method developed by Luna et al. (Unpublished results). In particular, we categorized off-line the ANTI trials as a function of the vertical distance between the position of the target and the closest adjacent flanker, to select only those trials wherein there was a higher chance to observe a FA. Note that, in the ANTI-Vea task, the target and distractors are presented with a random variability on its position (i.e., ±2 px both upwards/downwards and leftwards/rightwards), thus making more difficult the detection the large displacement of the infrequent target in the EV trials (wherein the target is fixed and displaced 8 px, either upwards/downwards). Therefore, the FA rate was computed only considering those trials in which this distance was between 3 and 4 px, and the trials wherein this distance was between 0 and 2 px were excluded from EV analyses.

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

2.5.2. EEG data

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

3. Results and discussion

3.1. Phasic alertness, orienting, and executive control

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 [$F\,(1, 87) = 102.43, p < 001, \eta_p^2 = 0.54$]; errors [$F\,(1, 87) = 16.15, p < 001, \eta_p^2 = 0.16$]), 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 [$F\,(1, 87) = 301.79, p < .001, \eta_p^2 = 0.78$]; errors [$F\,(1, 87) = 20.31, p < .001, \eta_p^2 = 0.19$]), 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 ([$F\,(2, 174) = 99.33, p < .001, \eta_p^2 = 0.53$]; errors, [$F\,(2, 174) = 1.95, p = .145, \eta_p^2 = 0.02$]), 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.

Additionally, the usual two-way interactions were also replicated: Visual cue × Congruency (RT: [$F\,(2, 174) = 8.31, p < .001, \eta_p^2 = 0.09$]; errors: [$F\,(2, 174) = 7.23, p < .001, \eta_p^2 = 0.08$]), Warning signal × Visual cue (only for RT [$F\,(2, 174) = 25.43, p < .001, \eta_p^2 = 0.23$]; errors: [$F\,(2, 174) = 2.11, p = .124, \eta_p^2 = 0.02$]), and Warning signal × Congruency (only for RT: [$F\,(1, 87) = 7.58, p = .007, \eta_p^2 = 0.08$]; errors: $F < 1$), providing additional empirical support in favor of the effectiveness of the ANTI-Vea task to assess both the independence and interactions of the classic attentional functions in the present study (see Tables 1 and 2).

A significant main effect of group was observed for RT [$F\,(2, 87) = 3.71, p = .028, \eta_p^2 = 0.08$], but not for errors [$F\,(2, 87) = 1.03, p = .360, \eta_p^2 = 0.02$]. The PPC HD-tDCS group showed slower RT ($M = 620$ ms, $SE = 17$) as compared to sham ($M = 565$ ms, $SE = 18$) and DLPFC HD-tDCS groups ($M = 561$ ms, $SE = 16$). Note that this effect is unexpected, and likely meaningless, as it was even present in the baseline block [$F\,(2, 87) = 4.37, p = .016, \eta_p^2 = 0.09$].

There were no modulations of HD-tDCS over visual cue (RT: $F < 1$, errors: [$F\,(4, 174) = 2.18, p = .073, \eta_p^2 = 0.05$]) nor congruency (both for RT and errors: $Fs < 1$) effects. Therefore, it might be possible that online HD-tDCS does not effectively modulates orienting, as reported by previous studies with offline tDCS (Lo et al., 2019; Roy et al., 2015). Furthermore, the present results are consistent with previous evidence regarding executive control, wherein no modulation was observed with offline tDCS (Coffman et al., 2012; Lo et al., 2019; Roy et al., 2015).

Interestingly, during the stimulation period, HD-tDCS significantly modulated the main effect of phasic alertness on errors [$F\,(2, 87) = 5.13, p = .008, \eta_p^2 = 0.11$], but not on RT [$F\,(2, 87) = 1.87, p = .161, \eta_p^2 = 0.04$]. Phasic alertness (i.e., the difference between the no tone and tone condition) was importantly reduced in the PCC HD-tDCS ($M = 0.59\%$, $SE = 0.61$) and DLPFC HD-tDCS ($M = 0.83\%$, $SE = 0.59$) groups, in contrast to the sham one ($M = 3.44\%$, $SE = 0.87$). Note that a specific comparison showed a similar reduction in phasic alertness with RT for the PPC (39 ms) and DLPFC (37 ms) HD-tDCS groups compared to the sham one (55 ms), which was significant specifically at the no cue condition [$F\,(1, 87) = 5.33, p = .023, \eta_p^2 = 0.06$], wherein the phasic alertness effect is more clearly observed (Callejas et al., 2004). These results indicates a relevant modulation of phasic alertness under online HD-tDCS regardless the stimulation site, in line with previous evidence concerning a modulation of offline tDCS over phasic alertness (Coffman et al., 2012).

Lastly, HD-tDCS did not modulated neither the two-way interactions

Table 1
Mean correct RT for warning signal, visual cue, and congruency conditions, as a 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)

Table 2
Percentage of errors for warning signal, visual cue, and congruency conditions, as a 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)

(both for RT and errors: all *F*s < 1.20, all *p*s > .300), nor the Warning signal × Visual cue × Congruency interaction (RT: [F (4, 174) = 1.41, p = .229, $\eta_p^2 = 0.03$], errors $F < 1$).

3.2. Executive vigilance

The main effect of group was significantly observed only for FA [F (2, 87) = 5.33, p = .007, $\eta_p^2 = 0.11$], but not for hits [F (2, 87) = 2.62, p = .078, $\eta_p^2 = 0.06$], A′ [F (2, 87) = 1.56, p = .216, $\eta_p^2 = 0.03$] or B″ [F (2, 87) = 2.69, p = .073, $\eta_p^2 = 0.06$]. The PPC HD-tDCS group made more FA (M = 6.01%, SE = 0.71) than the sham (M = 2.98%, SE = 0.72) and the DLPFC HD-tDCS (M = 3.36%, SE = 0.74) groups. Note that the difference in the FA rate between groups was present even in the baseline block [F (2, 87) = 5.76, p = .004, $\eta_p^2 = 0.12$] (see Fig. 4), and so this effect might not be due to HD-tDCS.

As can be seen in Fig. 4, the EV decrement was observed as previously reported with the ANTI-Vea task (Luna et al., 2018). There was a significant decrement on hits [F (5, 435) = 12.34, $p < .001$, $\eta_p^2 = 0.12$] and FA [F (5, 435) = 9.31, $p < .001$, $\eta_p^2 = 0.10$], and as consequence, a relevant decrement of A′ [F (5, 435) = 2.89, p = .014, $\eta_p^2 = 0.03$] and an increment of B″ [F (5, 435) = 7.40, $p < .001$, $\eta_p^2 = 0.08$] across blocks. Note that, interestingly, HD-tDCS modulated the decrement of hits [F (10, 435) = 2.04, p = .028, $\eta_p^2 = 0.04$] and A′ [F (10, 435) = 2.04, p = .028, $\eta_p^2 = 0.04$], but not of FA [F (10, 435) = 1.43, p = .164, $\eta_p^2 = 0.03$] and B″ [F (10, 435) = 1.12, p = .345, $\eta_p^2 = 0.03$].

Thus, while there was no difference on hits at baseline between groups [F (2, 87) = 3.06, p = .052, $\eta_p^2 = 0.07$], the expected linear decrement observed in the sham group [F (2, 87) = 24.72, $p < .001$, $\eta_p^2 = 0.22$], was significantly different compared to that observed in the PPC HD-tDCS [F (1, 87) = 4.54, p = .036, $\eta_p^2 = 0.05$] and the DLPFC HD-tDCS [F (1, 87) = 4.02, p = .048, $\eta_p^2 = 0.04$] groups, which did not differ from

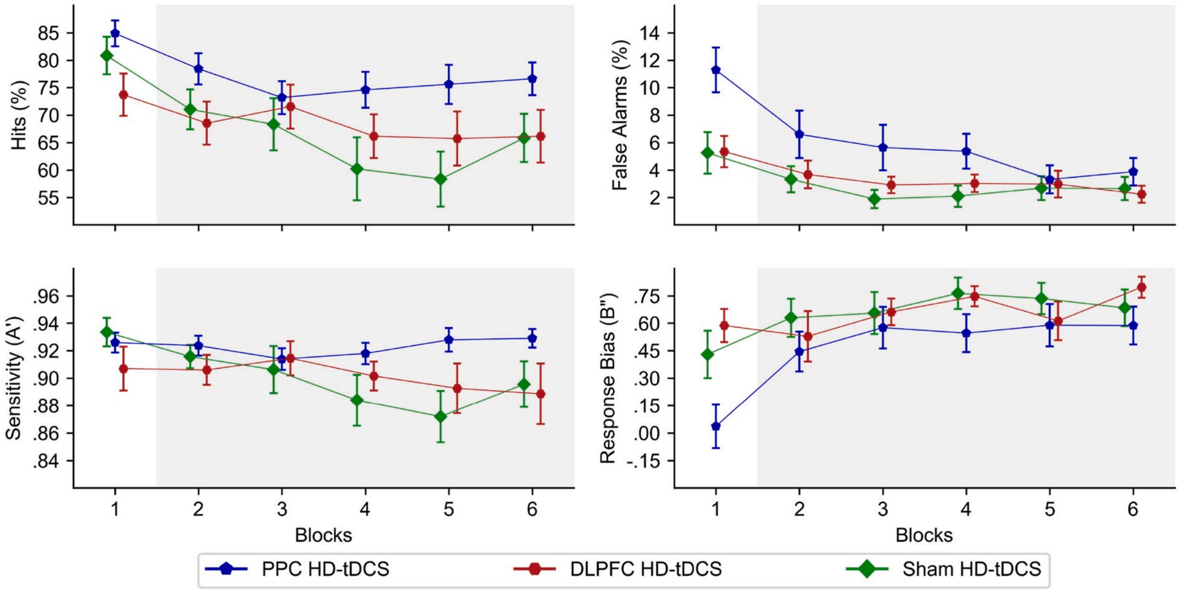

Fig. 4. Executive vigilance decrement as a function of HD-tDCS conditions. Graphs represents the hits (superior left), FA (superior right), sensitivity (inferior left), and response bias (inferior right) per block of trials. The shadowed region at each graph denotes the real/sham stimulation period.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

each other ($F < 1$).

Regarding sensitivity, as observed on hits, groups did not differ on A' at the baseline [F (2, 87) = 1.37, p = .259, $\eta_p^2 = 0.03$]. Moreover, the linear decrement of A' in the sham HD-tDCS group [F (1, 87) = 16.17, p < .001, $\eta_p^2 = 0.16$] was significantly different from that observed in the two HD-tDCS groups [F (1, 87) = 7.53, p = .007, $\eta_p^2 = 0.08$], which did not differ from each other [F (1, 87) = 2.15, p = .146, $\eta_p^2 = 0.02$].

3.3. Arousal vigilance

The main effect of group was found as significant for mean RT [F (2, 87) = 6.49, p = .002, $\eta_p^2 = 0.13$] but not for SD of RT [F (2, 87) = 1.90, p = .155, $\eta_p^2 = 0.04$]. The PPC HD-tDCS group showed slower responses (M = 502 ms, SE = 9), than the DLPFC HD-tDCS (M = 460 ms, SE = 9) and the sham HD-tDCS (M = 468 ms, SE = 9) groups, a difference observed even at the baseline block [F (2, 87) = 4.99, p = .009, η_p^2 = 0.10] and therefore independent of stimulation.

As shown in Fig. 5, the AV decrement was observed as an increment in RT variability across blocks [F (5, 435) = 6.54, p < .001, $\eta_p^2 = 0.07$], with a significant linear component [F (1, 87) = 21.06, p < .001, η_p^2 = 0.19] –a pattern usually observed with the PVT (Basner and Dinges, 2011) and the ANTI-Vea (Luna et al., 2018)–, while mean RT did not change across blocks ($F < 1$). Importantly, neither mean RT nor RT variability changes across blocks were modulated by the HD-tDCS group (both $Fs < 1$).

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

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

For the EV component, hits showed no main effect of group [F (1, 88) = 1.87, p = .174, $\eta_p^2 = 0.02$], but it was observed a clear significant shift across blocks [F (5, 440) = 14.92, p < .001, η_p^2 = 0.14] that was modulated by HD-tDCS [F (5, 440) = 3.00, p = .011, η_p^2 = 0.03]. As depicted in Fig. 6, groups did not differ at the baseline ($F < 1$). Most important, the sham group showed a more prominent linear decrement [F (1, 88) = 25.01, p < .001, η_p^2 = 0.22], in contrast to the HD-tDCS group [F (1, 88) = 8.47, p = .004, η_p^2 = 0.09], which indeed showed no decrement at all within the stimulation period (i.e., from the 2nd to the 6th block: $F < 1$). Therefore, regardless the stimulation site (either DLPFC or PPC), online HD-tDCS effectively mitigates the EV decrement, supporting previous evidence obtained with online tDCS protocols (Nelson et al., 2014).

In contrast, AV (measured as the RT variability) showed a considerable increment across blocks [F (5, 440) = 6.20, p < .001, $\eta_p^2 = 0.07$] with a clear linear trend [F (1, 88) = 18.92, p < .001, η_p^2 = 0.18]. Nevertheless, the RT variability increment was independent of the HD-tDCS group [F (5, 440) = 1.04, p = .392, η_p^2 = 0.01] (see Fig. 6). Lastly, there was not a main effect of group for RT variability ($F < 1$). Thus, in contrast with previous evidence obtained with offline tDCS under sleep deprivation conditions (McIntire et al., 2014), here online HD-tDCS did not reduce the AV decrement.

3.5. HD-tDCS effects on alpha power

Alpha power was not significantly different between groups [F (1, 82) = 1.52, p = .224, $\eta_p^2 = 0.04$], but there were significant main effects for region [F (1, 82) = 51.43, p < .001, $\eta_p^2 = 0.39$] and period [F (1, 82) = 82.89, p < .001, η_p^2 = 0.50] (see Fig. 7). Thus, in line with previous findings with vigilance tasks (Boksem et al., 2005; Clayton et al., 2015), alpha power was higher over the parietal than over the frontal region, and increased notably from the beginning to the task end.

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

Most importantly, there was a significant Group × Region × Period interaction [F (2, 82) = 4.95, p = .009, $\eta_p^2 = 0.11$]. In particular, in the frontal region, alpha power increased significantly between periods [F (1, 82) = 69.25, p < .001, $\eta_p^2 = 0.46$], with no modulation by group (F < 1). Instead, as shown in Fig. 7, in the parietal region alpha power increased differently as a function of group [F (2, 82) = 4.27, p = .017, $\eta_p^2 = 0.09$], with a slighter increment in the PPC [F (1, 82) = 4.00, p = .049, $\eta_p^2 = 0.05$], than in the DLPFC and sham HD-tDCS groups [F (1, 82) = 60.52, p < .001, $\eta_p^2 = 0.42$].

4. General discussion

The present study aimed at examining whether anodal tDCS over the right PPC and DLPFC effectively modulates the attentional networks

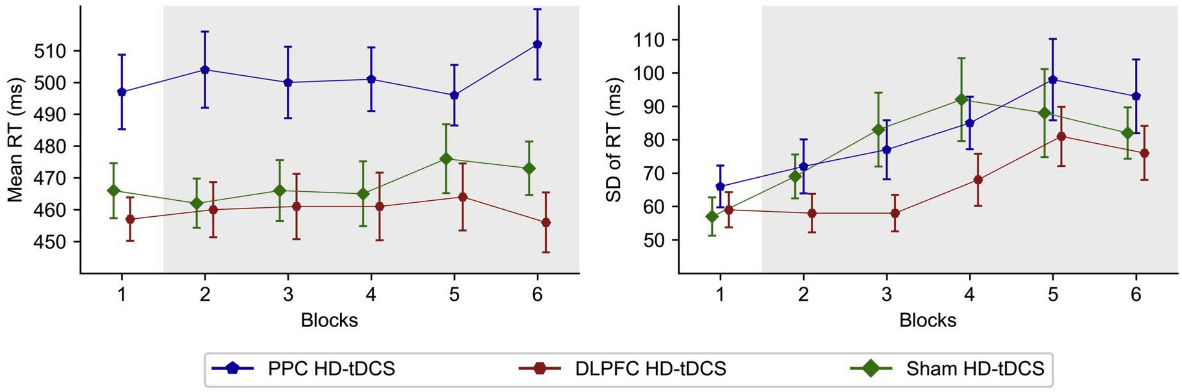

Fig. 5. Arousal vigilance decrement as a function of HD-tDCS conditions. Graphs represents the mean RT (left) and RT variability as SD of RT (right) per block of trials. The shadowed region at each graph denotes the real/sham stimulation period. Error bars shows SE of mean.

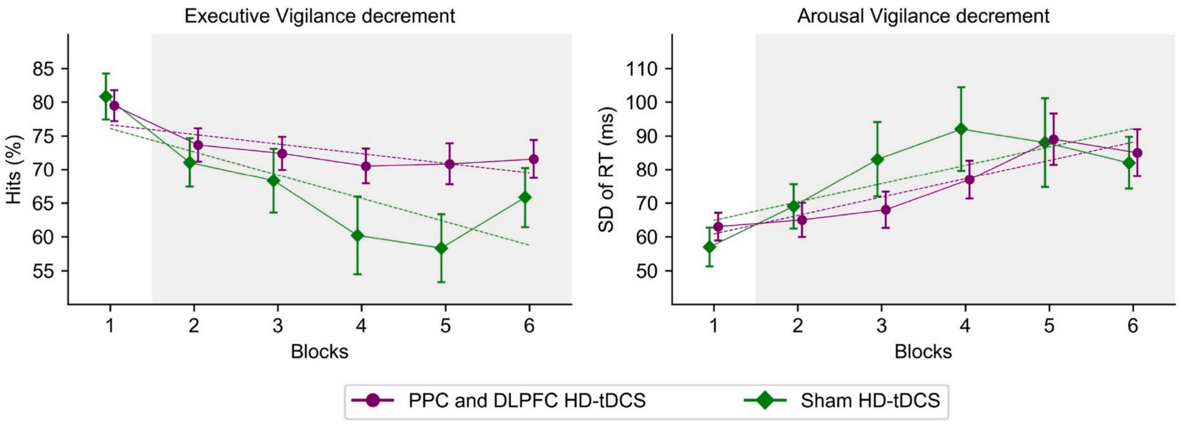

Fig. 6. Executive and arousal vigilance decrement as a function of HD-tDCS in the right hemisphere and sham condition. Graphs represents the hits rate (left) and SD of RT (right) per block of trials. The shadowed region at each graph denotes the real/sham stimulation period. Dotted line represents the linear trend for each dependent variable and group. Error bars show SE of mean.

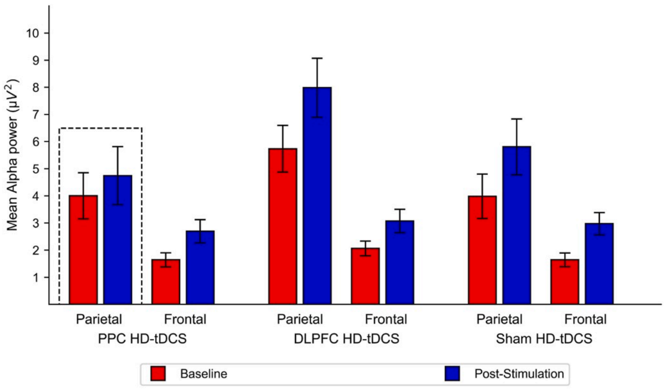

Fig. 7. Mean alpha (7.5–12.5 Hz) power by region (parietal: CP2, P4, PO8; and frontal: AF4, FC2, FC2) as a function of period (baseline/post-stimulation) and group (PPC HD-tDCS, DLPFC HD-tDCS, sham HD-tDCS). Note that the most reduced alpha power shift between periods is observed in parietal region of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

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

It is important to note that here, at difference with previous researches on attention or vigilance with anodal tDCS (Coffman et al., 2012; Lo et al., 2019; McIntire et al., 2017; Nelson et al., 2014; Roy et al., 2015), we assessed multiple attentional and vigilance components within a single task, i.e., the ANTI-Vea (Luna et al., 2018). Although the ANTI-Vea requires several different responses to multiple tasks, it must be noticed that it is indeed as effective as previous versions of the attentional networks test such as the ANTI (Callejas et al., 2004) and the ANTI-Vigilance (Roca et al., 2011) to assess the independence and interactions of the classic attentional components (as demonstrated in the Results of the present study; see section 3.1). In addition, whereas vigilance has been traditionally assessed by single and monotonous behavioral tasks (Thomson et al., 2016), it is worth mentioning that the ANTI-Vea is additionally suitable to assess the EV decrement as in the MCT (Mackworth, 1948) and the AV decrement as in the PVT (Lim and Dinges, 2008). Therefore, while a task with multiple demands might somewhat modify the dynamic of traditional methods to assess attentional and vigilance components, note that our method has already demonstrated to be effective in including a direct and separate measure of several attentional and vigilance functions (Luna et al., 2018). In this context, we found a clear modulation of online anodal HD-tDCS on two distinct components of the alerting network (i.e., phasic alertness and EV, but not AV).

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

Importantly, one of the main findings of the present study is to have shown that online anodal HD-tDCS over the right PPC and the right DLPFC mitigated the EV decrement across time-on-task, but did not modulated the AV one. Note that previous research aiming to modulate vigilance performance by anodal tDCS has found inconsistent results, in particular concerning the EV component (Jacoby and Lavidor, 2018; Nelson et al., 2014). In addition, it is important to highlight that some studies have measured the EV component as the global score of performing a signal detection task (Jacoby and Lavidor, 2018; Roe et al., 2016). However, the vigilance decrement is a phenomenon that is observed as a progressive loss of sustained attention across time-on-task (Hancock, 2017; Mackworth, 1948), and therefore to examine the modulation of anodal tDCS over vigilance the performance should be analyzed as a function of time-on-task. Regarding the AV component, the effects of anodal tDCS were observed in previous studies particularly under sleep deprivation conditions, a state wherein vigilance performance is usually hindered (McIntire et al., 2017, 2014).

In the present study, we examined both vigilance components with a behavioral task (i.e., the ANTI-Vea) that has proved to be suitable to observe both the EV and AV decrement across time-on-task within a single session (Luna et al., 2018). Indeed, note that in an ongoing behavioral study with 617 participants, the linear decrement on hits in the EV component [F (1, 589) = 155.48, $p < .001$, $\eta_p^2 = 0.21$] and the linear increment of RT variability in the AV component [F (1, 589) = 76.40, $p < .001$, $\eta_p^2 = 0.11$] were consistently observed, with both the standard and an online version (https://www.ugr.es/~neurocog/ANTI/) of the ANTI-Vea (Luna et al., Unpublished results). Importantly, here we have demonstrated that anodal online HD-tDCS over the right PPC and the right DLPFC are effective to moderate only the EV decrement, but not the AV one.

Thus, whereas previous studies have reported some overlapped brain activity for the EV and AV components, in the current study we provide novel evidence to support an empirical dissociation at the neural level between EV and AV. For instance, previous studies have found increased activity in the default mode network (i.e., a circuit of medial and posterior regions strongly linked to the cognitive functioning in resting-state) associated with both: (a) the AV component, when performing the PVT task after 36 h of total sleep deprivation (Drummond et al., 2005); and (b) the EV component, when performing a typical signal detection task (Danckert and Merrifield, 2016). Instead, here we have observed that stimulating two core regions (i.e., the right PPC and the right DLPFC) of the attentional networks system while participants perform a multiple attentional and vigilance task (i.e., the ANTI-Vea), mitigates particularly the EV decrement across time-on-task, but not the AV one. Importantly, these results are in line with some recent findings that demonstrated a clear dissociation of vigilance components at the physiological level (Sanchis et al., Unpublished results). In a study conducted in collaboration with sport scientists, we observed that whereas moderate exercise seems to stabilize the RT of responses on EV across time-on-task, the effects of caffeine intake seems to mitigate in particular the AV decrement independently on the exercise intensity (Sanchis et al., Unpublished results).

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

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

In the present research, we observed in a sample of healthy adults a clear mitigation of the alpha power increment over right PPC by anodal HD-tDCS that, nevertheless, seems to be independent on the performance of the vigilance components across time-on-task. Therefore, to further determine the role of the alpha band in the vigilance decrement phenomenon, future research should more deeply examine whether alpha power modulation is exclusively linked to the EV decrement but not to the AV one. In this vein, future studies might consider to modulate alpha power with transcranial alternating current stimulation (tACS), which is indeed a suitable stimulation technique to stabilize specifically a band of electrical cortical rhythms (Fertonani and Miniussi, 2017). For instance, in a recent study it has been proved that if alpha power is stabilized at 10 Hz across time-on-task by tACS in the occipitoparietal cortex while participants perform a signal detection task, then the EV decrement is mitigated in both hits and RT of responses (Clayton et al., 2019). Moreover, future studies might consider to analyze the role of others electrical cortical rhythms, in particular the delta (1–4 Hz) and theta (4–8 Hz) bands, which have been also associated with the AV decrement under sleep deprivation conditions (Hoedlmoser et al., 2011).

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

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

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Prior presentation at meetings

Preliminary results of this work has been presented at the First Joint Congress of the SEPEX, SEPNECA and AIP experimental, developed from 3rd to July 6, 2018 in Madrid, Spain; at the III International congress of Psychobiology, developed from 29th to May 31, 2018 in Granada, Spain; and also at the 60th Annual Meeting of Psychonomic Society, developed from 14th to November 17, 2019 in Motreal, Canada. This paper is part of the doctoral thesis by the first author, under the supervision of the last two authors.

Declarations of competing interest

None.

CRediT authorship contribution statement

Fernando G. Luna: Conceptualization, Methodology, Investigation, Software, Formal analysis, Data curation, Writing - original draft, Visualization. **Rafael Román-Caballero:** Investigation, Software, Formal analysis, Visualization. **Pablo Barttfeld:** Methodology, Software, Formal analysis, Supervision. **Juan Lupiáñez:** Conceptualization, Methodology, Supervision, Funding acquisition. **Elisa Martín-Arévalo:** Conceptualization, Methodology, Supervision, Visualization.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2020.107447.

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