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Effects of conventional and high-definition transcranial direct current stimulation (tDCS) on driving abilities: A tDCS-driving simulator study

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ABSTRACT

Due to the multitasking nature of driving, drivers are physiologically distracted by both relevant and irrelevant environmental stimuli. The ability to select relevant stimuli and suppress irrelevant distractors during driving are two relevant factors for safety. There is a lot of evidence suggesting that the frontal eye field (FEF) plays an important role in target selection and distractors suppression, as well as in attentional mechanisms crucial for safety driving performance. Taking these two points into account, this study was designed to examine the effects of different transcranial direct current stimulation (tDCS) montages over right FEF to determine whether stimulation of FEF could improve attentional mechanisms in a simulated driving environment. Twenty-seven adult participants took part in the study. A specific driving simulator task was developed in which participants had to respond to brake light events of a preceding car in front of them while driving. The second distracting task consisted of road signs of countries and cities that appeared together with braking lights or alone. Participants were required to respond to one of the two categories with their right hand. These two tasks could be performed alone or in a combined condition. Each participant completed three sessions comparing the effects of different tDCS montages, i.e. conventional, focal 4*1 ring high-definition (HD-tDCS) and sham stimulations over the right FEF. Results indicated an overall better performance under the focal HD-tDCS condition. In particular, participants improved their performance both in braking light RTs and in the second distracting task. Taken together these results are interesting from a theoretical and methodological point of view, by demonstrating a direct effect of anodal focal HD-tDCS on FEF in attentional response during an ecological driving task.

1. Introduction

Driving is a complex and multifaceted task that involves several cognitive domains. This process is dynamic and in continuous interaction with the driving environment, influenced by the driver's expertise and susceptible to factors that could compromise the driving performance. Many studies focused on the effect of visual and acoustic distracting stimuli (Karthaus et al., 2018, 2020) in the environment during driving. One of the main causes of traffic accidents is caused by driving distraction, which consists of performing a secondary task that reduces attentional resources from the main task. Driving is itself a multitasking behaviour that involves a variety of tasks. The overall attention resources need to be divided into each single task. In this delicate equilibrium, distractors could disrupt this balance (Johnson et al., 2014; Strayer & Johnston, 2001). Despite acoustic distraction such as the effect of cell phone conversations and conversations with other passengers can have negative effects on different aspects of driving performance (Strayer et al., 2003, 2006; Strayer & Johnston, 2001), it has been demonstrated that the detrimental effect of irrelevant visual distractors is higher than that of acoustic distractors (Sodnik et al., 2008; Wickens &

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Seppelt, 2002). This is due to the fact that in a driving context most of the relevant stimuli are visual. This observation is in line with the multiple resource model by Wickens (2008; 2002), who claims that performing similar tasks (or tasks within the same stimulus modality) is more complex than performing different tasks (or tasks in two different modalities), as attentional allocation and cognitive load are limited in capacity and allocatable amongst different tasks (Horrey & Wickens, 2003).

Furthermore, visual distractors can be relevant to the task (i.e. dashboard light, road signs, hard braking of other motor vehicles), thus, driving itself entails distractions. In fact, drivers were exposed to distractions in their natural driving environment (Stutts et al., 2005). During driving the large part of the distractions come from secondary tasks originated from 91% of the in-vehicle objects (Ma et al., 2018). The information provided by vehicle information systems has recently increased. The In-Vehicle Information System (IVIS), despite the potential to help drivers, has the ambivalent potential to distract drivers. In a simulator study, responding to messages slowed reaction times during tactical braking (Reyes & Lee, 2004). Braking reaction times to hazards were higher in the presence of secondary visual tasks moreover in the complex drive situations (Nowosielski et al., 2018). Thus, driving has its own set of distractions, as well as secondary tasks that may reduce driver attention levels.

In order to improve driving safety and to avoid distraction-related accidents, it is crucial to suppress relevant and irrelevant attention-grabbing stimuli, i.e., an efficient visual selective attention (Forster & Lavie, 2008; Jonides & Yantis, 1988; Marini et al., 2013; Yantis & Jonides, 1990). Congruently, consistent evidence demonstrated that performance in selective attention tests predicts an overall better safe-driving performance (Depestele et al., 2020). In particular, selective attention is related to a better driving performance (Stinchcombe et al., 2011), lower crash rate (Bélanger et al., 2015; Park et al., 2011) and safer lane changing (Park et al., 2011). Furthermore, it has been demonstrated that higher ability on selective attention is associated with less variable lane position (Andrews & Westerman, 2012). Besides, additional attentional mechanisms are crucial for a safe driving performance. Congruently, both younger and older adults who had better divided attention had a lower crash rate, safer speed control, steering, lane changing, and vehicle positioning (Bélanger et al., 2010, 2015; Park et al., 2011). Additionally, better sustained attention was associated with safer speed control and lane changing for both younger and older adults (Park et al., 2011). Finally, for safe driving performance, visuo-spatial cognitive function are essential abilities (Mathias & Lucas, 2009), such as visuo-spatial attention, visuo-motor abilities, executive functions, memory (Anderson et al., 2005), spatial orientation skills (Nori et al., 2020), spatial mental transformation skills (Tinella et al., 2020, 2021) and spatial navigation (Kunishige et al., 2020). This is supported by studies demonstrating that both younger and older individuals who performed better on visuospatial perception tests demonstrated better lane keeping, safer driving performance (Ledger et al., 2019) and fewer car crashes (Michaels et al., 2017).

Numerous functional imaging studies demonstrated that attentional control in the presence of potential distraction is supported by the dorsal frontoparietal attention network, whose core regions include the frontal eye field (FEF) and the posterior parietal cortex (PPC) (Corbetta & Shulman, 2002; Cosman et al., 2018; de Fockert & Theeuwes, 2012, 2012; DiQuattro et al., 2014; Leber, 2010; J. Lee & Geng, 2017; Marini et al., 2016; Serences et al., 2004, 2005; Talsma et al., 2010). Electrophysiological evidence in nonhuman primates demonstrated that both the selection of task-relevant information and suppression of task-irrelevant information involve parietal and frontal cortices, in particular FEF (Heinen et al., 2017; Ipata et al., 2006). Likewise, brain imaging studies in humans also reported a correlation between frontal neural activity and the magnitude of distractor interference, thus indicating a prominent role of frontal regions in actively preventing the interference from irrelevant distractors (Burle et al., 2008; De Fockert et al., 2004; de Fockert & Theeuwes, 2012; Marini et al., 2016) and in divided attentional mechanisms (Nebel et al., 2005). Frontoparietal activation, including the activation of FEF, has been demonstrated for visuo-spatial and divided attentional mechanisms during complex and naturalistic scenes (Fagioli & Macaluso, 2016; Macaluso, 2019). Furthermore, watching driving videos while actively detecting visual stimuli led to increased activation of the attentional networks, including superior parietal lobule, the bilateral superior frontal gyrus, the middle frontal gyrus (MFG) and the FEF (Graydon et al., 2004). Likewise, driving on a drive simulator while detecting visual stimuli confirmed the increased activation of the right superior parietal lobule and FEF, compared to the simulated driving-alone condition (Al-Hashimi et al., 2015).

Noninvasive brain stimulation techniques (NIBS) have proven effective in fostering attentional abilities, by decreasing the negative effects of task-irrelevant distractors. In particular, both transcranial magnetic stimulation (TMS) (Lega et al., 2019) and transcranial direct current stimulation (tDCS) (Cosman et al., 2015) demonstrated a causal involvement of frontal regions in distractor suppression mechanisms. However, only few studies have applied those techniques to complex and ecologically valid environments (Beeli et al., 2008; Choe et al., 2016; Sakai et al., 2014). In particular, tDCS is a portable technique, thus feasible to identify the direct contribution of specific brain regions in complex, human-environments interactions. Previous studies using tDCS over the dorsolateral prefrontal cortex (DLPFC) while driving found promising results for improving driving behaviour (Beeli et al., 2008; Sakai et al., 2014). Using a computerised driving simulator, Sakai et al. (2014) demonstrated that anodal (excitatory) tDCS over right DLPFC improved both car-following and lane keeping behaviour. In addition, Beeli et al. (2008) found that anodal tDCS over right DLPFC led to less risky driving behaviour compared with cathodal tDCS. Although those studies have demonstrated that anodal tDCS over prefrontal cortex does effectively improve attentional mechanisms in several daily life activities such as driving (Beeli et al., 2008; Sakai et al., 2014), the specific effects of anodal tDCS on attentional performance in healthy adults remain uncertain (Coffman et al., 2012; Jacoby & Lavidor, 2018; Luna et al., 2020). In this context, one critical component of tDCS-driven behavioural changes is the focality of stimulation. Indeed, large pad-type electrodes used in previous studies have comparatively poor focality as compared to the 4*1 ring montage with small high-definition electrodes (Focal HD-tDCS), which is suitable to focus transcranial stimulation by surrounding the anodal electrode with a ring of return electrodes (Datta et al., 2009; Dmochowski et al., 2011; Kuo et al., 2013). Indeed, consistent modelling evidence indicated that, by optimising currents to the brain, focal HD-tDCS improve focality to areas of interest by 80%, thus increasing the precision on the cortical region wherein current is delivered (Datta, 2012; Datta et al., 2011; Dmochowski et al., 2011; Edwards et al., 2013; Faria et al., 2011; Kuo et al., 2013). Using this approach, Choe et al. (Choe et al., 2016) demonstrated that HD-tDCS over the right DLPFC improved the performance during a flight simulation task, with this improvement associated with changes in electrophysiological activity (i.e. enhancement of the mid-frontal theta power).

Based on these premises, the aim of this study was to examine the effects of different tDCS montages on right FEF, which is part of the dorsal attentional network, to determine if stimulation of FEF could improve resistance to visual distractors in a simulated driving environment. The right hemisphere was selected based on several studies that indicate that neuromodulation of the right FEF (but not the left FEF) affects both left and right extrastriate visual cortices: Consistent evidence indicated that TMS applied to the right FEF modifies performance on visual tasks in both hemifields, whereas TMS applied to the left FEF only affects the right hemifield (Grosbras & Paus, 2003; Silvanto et al., 2006; Smith et al., 2005). Furthermore, while FEF is generally involved bilaterally in attention control (Corbetta & Shulman, 2002), there is a large body of evidence suggesting a right FEF hemispheric dominance for the control of visuo-spatial attention (Capotosto et al., 2009; Duecker et al., 2013; Grosbras & Paus, 2003; Marshall et al., 2015; Silvanto et al., 2006; Wang et al., 2016), as well in distractor suppression mechanisms (Cosman et al., 2015, 2018; Lega et al., 2019; Suzuki & Gottlieb, 2013). The use of a driving simulator allows for a standardised and systematically controlled evaluation of different driving-related measures and consistent evidence assess the validity of driving simulators in predicting driving performance both in young and older healthy adults (Aksan et al., 2016; Classen, 2014; Eramudugolla et al., 2016; Karthaus et al., 2018, 2020; Lee et al., 2003). In particular, we wanted to investigate the causal contribution of right FEF in affecting driving performance of younger healthy adults, as well as identifying the most effective neuromodulation approach to improve driving behaviour, whether anodal conventional tDCS or anodal focal HD-tDCS.

2. Material and methods

2.1. Participants

Twenty-seven young Italian healthy participants (Mean age = 24.7, *SD* = 2.6, range 21–30; 14 female and 13 male; 25 right handers and 2 left handers) were recruited using our University's Sona System. The inclusion criteria were: age between 20 and 35 years old, having a driving licence for at least two years, normal or corrected-to-normal vision, normal hearing, as reported by participants. The exclusion criteria were: present or history of neurological or psychiatric disorders, epileptic seizures, intracranial metallic implants, cardiac diseases, substance abuse or dependence. These criteria meet the safety guidelines for the use of noninvasive brain imaging techniques (Nitsche et al., 2003; Rossi et al., 2009, 2021; Rossini et al., 2015). A sample of 27 participants allows detecting a medium effect size of $f = 0.25$ with 80% power, at the conventional alpha level of 0.05. Written informed consent was signed from all participants before participating in the study. The study was carried out following the guidelines given in the Declaration of Helsinki and it was approved by the University of Milano-Bicocca Ethical Committee (605/2021; 27/04/2021).

2.2. Driving simulation

The driving simulation task was an adapted version of those used by Karthaus et al. (2018, 2020) and was implemented using a driving simulator software (Carnetsoft BV, Groningen, The Netherlands), using the recommended hardware setup (a Personal Computer equipped with Nvidia Geforce RTX 3080, 3 HP 24" widescreen FHD monitors, Logitech G29 Driving Force steering wheel and pedals). The experiment was conducted at the University of Milano Bicocca in a black-painted laboratory.

Participants sat down at a desk in which a steering wheel and pedals were installed. They viewed the simulated car in a set of three side by side monitors with an angle of about 120°. During the driving simulation task, participants drove a virtual car on a two-lane road and were required to perform two tasks: the brake-light task and the road-sign task. In the brake-light task, participants had to brake as fast as possible with their right foot in response to the brake lights of an oncoming second car moving at a constant distance of 15m in front of the drived car. At irregular intervals between 6 and 8 s, the brake lights of the car ahead flashed up for 500 ms. The speed of the leading car remained constant at 50 km/h and the distance between them did not change after braking. The speed of the main car was not controlled by the participant; instead, it was set by the simulator at a fixed value of 50 km/h, with only subtle variations necessary to keep the distance between the main and leading car constant. Besides responding to the stimuli, participants should also keep the car in the middle of the right lane as accurately as possible using the steering wheel.

During driving, participants had to perform a second go-nogo task, the road-sign task, in which they responded to road signs (768 x 140 pixels) that appeared at random times in the upper part of the road. The road signs looked like highway road signs, and were green with white names. These stimuli could contain 18 names of cities or 18 names of countries in Italian language. The presentation of the stimuli lasted 500ms. Participants were instructed to respond either to the presentation of countries or cities (balanced between participants) by pressing a lever on the steering wheel. Task-relevant and task-irrelevant stimuli (braking and road signs detection) were displayed centrally, thus preventing us from drawing any conclusion about asymmetric tDCS effects.

The two tasks (brake-light and road-sign) could be presented alone or combined, as follows: 72 trials only required to perform a brake-light task; 72 trials required to perform only the road-sign task, with a 50% go and 50% no-go trials; 72 trials combined the two tasks with both the brake light and a road sign appearing. In this combined condition, depending on the road signs, participants had to brake and respond (go condition) or brake only (no-go condition) to road signs, with a balanced proportion of 50% go and 50% no-go trials. The total number of trials were 216 and the whole procedure lasted about 25 min. Braking light foot reaction times and accuracies, as well as road signs manual reaction times and accuracies, were recorded by the software (Fontana et al., 2022).

During the task, for each response, the lane keeping position was recorded using two different metrics. SDLP1 represents the standard deviation of lane keeping position between the target presentation and the response, while SDLP2 represents the standard deviation of lane keeping position between the response and 1.5 s after (Carnetsoft BV, Groningen, The Netherlands). Lab lights were switched off during the simulation. Two experimenters stayed in the lab with the participants for safety reasons but did not interact with participants during the stimulation.

2.3. Conventional tDCS

Transcranial direct current stimulation (tDCS) was administered by a battery-powered constant current stimulator (BrainStim, EMS, http://brainstim.it) using a pair of saline-soaked sponge electrodes (7 × 5 cm: 35 cm^2) retained by an elastic band. The anodal electrode was placed over the right FEF localised to position FC4 in the 10–20 electroencephalography (EEG) system (Herwig et al., 2003), whereas the cathodal electrode was placed over the left supra-orbitary region. This set-up (anodal electrode over FEF with the cathodal electrode over the contralateral supraorbital area) is thought to induce unilateral modulation of FEF and several studies have demonstrated its effectiveness (Esterman et al., 2015; Schall, 2002; Treue, 2003). The stimulation was performed with an intensity of 2 mA in 35 cm^2 which corresponds to a current density of 57 $\mu A/cm^2$.

2.4. Focal HD-tDCS

A multi-channel tES stimulator wearable device (Starstim R32, NeuroElectrics®, Spain) delivered the focal HD-tDCS stimulation. The setup was configured with a central anodal HD electrode (NG Pistim, 12 mm diameter) positioned on the right FEF (FC4) and 4 return electrodes in the adjacent EEG positions (CP4 - FT8 - AF4 and FCZ), forming a "ring" montage (4x1 ring HD-tDCS, see Fig. 1). They were attached to the skin with conduction-enhancing gel by using an electrode cap. The current stimulation through the anode was set to 2 mA, with each return electrode returning 25% of the anodal current. The device was connected via USB port with its software (Neuroelectrics® Instrument Controller (NIC2)) running on a battery-powered laptop computer. Studies showed how changes in cortical excitability, after-effects, safety and tolerability are comparable between HD-tDCS and conventional tDCS (Reckow et al., 2018; To et al., 2016).

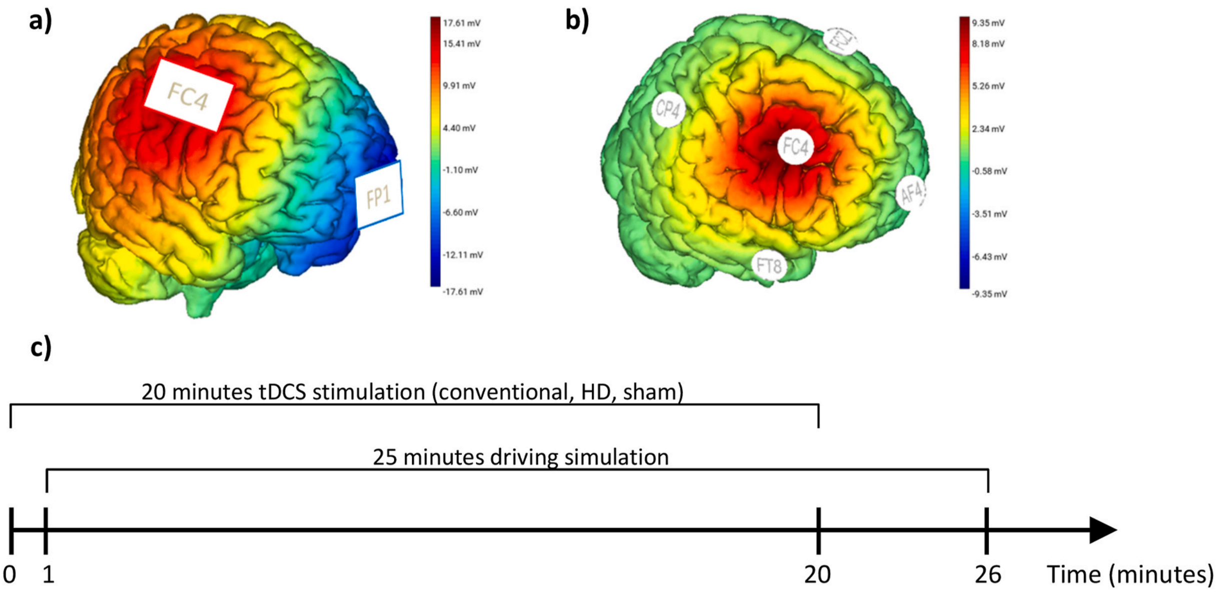

Fig. 1. Simulation of the flow of electric current for conventional tDCS (a) and focal HD-tDCS (b). In (c) was reported the timeline of the whole procedure.

2.5. Procedure

After signing the informed consent, participants filled in the tDCS eligibility questionnaire (Rossi et al., 2021) as well as a series of questions about their driving habits (Table 1) and sleep quality (Table 2). Participants were explained the task on a drive simulator, and they performed a trial task for at least 5 min. Each participant underwent three anodal stimulation sessions: real conventional, real focal HD and sham (balanced between participants using conventional and HD) separated by at least two days. The sequence of stimulation (conventional, focal HD and sham) were counterbalanced between participants. For conventional and focal HD anodal stimulation, the current was ramped up in 10 s, constant at 2 mA for 20 min and then ramped down in 10 s. Previous studies have confirmed that the 2 mA stimulation is safe and more effective than a 1 mA (Fecteau et al., 2007). The stimulation lasted 20 min, as it has been demonstrated that 20 min of 2 mA tDCS results in an excitability enhancement that is still observable 90 min after the end of the stimulation (Cattaneo et al., 2014). In the sham stimulation, the current was ramped up in 10 s and immediately ramped down in 10 s and it had no effects on brain polarisation (Gandiga et al., 2006). After 20 min the ramp-up and down was repeated. Thus, participants experienced the initial and final itching sensation associated with tDCS, but received no active current thereafter. Therefore, real vs. sham tDCS can effectively be blinded for participants, as it prevents cortical excitability from being modulated by sham tDCS (Moos et al., 2012). Finally, participants in each session filled in two questionnaires about presence (Schubert et al., 2001), a series of task-related nuisances questions and the simulation sickness questionnaire (SSQ) (Kennedy et al., 1993).

Table 1
Descriptive results of questionnaire of drive habits.

n.	Question	Results mean (SD), range or yes/no (%)
1	How many years have you had your licence? (years)	6.3(2.5), 3-12
2	Do you currently drive?	26/1 (96.3%/3.7%)
3	How many times do you drive per week? (1–7)	4.5 (2.5), 0–7
4	How many kilometers do you drive per week on average?	104 (124), 0 - 500
5	Do you wear glasses while driving?	17/10 (63%/37%)

Table 2
Questions and results about sleep quality. The value reported represents the mean of the three sessions. * one participant did not fill the questionnaire.

n.	Question	Results mean (SD), range or yes/no (%)*
1	How many hours do you sleep on average per night?	7.4 (0.8), 6–9
2	How many hours did you sleep last night?	7.0 (1.2), 3 - 10
3	Did you happen to wake up during last night? If yes, for how long? (minutes)	7.3 (21.0), 0 - 120
4	How do you rate in general the quality of your sleep last night? (from 1 Very poor to 10 Very good)	7.3 (1.4), 4 - 10
5	Did you consume any activating substances in the 2 h before your arrival (e.g. coffee, tea, fizzy drinks, and alcohol)?	14/64 (17.9%/82.1%)

2.6. Data pre-processing

Since the simulation scenario did not allow implementing a specific time window for responses, a series of slow outliers emerged. In order to remove them, we applied a nonparametric approach and filtered RTs slower than 1.5 times the IQR over the third quartile, separately for each participant and condition. This resulted in the deletion of 4.0% and 3.6% of the trials for the braking and the road sign tasks, respectively. We applied the same outlier-exclusion criterion (1.5 times the IQR over the third quartile) to outliers in the lane-keeping task, which occurred in terms of very strong lane deviation. This resulted in the deletion of 5.6% of trials for braking light and SDLP1, and 4.6% for SDLP2; 6.2% for the Go-NoGo task and SDLP1 and 4.6% for SDLP2.

2.7. Statistical methods

Analyses were performed using linear mixed models (LMM) (Baayen et al., 2008), as implemented by the lme4 package (Bates et al., 2014) in the R statistical software (R Core Team, 2022). In particular, we fitted LMMs predicting foot reaction time for the braking light task, hand reaction times for the go/no-go task, missed response for the accuracy, and standard deviation of lateral position (SDLP) for lane keeping. The analysis design was slightly different based on the task. The braking light task performance indicators (RT, accuracy, and lane keeping) were predicted by two within-person repeated measure factors: Stimuli (with three levels; Lightonly, Go, and NoGo) and tDCS (with three levels: Sham, conventional, and HD). The go/no-go task performance indicators (RT, accuracy and lane keeping) were predicted by two within-person repeated measure factors: Stimuli (with two levels: alone and combined) and tDCS (with three levels: Sham, conventional, and HD). A random intercept by participants was included in all models. Post hoc tests were implemented by using the *pairwise.t.test* function with the Holm correction for multiple comparisons. In the analysis of questionnaire data, we used random-intercept LMM/GLMM ANOVAs to examine whether driving habits, sleep quality, nuisance and presence, and SSQ varied between the three tDCS conditions.

3. Results

3.1. Braking light task

The results of LMM ANOVA on reaction times (RTs, see Fig. 2A) showed a significant main effect of Stimuli [$F_{(2,10704)} = 837.22$, $p < .001$] and a significant main effect of tDCS [$F_{(2,10704)} = 11.16$, $p < .001$]. No significant interaction emerged. Post-Hoc analyses for the main effect of Stimuli showed a significant difference between all kinds of stimuli (all ps $< .001$): RTs were generally slower when two tasks had to be performed, especially if the response needed to be suppressed. For the main effect tDCS, a significant difference emerged between sham and focal HD-tDCS ($p < .01$) and between conventional and focal HD-tDCS ($p < .05$). Regardless of the type of stimuli, focal HD-tDCS significantly decreased RTs compared to both conventional and sham stimulations.

The analysis of missed braking response ANOVA (Fig. 2B) showed only a significant main effect of Stimuli [$F_{(2,208)} = 12.00$, $p < .001$]. Post-Hoc analyses showed a significant difference only between Lightonly – Go ($p < .01$) and Lightonly – Nogo ($p < .005$). Missed braking occurred most frequently when participants needed to perform two tasks simultaneously.

The analyses of lane keeping during the braking light task (Fig. 2C) showed a significant effect of Stimuli [$F_{(2,10973)} = 3117.33$, $p < .001$] in predicting SDLP1. Post-Hoc analyses showed a significant difference between all stimuli (all *ps* $< .001$), with a pattern of results similar to that observed for RTs: Variability in lane keeping increased when a dual task had to be performed, and even more so if the response had to be suppressed. The analysis of SDLP2 did not show significant results.

3.2. Road signs task

The results of LMM ANOVA on RTs (Fig. 3A) showed a significant main effect of Stimuli [$F_{(1,5550)} = 852.69$, $p < .001$] and more importantly a significant effect of tDCS [$F_{(2,5550)} = 20.31$, $p < .001$]. Post-hoc analysis for the main factor tDCS showed a significant difference between sham and focal HD ($p < .005$) and between conventional and focal HD ($p < .001$). These results are in line with the braking light results, indicating that manual responses are significantly affected by the stimulation, with the focal HD-tDCS significantly reducing RTs.

The analysis of missed responses (Fig. 3B) only showed a significant effect of Stimuli [$F_{(1,156)} = 10.26$, $p < .005$].

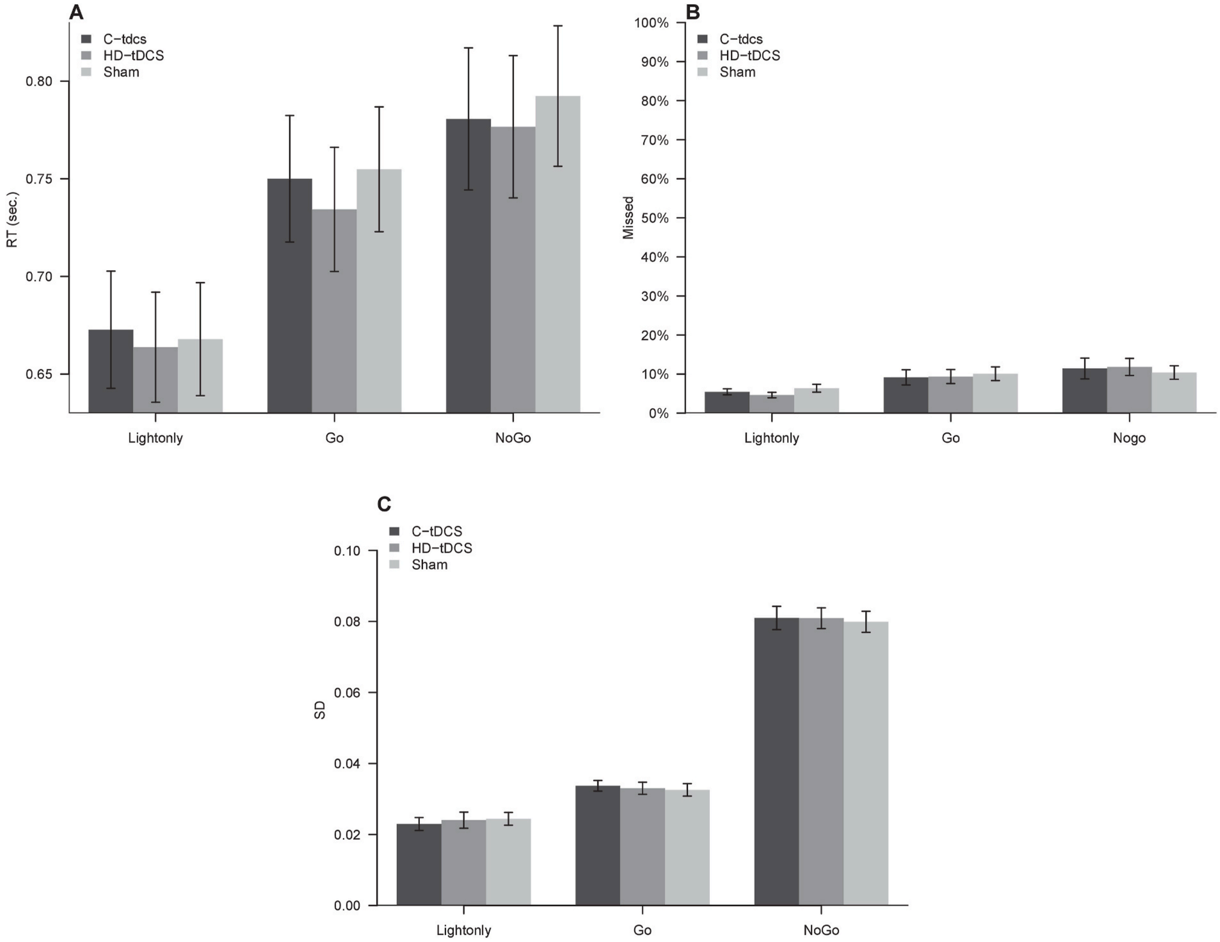

Fig. 2. Composite results of the braking light tasks in different stimulation conditions. A: Foot Reaction Times to braking light. B: Missed response to braking light. C: Lane keeping expressed through SDLP1 during braking light. C-tDCS = conventional stimulation, HD-tDCS = high definition tDCS and Sham = Sham stimulation. Bars represent ± 1 SEM.

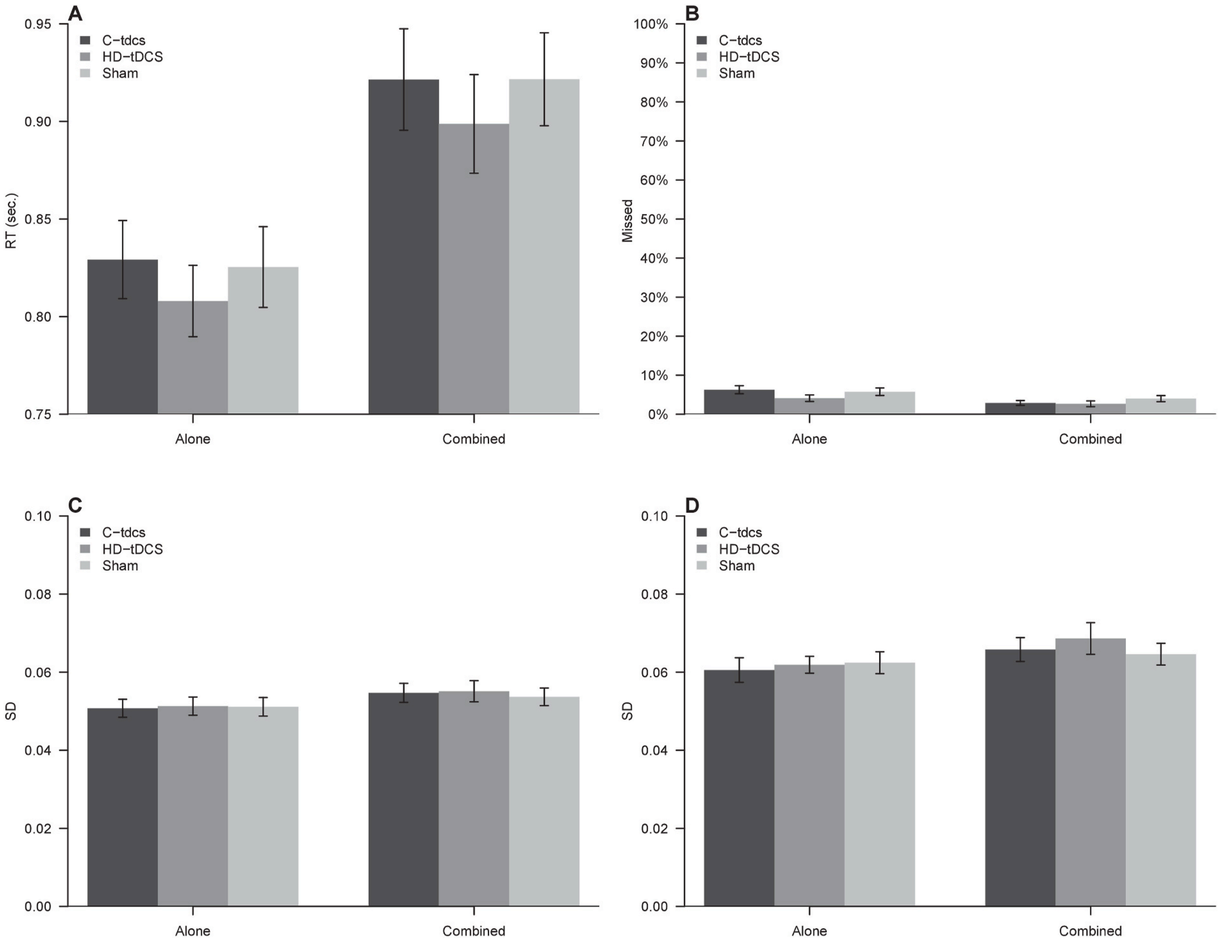

Fig. 3. Composite results of the road signs go/no-go task in different stimulation conditions. A: Hand Reaction Times to road signs go/no-go task. B: Missed response to road signs go/no-go task. C: lane keeping expressed through SDLP1 during road signs go/no-go task. D: lane keeping expressed through SDLP2 during road signs go/no-go task. C-tDCS = conventional stimulation, HD-tDCS = high definition tDCS and Sham = Sham stimulation. Bars represent ± 1 SEM.

The analyses of lane keeping during the road signs task (Fig. 3C and D) revealed a significant effect of Stimuli both for SDLP1, $F_{(1,10909)} = 18.88$, $p < .001$, and for SDLP2, $F_{(1,11096)} = 29.91$, $p < .001$. The pattern of results indicated that whenever two tasks needed to be executed, lane keeping was more variable.

We further compared the proportion of missed responses to the braking light task to the proportion of missed responses to the road signs task during the combined task. The results showed a significant effect of task [$F_{(1,130)} = 25.96$, $p < .001$]: The foot response was missed in the 8.7%, $SD = 7.2$ and the hand response in the 4.3%, $SD = 3.4$. The results thus indicated that in dual tasks that required both braking and responding to road signs, participants were more likely to omit the braking task.

3.3. Questionnaires

Table 1 reports the descriptive results of the questionnaire of drive habits, Table 2 reports those of the sleep questionnaire, and Table 3 those of the questionnaire about presence. Since the questionnaire about sleep quality was administered in each session, a comparison between sessions was performed. Results did not show significant effects of tDCS.

The comparison of the score for each question between tDCS conditions did not show significant differences. The results of the task-related nuisance questionnaire are visible in Table 4. Participants reported itching sensations, which resulted (in different participants and sessions) partially related to stimulation. Conversely, fatigue, drowsiness and concentration problems seemed to be related to driving behaviour. However, these symptoms were not reported in all sessions of stimulation and the most frequent symptom was a prickly sensation. The

Table 3
Results of the four questions about presence. The frequency represents the response in percentage of the three sessions taken together.

Question	Answers (%)						
	Strongly disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
How aware were you of the real world surrounding you while navigating in the virtual world?	20	20	15	20	10	10	5
How real did the virtual world seem to you?	27	21	21	0	0	0	31
How much did your experience in the virtual environment seem consistent with your real world experience	4	4	18	0	35	11	28
In the computer generated world I had a sense of "being there"	15	9	19	9	28	0	19

Table 4
nuisance reported during a driving simulation task. Data were collapsed for all participants and sessions over a total of 81 sessions.

Symptom	Never	Drive	Stimulation	Both
Itch	0	1	40	0
Tingle	0	0	70	0
Burning	0	0	33	0
Redness	0	0	3	0
Neck Pain	0	0	2	0
Head Pain	0	0	2	0
Headache	0	4	6	2
Heat	0	1	8	0
Metallic taste	0	0	1	0
Fatigue	0	15	2	1
Drowsiness	0	28	3	0
Concentration problems	0	21	0	1
Mood changes	0	0	0	0

comparison of these symptoms between tDCS sessions did not show significant differences.

These symptoms appeared, in relation to stimulation: "at the beginning" (50%) and "at the end" (22%) followed by "in the middle" (16%), "to the middle" (6%), "at the beginning and at end" (4%), "from the middle to the end" (2%) and "the whole time" (2%). Finally, the analysis of SSQ questionnaire did not show a significant difference between sessions of tDCS, both for the total score ($p = .44$) and for its subscales (nausea, oculomotor and disorientation, all $ps > 0.43$). Overall, self-report questionnaires did not show differences between the three tDCS conditions in terms of the symptoms reported by participants.

4. Discussion

The aim of this study was to examine the effects of different tDCS montages, conventional and focal HD-tDCS, over right FEF to assess if these stimulations could improve driving performance in an immersive simulated driving environment. Overall, the results have shown a specific influence of focal HD-tDCS on performance. In particular, we demonstrated that right FEF stimulation significantly improves driving performance, by decreasing reaction times both in response to brake lights of a preceding car and in manual responses to relevant visual distractors during driving. Taken together, these results attest the causal contribution of a key node of the fronto-parietal attention network, namely the Frontal Eye Field (FEF), in attentional mechanisms that are necessary for a safe driving behavior. Furthermore, from a methodological perspective, results suggest the 4*1 ring HD-tDCS as the most effective neuromodulation protocol to improve attentional-related driving skills.

Driving abilities and response to visual distractors were assessed using an adapted version of Karthaus et al.'s (2020) driving simulator task. This task is meant to reproduce the basic processes that can affect driving performance in real-life complex situations. When driving, distractions can arise from sources such as driving navigators or the IVIS, the presence of complex roads, traffic signs, or traffic flows, just to mention a few examples (Horberry et al., 2006; Strayer & Johnston, 2001). In our driving task, they were mimicked by a secondary task requiring participants to respond to road signs. Results at the behavioral level showed that, compared to a simple braking condition, participants exhibited longer response times when they were forced to perform two tasks at the same time, with this effect particularly pronounced when the secondary task (road-sign detection) required the inhibition of response (No-Go condition). These results perfectly replicated Karthaus et al.'s findings (2018, 2020). Furthermore, this study confirmed the findings of environmental studies, which indicated that the presence of a secondary task, even if part of a normal driving environment, can lead to distractions (Stutts et al., 2005), particularly if the secondary information needs to be processed in order to be recognized and classified as irrelevant for driving (Ma et al., 2018). Interestingly, in the dual task condition, participants tended to omit more frequently the braking task compared to the secondary task. This result, which has practical implications for safe driving, is in line with Wickens' multiple resource theory, which states that the distraction effect is increased when the stimulus and distractor are presented in the same modality (Palmiero et al., 2019; Wickens, 2008; Wickens & Seppelt, 2002). This suggests that devices such as IVIS, increasingly present in today's vehicles to facilitate driving, may also be a source of unwanted interference, especially when information is presented in a visual format (e.g., dashboard).

Neuromodulation results were particularly interesting. Focal HD-tDCS enabled to assess the causal contribution of the right FEF during a driving performance: the anodal stimulation effectively enhanced the visual selective attention by improving the reaction times in two different tasks connected to driving behavior. This result well aligns with the general idea that the human FEF is responsible for target selection and for filtering task-irrelevant visual information (Shimamura, 2000; Kane and Engle, 2002; de Fockert et al., 2004; de Fockert & Theeuwes, 2012; Geng, 2014; Marini et al., 2016). Furthermore, previous neuromodulation studies using computerised attentional tasks demonstrated that the selective stimulation of right FEF can increase attentional abilities, in particular by decreasing the negative effects of task-irrelevant distractors (see Lega et al., 2019).

Furthermore, the significant positive effect of focal HD-tDCS generalised to all our experimental conditions (brake light alone, brake light plus go condition, brake light plus no-go condition and go condition alone). In light of these results, we cannot exclude the possibility that the observed tDCS effect is not exclusively attributable to an increase in selective attention and distractor suppression mechanisms, but also in divided and sustained attention. Indeed, all these forms of attention are supported by the dorsal frontoparietal attentional network and more importantly are related to a better driving performance (Depestele et al., 2020). Future studies are needed to better understand the selective involvement of each sub-component of attention in driving behaviour, as well as their neural substrates. Additionally, considering that FEF is generally involved bilaterally in attentional control (Corbetta & Shulman, 2002) it would be interesting to explore the effect of left FEF tDCS stimulation on driving performance. Finally, given the pivotal role of FEF in the execution of some of visuospatial tasks related to driving performance (Burle et al., 2008; Cohen et al., 1996; Weiss et al., 2009) and the fact that FEF primarily represents contralateral space (Crapse & Sommer, 2009), it would be interesting for future studies to investigate the effect of lateralized presentation of target and distractors stimuli. The present findings demonstrated for the first time that the selective stimulation of right FEF is able to modulate attentional performance also during complex real-life situations, corroborating the idea that HD-tDCS can offer a promising neuromodulation technique to those interested in enhancing performance in challenging real-life situations (Choe et al., 2016). Crucially, conventional tDCS did not significantly affect driving performance. It is noteworthy that the null effect obtained by conventional tDCS is not in line with previous studies applying this stimulation on the right FEF in order to actively modulate attention (e.g. Diana et al., 2021), and more generally with studies investigating tDCS modulation of driving behavior (e.g. Beeli et al., 2008; Sakai et al., 2014). One important difference from previous studies that used conventional tDCS to modulate driving performance (Beeli et al., 2008; Sakai et al., 2014) is the localization of the stimulation site, which indeed focuses on the role of the dorsolateral prefrontal cortex (DLPFC). Given the higher spatial resolution of HD-tDCS, an important future development is to use this technique to disentangle the selective role of FEF and DLPFC in attentional abilities during driving performance. Furthermore, it is noteworthy that mixed and negative results after conventional tDCS neuromodulation are not uncommon (Jacoby & Lavidor, 2018; Maddaluno et al., 2019; Massetti et al., 2022; Radman et al., 2018; Reteig et al., 2018; Tseng et al., 2018), and we argue that more research is needed to evaluate the possibility to use tDCS to modulate attention-related driving behavior. Importantly, from a tolerability point of view, no differences were systematically found between tDCS stimulation sessions, replicating and confirming the high tolerability of HD-tDCS (Borckardt et al., 2012). Indeed, we found the most common symptoms associated with stimulation: itching, tingling and burning sensation, were independent from the stimulation used. This observation allows us to exclude that the results obtained may depend on different degrees of discomfort associated with the different types of stimulations.

In the present study, we tested only young adults in a restricted age range. This can be considered as a potential limitation, especially considering that age has been demonstrated to affect not only driving abilities but also sensitivity to distractors (Karthaus et al., 2020). This is particularly true for the older population which is more sensitive to distraction and attentional decline (Ashinoff et al., 2019; Bauer et al., 2012; Gazzaley et al., 2005; Madden et al., 2014; Mevorach et al., 2016; Potter et al., 2012; Tsvetanov et al., 2013), which is neurally associated with anatomical alteration in white matter integrity (Bennett et al., 2012; Bennett & Madden, 2014; Lockhart et al., 2015) and increased compensatory activity in the frontoparietal attention network (Reuter-Lorenz & Park, 2010). This age-related decline in attentional mechanisms can be one of the reasons why older drivers have a higher risk of involvement in vehicle car crashes (Depestele et al., 2020; Langford & Koppel, 2006; Lombardi et al., 2017). However, driving is a crucial part of older persons' life and previous studies indicated that driving cessation has detrimental psychological and neural consequences (Burkhardt, 1999; Chihuri et al., 2016; Siren & Haustein, 2015; Yamin et al., 2015). The identification of neurophysiological and functional markers is necessary for designing targeted strategies aimed at maintaining and improving safe driving behaviour both in the younger and older population. Clarifying the cognitive and neural mechanisms underlying vehicle driving, as well as using advanced technology such as state-of-the art driving simulators and virtual reality environment, will be of vital importance for the development of transportation safety systems and neurorehabilitation strategies.

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