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Repeated Use of Transcranial Direct Current Stimulation Over the Dorsolateral Prefrontal Cortex Before Training Changes Visual Search and Improves Decision-Making Response Time in Soccer Athletes

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1 Repeated use of transcranial direct current stimulation over the dorsolateral prefrontal cortex  
2 before training changes visual search and improves decision-making response time in soccer  
3 athletes

4

## 5 Abstract

6 The study aimed to analyze the effect of anodal transcranial direct current stimulation  
7 (a-tDCS) over the left dorsolateral prefrontal cortex on soccer athletes' decision-making and  
8 visual search behavior (VSB). It is a single-blind, randomized, and experimental investigation  
9 with parallel groups. The twenty-three soccer athletes were pair-matched according to  
10 decision-making performance (pass) and, then, randomized into two groups: a-tDCS (n = 11)  
11 and Sham (n = 12). The decision-making (passing during small-sided game and screen task)  
12 and visual search behavior (number of fixations and duration of fixation during the small-  
13 sided game) were measured before (baseline) and after (post-experiment) the eight weeks  
14 intervention. Only the a-tDCS group reduced response time in the decision-making screen  
15 task ( $p < 0.05$ ). The a-tDCS group increased the number of fixations ( $p < 0.05$ ) and showed a  
16 higher number of fixations in comparison to the Sham group ( $p < 0.05$ ) during the small-  
17 sided game. The a-tDCS group showed a lower duration of fixation in comparison to the  
18 Sham group ( $p < 0.05$ ) in post-experiment during the small-sided game. Our results support  
19 the effectiveness of using a-tDCS over left DLPFC to change visual search behavior and  
20 improve the response time of decision-making skills in soccer athletes.

21 *Keywords:* cognition, neuroscience, athletic performance, psychology, skill.

22

## 23 **Introduction**

24 Transcranial direct current stimulation (tDCS) is a noninvasive, low intensity, well-  
25 tolerated electrical brain stimulation technique that modulates neurons' membrane potential  
26 and affects the cortical function (Huang et al., 2019; Nitsche & Paulus, 2000). Studies have  
27 shown that applying anodal (a-tDCS) or cathodal (c-tDCS) direct currents to the cortical  
28 surface leads to neuronal excitement or inhibition, respectively (Steinberg et al., 2019). Thus,  
29 it seems that tDCS increases physical and cognitive performance in athletes, which is  
30 considered a promising ergogenic tool (Angius et al., 2017, 2019; Edwards et al., 2017;  
31 Machado et al., 2019). Although some studies lack ecological validity and others reported  
32 small sample sizes, it seems plausible that these emerging techniques will be a legitimate way  
33 to enhance cognitive performance in sports (Colzato, Stern, & Kibele, 2017).

34 The effects of noninvasive brain stimulation procedures on athletic performance, such  
35 as tDCS, have been investigated in several studies (Colzato et al., 2017; Machado et al.,  
36 2019; Moreira et al., 2021). The studies have been showing that when applied over the  
37 prefrontal cortex or dorsolateral prefrontal cortex (DLPFC), a-tDCS improves executive  
38 functions (e.g., inhibitory control and attention) (Angius et al., 2019; Borducchi et al., 2016)  
39 and wellbeing in athletes (Moreira et al., 2021). For example, Angius et al. (2019) found an  
40 improvement in Stroop task (i.e., improved accuracy) following a-tDCS over the left-DLPFC.  
41 Moreira et al. (2021) found increased wellbeing following official soccer matches in  
42 professional male players after a-tDCS over the left-DLPFC. Other studies stimulated  
43 different cerebral areas by tDCS. Antal et al. (2004) found that the tDCS applied over the  
44 visual cortex improved motion perception in the visuomotor tracking task. Harris et al. (2019)  
45 found no effect of tDCS over the frontal, motor, or visual cortex on the performance of a self-  
46 paced visuomotor skill in amateur golfers. These scientific investigations abovementioned  
47 analyzed the acute effect of tDCS. Although the tDCS seems to be an interesting strategy in

48 sports performance, it becomes essential to investigate the repeated use of tDCS on  
49 perceptual-cognitive skills.

50         In the long-term, the repeated use of tDCS seems to improve cognitive abilities, such  
51 as inhibitory control, attention, and memory (Borducchi et al., 2016; Lo, Van Donkelaar, &  
52 Chou, 2019). However, a few investigations focused on testing the effectiveness of the tDCS  
53 on perceptual-cognitive skills in a more ecologically setting for team sports context, and the  
54 current evidence on perceptual-cognitive skills seems insufficient to encourage the use of  
55 tDCS in athletic routines (Harris et al., 2019).

56         A combination of general visual skills (e.g., visual search behavior) and performance-  
57 relevant perceptual-cognitive skills (e.g., decision-making) are essential to elite athletes'  
58 performance in team sports, mainly because those modalities require attention in different  
59 visual key areas related to decision-making with high speed, accuracy, and complexity  
60 (Faubert & Sidebottom, 2012; Hadlow et al., 2018). In this sense, perceptual-cognitive skills  
61 are crucial for team sports, especially soccer, due to great cognitive and sustained attention  
62 demands to make quick and accurate decisions based on the perceived information from a  
63 dynamic environment (North & Williams, 2008; Romeas et al., 2016; Smith et al., 2016).

64         There are three theoretical frameworks to explain the decision-making in team sport  
65 athletes [e.g., processing information (cognitive knowledge), ecologic dynamic (perception-  
66 action coupling), and naturalistic] (Ashford, Abraham, & Poolton, 2021), which are from  
67 inherently different views of human behavior (Cotterill & Discombe, 2016). It is important, at  
68 this point, to clarify the focus on decision-making adopted in the present paper. Decision-  
69 making is known as a deliberate process of selection. Expert players excel in their capability  
70 to extract and process cues from the environment, recognize and interpret familiar patterns of  
71 play, and form expectations by computing situational probability (Ashford, Abraham, &  
72 Poolton, 2021). These selection processes are an intermediate agent between what a player

73 perceives and how a player responds to the play unfolding about them. In that sense, the  
74 present study utilizes processing information and naturalistic approaches to explain decision-  
75 making. The processing information perspective defines decision-making as a structured and  
76 higher cognitive process (Cotterill & Discombe, 2016).

77 On the other hand, the naturalistic perspective assumes that decisions are made by  
78 holistic evaluation of potential courses of action. Also, the decisions are based on the  
79 decision-maker relying on recognizing the situation and pattern of actions rather than  
80 comparing alternatives (Cotterill & Discombe, 2016). According to the naturalistic  
81 perspective, the decision maker's workload, task familiarity, and level of experience appear to  
82 be crucial for decision-making (Ashford, Abraham, & Poolton, 2021).

83 Regardless of the theoretical framework of decision-making adopted for the present  
84 investigation (i.e., processing information or naturalistic), the visual search behavior is part of  
85 the mechanisms or pathways that can explain decision-making in sports (Vaeyens, Lenoir,  
86 Williams, & Philippaerts, 2007). Changes in visual search patterns, such as the number and  
87 duration of fixations, are often considered essential factors underlying the mechanisms of  
88 decision-making skills (Afonso et al., 2012; Smith et al., 2016; Vaeyens, Lenoir, Williams,  
89 Mazyn, & Philippaerts, 2007). Regarding visual search behavior in team sport athletes,  
90 previous studies revealed a higher quiet eye pattern for skilled players than the less skilled  
91 ones (Lex et al., 2015; Roca et al., 2013). However, previous results have shown that many  
92 fixations of relatively short duration are required to make athletes aware of other players'  
93 positions, movements, and passing opportunities (Afonso et al., 2012; Fortes et al., 2021;  
94 McRobert et al., 2011; Vaeyens et al., 2007; Smith et al., 2016). Some scientists attributed the  
95 higher number of fixations made by skilled players to their tendency to search for additional  
96 locations to identify the gaps between opponents (Fortes et al., 2021; McRobert et al., 2011).

97 The authors of these studies seem to agree that differences in fixations reflect the ability of  
98 skilled players to adapt their visual search behavior to the continuously changing demands.

99 Both visual search behavior and decision-making skill depend on attentional resources  
100 and executive functions (Hülsdünker, Strüder, & Mierau, 2018), such as inhibitory control  
101 and memory (Angius et al., 2019; Minati, Campanhã, Critchley, & Boggio, 2012). Moreover,  
102 brain areas as the prefrontal cortex (PFC), DLPFC, and anterior cingulate anterior (ACC)  
103 regulate these cognitive abilities (Angius et al., 2019; Li et al., 2021). Hence, positive  
104 changes in an athlete's visual search behavior might improve decision-making accuracy and  
105 response time. Thus, ergogenic tools that might fire and recover brain areas linked to these  
106 cognitive abilities might help athletes' performance.

107 A recent study revealed that catecholamines increase activity (e.g., dopamine and  
108 norepinephrine) in the brain's front region improved attentional resources and executive  
109 functions (McMorris, 2020). Interestingly, the increase of cortical excitability in these brain  
110 areas induced by a-tDCS might increase norepinephrine neurotransmitter activity (Adelhöfer,  
111 Mückschel, Teufert, Ziemssen, Beste, 2019). In addition, the DLPFC seems to have a critical  
112 role in cognitive control, decision-making, and approach motivation (Grandperrin et al.,  
113 2020). Thus, using a-tDCS on frontal brain areas, such as the DLPFC, might be a promising  
114 strategy to improve perceptual-cognitive abilities (e.g., decision-making and visual search  
115 behavior) in soccer athletes.

116 According to the identical elements' theory (Dahlin, Neely, Larsson, Bäckman, &  
117 Nyberg, 2008), perceptual-cognitive skills, as decision-making and visual search behavior,  
118 can be improved with off-field training that stimulates similar brain areas. Therefore, it is  
119 reasonable to speculate that the a-tDCS might activate brain areas commonly stimulated in  
120 soccer games, such as the DLPFC or visuomotor system (Hülsdünker, Strüder, & Mierau,  
121 2018). In this case, a positive cognitive-transfer effect might occur to specific perceptual-

122 cognitive skills (e.g., visual search and decision-making task) in soccer match situations.  
123 Complexity and creative solutions in sports decision-making situations seem to recruit  
124 general-domain brain networks, supporting executive functions and semantic memory  
125 demands controlled by the frontal brain area (Fink et al. 2019), for example, the DLPFC.  
126 Thus, the objective of this study was to analyze the long-term effect of a-tDCS in DLPFC on  
127 decision-making and visual search behavior in soccer athletes. We expected that a-tDCS over  
128 the DLPFC would promote improvements in decision-making performance and changes in  
129 visual search behavior in soccer athletes.

130

## 131 **Materials and Methods**

### 132 **Participants**

133 A priori sample size calculation was performed using G\*Power software version  
134 3.1.9.2 (Universität Kiel, Kiel, Germany), for an analysis of variance (ANOVA) with  
135 repeated measures within-between groups interaction using the option “ANOVA: repeated  
136 measures, within-between factors interaction” for decision-making skill (Gantois et al.,  
137 2020), including the following criteria: (a) power = 0.8; (b) medium ES ( $\eta^2 = .07$ ); (c)  $\alpha$   
138 = .05; (d) the number of groups = 2; (e) number of measurements = 2; (f) correlation among  
139 repeated measures = 0.5; and (g) nonsphericity correction = 1. Results indicated that twenty  
140 subjects would be necessary for the study. An additional 30% of subjects were recruited to  
141 prevent any dropout, totaling 26 participants. Using the non-probabilistic method for sample  
142 recruitment, twenty-six male soccer athletes were recruited for this investigation ( $M = 22.6$   
143 years,  $SD = 2.3$ ;  $M = 76.2$  kg,  $SD = 5.9$ ;  $M = 1.75$  m,  $SD = 0.06$ ). They played at the third  
144 division of the Brazilian Championship of Soccer for an average of 8.5 years ( $SD = 2.7$ ).  
145 They were randomly divided into two equal groups: a-tDCS and Sham groups. Three soccer  
146 athletes (one of a-tDCS and two of the Sham group) were excluded from the study because of

147 absence in over 10% of experimental sessions and muscle-skeletal injury. All experimental  
148 sessions were conducted during the participants' in-season; therefore, they participated in  
149 team practices during the study. The local Ethics committee approved the study, and we  
150 followed all the guidelines of the Declaration of Helsinki.

151

## 152 **Experimental design**

153 It was a single-blind, randomized, and experimental investigation with parallel  
154 groups. The participants underwent the ten weeks of experiment (1-week = baseline  
155 assessment; 8-weeks = experimental sessions [five sessions per week]; and, 1-week = post-  
156 experiment assessment) (Figure 1). The athletes performed 40 experimental sessions (a-tDCS  
157 or Sham) and 54 training sessions that involved physical, technical, and tactical skills.

158 The athletes were pair-matched according to decision-making performance (pass)  
159 and, then, randomized into two groups: a-tDCS (n = 11) and Sham (n = 12). Regarding the  
160 randomization, the survey coordinator manually generated numbers to determine the  
161 allocation of athletes in each group. The randomized distribution between a-tDCS and Sham  
162 was stratified by a website ([www.randomizer.org](http://www.randomizer.org)). After randomization, it was not necessary  
163 to counterbalance the groups. It is important to highlight that the 54 training sessions were  
164 standardized between groups. Only the experimental sessions (a-tDCS or Sham) were  
165 different between groups.

166 The decision-making and visual search behavior (number of fixations and fixations  
167 duration) were measured before (baseline) and after (post-experiment) the eight weeks of  
168 intervention. It was adopted an interval of 48-72 h between each test in both baseline and  
169 post-experiment. For passing decision-making and visual search behavior analysis, the  
170 athletes participated in small-sided games (SSG) with configurations of 5 vs. 5 with the  
171 goalkeeper, adopting official soccer rules. The SSG was filmed using a CANON® camera

172 (SX60 model, Yokohama, Japan) to analyze passing decision-making performance further, as  
173 well as the athletes used a head-mounted eye-tracking device to analyze visual search  
174 behavior. The decision-making performance was evaluated for soccer-specific tasks with  
175 film-based simulations of offensive soccer playing (Vaeyens, Lenoir, Williams, Mazyn, et al.,  
176 2007).

177         The participants abstained from any physical exercise and alcohol ingestion 24-h  
178 before testing during the eight weeks of the experiment and abstained from caffeine at least  
179 3-h before each training session.

180

181

**\*\*\*Figure 1\*\*\***

182

183 *Brain stimulation.* The a-tDCS or Sham was applied using an automated tDCS device  
184 (MicroEstim, NKL, São Paulo, Brazil). The anodal electrode was positioned over the left  
185 DLPFC (F3, according to the international 10–20 EEG system), and the cathodal electrode  
186 was placed over the right shoulder (see Figure 1). The a-tDCS was applied with 2.0 mA for  
187 15 min using rubber conductive electrodes (5 x 5 cm; 25 cm<sup>2</sup>; 0.08 mA/cm<sup>2</sup>) covered with  
188 sponges soaked in saline solution (0.8% NaCl). The current was ramped up and down at the  
189 beginning and end of a-tDCS for 30-s. The impedance was kept below 20 Kohm during a-  
190 tDCS. For the Sham group, the same montage was used, but the current was turned off after  
191 30-s. The participants reported itching and tingling sensation under the electrodes during  
192 tDCS but did not report any adverse effects. tDCS or Sham intervention was performed in a  
193 single-blind configuration.

194

195 **Measures**

196            Passing decision-making and visual search assessments were conducted during  
197 standardized SSG before and after the intervention period. SSG consisted of standard 5 vs. 5  
198 soccer matches with the goalkeeper on a 40 m x 30 m interior turf soccer field to avoid  
199 weather influence. Every player participated in four halves of a 5-min of a 20-min total,  
200 adopting 3-min rest between the halves. Players who were waiting for the start of the next  
201 game were stretching or exercising with the ball. SSG was recorded using two video cameras  
202 (Canon<sup>®</sup> SX60, Japan). Cameras were positioned in the stadium's bleachers, approximately  
203 10 m above the playing field, covering the entire playing area. Jerseys and numbers identified  
204 players, and the video recordings were analyzed using Dartfish Connect v6.0.

205            Decision-making skill was assessed adopting a visual screen task. The soccer players  
206 watched film-based simulations of offensive soccer playing, projected onto a 4.3 × 2.5-m  
207 screen positioned 4.4 m in front of the participant. This assessment was conducted before and  
208 after the intervention period.

209

210 *Passing decision-making in SSG.* The passing decision-making skill was coded using  
211 standardized coding criteria adapted from a previous study (Romeas et al., 2016). The  
212 decision component involves the selection of the skill (e.g., pass), as well as which teammate  
213 to pass. The quality of each decision was coded as 1 for an appropriate decision and 0 for an  
214 inappropriate decision according to the following criteria: 1) one point decision; the player  
215 made a good decision when the pass went to an open teammate and: a) directly or indirectly  
216 created a shot attempt, or; b) passed the ball to a teammate who was in a better position than  
217 himself; 2) zero-point decision; the player made a poor decision when the pass because: a) he  
218 passed the ball to a player who was closely guarded or when there was a defensive player  
219 positioned in the passing line, or; b) the pass was intercepted or turned over, or; c) the pass  
220 was directed to an area of the field where no teammate was positioned, or; d) he kicked the

221 ball out of the field of play. Decisions that were neither appropriate nor inappropriate were  
222 not coded. These procedures for assessing the passing decision-making skill were similar to  
223 other studies (Gantois et al., 2020; Romeas et al., 2016). Decision-making coding was  
224 assessed by two experienced soccer coaches blinded to the experiment and trained to use the  
225 instrument for coding. Then, the total score of each player by session was converted to a  
226 percentage for analysis. Percentage accuracy values were established for each participant by  
227 dividing the number of points awarded by the total number available and then multiplying by  
228 100. The intraclass coefficient correlation (ICC) was used to determine the inter-rater  
229 reliability of passing decision-making accuracy in baseline (ICC = 0.79, CI<sub>95%</sub> = 0.72 to 0.88)  
230 and post-experiment (ICC = 0.83, CI<sub>95%</sub> = 0.75 to 0.90).

231

232 *Decision-making task.* It was utilized the soccer-specific decision-making task previously  
233 developed and validated (Vaeyens, Lenoir, Williams, Mazyn, et al., 2007). This task required  
234 participants to observe film-based simulations of offensive soccer play, projected onto a 4.3 ×  
235 2.5-m screen positioned 4.4 m in front of the participant. Participants were required to  
236 imagine themselves as offensive midfielders, playing in a central position, easily identifiable  
237 on screen, as they wore a yellow vest over their playing jersey. In the test, play sequences  
238 varied in number and position of players on-screen (2 vs. 1, 3 vs. 1, 3 vs. 2, 4 vs. 3, and 5 vs.  
239 3). Each sequence ended with a pass to the yellow player, and the film was occluded as the  
240 yellow player received the ball. As the ball was passed to the yellow player on the screen,  
241 participants were required to make quick and accurate decisions by taking the appropriate  
242 action with the ball positioned in front of them. In each sequence, participants chose between  
243 passing to players on the screen, shooting towards the goal, or dribbling.” Participants were  
244 then required to verbalize their responses to ensure that they had carried out the intended  
245 action. Task performance was assessed using response accuracy and response time.

246 Response accuracy was based on a scoring system from zero to three points for each  
247 sequence. Therefore, accuracy was calculated as the percentage of points awarded out of a  
248 possible 99 points. A panel of coaches allocated scores for each response according to the  
249 following criteria: 3 points = The most goal-oriented action; 2 points = An action “indirectly”  
250 leading to a goal-scoring opportunity; 1 point = Maintenance of ball possession, not leading  
251 to a goal-scoring opportunity; 0 points = Poor decision leading to loss of possession. During  
252 each clip, participants stood on pressure-sensitive switches, which were used to measure  
253 response time, defined as the time (ms) from the start of the pass towards the yellow player  
254 until the participant raised a foot off the pressure switch to play the ball. The ICC was used to  
255 determine the inter-rater reliability of soccer-specific decision-making accuracy in baseline  
256 (ICC = 0.85, CI<sub>95%</sub> = 0.80 to 0.89) and post-experiment (ICC = 0.87, CI<sub>95%</sub> = 0.82 to 0.91).  
257 The same test also was utilized for to determine the inter-rater reliability of decision-making  
258 response time in baseline (ICC = 0.90, CI<sub>95%</sub> = 0.84 to 0.93) and post-experiment (ICC =  
259 0.91, CI<sub>95%</sub> = 0.87 to 0.95).

260

261 *Visual search behavior.* The visual search data was measured using portable Eye Tracking-  
262 XG (Applied Science Laboratories, USA) equipment with a sampling frequency of 60 Hz. A  
263 second camera with a 25 Hz frequency, attached to the eye-tracking-XG glasses, recorded the  
264 game scenario. Data of both cameras were combined using the Gaze Tracker software  
265 (Applied Science Laboratories, USA). It is important to highlight that all line players used  
266 eye-tracking devices during small-sided games 5 vs. 5. Visual search data were analyzed  
267 frame-by-frame using video software (Kinovea open source project, [www.kinovea.org](http://www.kinovea.org)). The  
268 number and duration of fixations were obtained, and recorded values were averaged across  
269 each participant's trials. A fixation was defined as when the individual's gaze remained  
270 stationary at a specific location for a minimum of 100 ms or four video frames within a 30

271 visual angle (or less). So, the number of fixations was the sum of all fixations during the  
272 experiment. Besides, the fixation duration was defined as the mean duration of all fixations  
273 higher than 100 ms observed during the experiment. The ICC was used to determine the  
274 inter-rater reliability of duration of fixations in baseline (ICC = 0.92, CI<sub>95%</sub> = 0.86 to 0.94)  
275 and post-experiment (ICC = 0.89, CI<sub>95%</sub> = 0.85 to 0.92). The same test also was utilized for to  
276 determine the inter-rater reliability of number of fixations in baseline (ICC = 0.93, CI<sub>95%</sub> =  
277 0.89 to 0.97) and post-experiment (ICC = 0.92, CI<sub>95%</sub> = 0.85 to 0.95).

278

### 279 **Statistical analysis**

280 The Shapiro Wilk test was conducted to evaluate data distribution. The Levene test  
281 assessed homoscedasticity. The two-way mixed ANOVA of repeated measures was used to  
282 analyze group (a-tDCS vs. Sham) vs. time (baseline-vs post-experiment) interaction for  
283 passing decision-making, visual search behavior (number of fixations, and fixation duration),  
284 and specific-soccer decision-making task (accuracy and response time) performance. The  
285 Bonferroni post hoc test, when necessary, was used to identify statistical differences. The  
286 effect size (ES) was indicated by eta square partial ( $\eta^2$ ). It was adopted the following  
287 classifications (Cohen, 1992): small effect,  $\eta^2 < 0.03$ ; moderate effect,  $0.03 \leq \eta^2 < 0.10$ ;  
288 large effect,  $.10 \leq \eta^2 < 0.20$ ; very large effect,  $\eta^2 \geq .020$ . Data were processed in the  
289 Statistical Package for Social Sciences Version 21.0 (IBM Corp., Armonk, NY, USA) and  
290 GraphPad Prism 8 (San Diego, CA, USA) with a significance level of 5%.

291

## 292 **Results**

### 293 **tDCS-induced sensations and blinding**

294 All 23 participants received the experimental conditions according to the experimental  
295 group, and there was no dropout. No serious adverse effects were reported. The most

296 common sensations reported were itching, burning, and pitching. At the beginning of the  
297 stimulation, the sensations were located on the head and stopped quickly after stimulation.

298

### 299 **Passing decision-making in SSG**

300 The findings showed no group [Figure 2A;  $F_{(1, 21)} = 0.08$ ;  $p = 0.92$  ( $CI_{95\%} = 0.80$  to  
301  $0.97$ );  $\eta p^2 = 0.01$  ( $CI_{95\%} = 0.05$  to  $0.02$ ); ES = small] and time effect [ $F_{(1, 21)} = 0.24$ ;  $p = 0.62$   
302 ( $CI_{95\%} = 0.55$  to  $0.67$ );  $\eta p^2 = 0.01$  ( $CI_{95\%} = 0.006$  to  $0.02$ ); ES = small] for passing decision-  
303 making performance. Also, no interaction effect was found [ $F_{(1, 21)} = 1.57$ ;  $p = 0.22$  ( $CI_{95\%} =$   
304  $0.18$  to  $0.29$ );  $\eta p^2 = 0.02$  ( $CI_{95\%} = 0.001$  to  $0.03$ ); ES = small; Sham:  $87.06 \pm 5.64$  % and  
305  $88.51 \pm 6.26$  % for baseline and post-experiment, respectively; a-tDCS:  $88.38 \pm 4.81$  % and  
306  $90.79 \pm 5.63$  % for baseline and post-experiment, respectively].

307

### 308 **Decision-making task**

309 *Accuracy.* The results showed no group [Figure 2B;  $F_{(1, 21)} = 0.61$ ;  $p = 0.43$  ( $CI_{95\%} = 0.35$  to  
310  $0.46$ );  $\eta p^2 = 0.01$  ( $CI_{95\%} = 0.05$  to  $0.02$ ); ES = small] and time effect [ $F_{(1, 21)} = 0.95$ ;  $p = 0.33$   
311 ( $CI_{95\%} = 0.28$  to  $0.37$ );  $\eta p^2 = 0.01$  ( $CI_{95\%} = 0.006$  to  $0.02$ ); ES = small] for specific-soccer  
312 decision-making performance. Also, no interaction effect was found [ $F_{(1, 21)} = 0.34$ ;  $p = 0.56$   
313 ( $CI_{95\%} = 0.51$  to  $0.62$ );  $\eta p^2 = 0.02$  ( $CI_{95\%} = 0.001$  to  $0.03$ ); small ES; Sham:  $84.27 \pm 6.08$  %  
314 and  $85.42 \pm 6.95$  % for baseline and post-experiment, respectively; a-tDCS:  $86.29 \pm 5.33$ %  
315 and  $85.17 \pm 5.38$  % for baseline and post-experiment, respectively].

316

317 *Response time.* The results showed group [Figure 2C;  $F_{(1, 21)} = 3.08$ ;  $p = 0.04$  ( $CI_{95\%} = 0.02$  to  
318  $0.06$ );  $\eta p^2 = 0.03$  ( $CI_{95\%} = 0.02$  to  $0.05$ ); ES = moderate) and time effects [ $F_{(1, 21)} = 2.56$ ;  $p =$   
319  $0.02$  ( $CI_{95\%} = 0.001$  to  $0.003$ );  $\eta p^2 = 0.07$  ( $CI_{95\%} = 0.05$  to  $0.10$ ); ES = moderate] for  
320 response time in specific-soccer decision-making performance. Also, it was found a group x

321 time interaction [ $F_{(1, 21)} = 5.45$ ;  $p = 0.02$  ( $CI_{95\%} = 0.01$  to  $0.04$ );  $\eta p^2 = 0.05$  ( $CI_{95\%} = 0.04$  to  
322  $0.08$ ); ES = moderate; Sham:  $647.14 \pm 116.35$  ms and  $653.28 \pm 140.98$  ms for baseline and  
323 post-experiment; a-tDCS:  $655.03 \pm 131.68$  ms and  $626.39 \pm 145.23$  ms for baseline and post-  
324 experiment]. Only the a-tDCS group reduced response time in specific-soccer decision-  
325 making performance ( $p = 0.01$ ) and showed lower response time in comparison to Sham  
326 group ( $p = 0.01$ ) in post-experiment.

327

328 **\*\*\*Table 1\*\*\***

329

330 **\*\*\*Figure 2\*\*\***

331

### 332 **Visual search behavior**

333 *Number of fixations.* The findings showed group [Figure 3A;  $F_{(1, 21)} = 3.02$ ;  $p = 0.03$  ( $CI_{95\%} =$   
334  $0.01$  to  $0.04$ );  $\eta p^2 = 0.04$  ( $CI_{95\%} = 0.02$  to  $0.06$ ); ES = moderate) and time effects [ $F_{(1, 21)} =$   
335  $2.62$ ;  $p = 0.04$  ( $CI_{95\%} = 0.01$  to  $0.06$ );  $\eta p^2 = 0.04$  ( $CI_{95\%} = 0.03$  to  $0.09$ ); ES = moderate] for  
336 number of fixations. Also, it was found a group x time interaction [ $F_{(1, 21)} = 4.05$ ;  $p = 0.02$   
337 ( $CI_{95\%} = 0.01$  to  $0.04$ );  $\eta p^2 = 0.05$  ( $CI_{95\%} = 0.04$  to  $0.08$ ); ES = moderate; Sham:  $1.7 \pm 0.2$   
338  $n.s^{-1}$  and  $1.8 \pm 0.2 n.s^{-1}$  for baseline and post-experiment; a-tDCS:  $1.8 \pm 0.2 n.s^{-1}$  and  $2.0 \pm 0.2$   
339  $n.s^{-1}$  for baseline and post-experiment]. Only the a-tDCS group increased number of fixations  
340 ( $p = 0.01$ ) and showed higher number of fixations in comparison to Sham group ( $p = 0.01$ ) in  
341 post-experiment.

342

343 *Fixations duration.* The results showed a significant group effect [Figure 3B;  $F_{(1, 21)} = 4.36$ ;  $p$   
344  $= 0.02$  ( $CI_{95\%} = 0.01$  to  $0.04$ );  $\eta p^2 = 0.04$  ( $CI_{95\%} = 0.02$  to  $0.06$ ); ES = moderate) but showed  
345 not time effect [ $F_{(1, 21)} = 0.33$ ;  $p = 0.56$  ( $CI_{95\%} = 0.43$  to  $0.60$ );  $\eta p^2 = 0.01$  ( $CI_{95\%} = 0.006$  to

346 0.02); ES = small] for fixations duration. It was not found a group x time interaction [ $F_{(1, 21)} =$   
347 0.61;  $p = 0.44$  (CI<sub>95%</sub> = 0.38 to 0.52);  $\eta^2 = 0.008$  (CI<sub>95%</sub> = 0.004 to 0.01); ES = small;  
348 Sham:  $436.13 \pm 76.35$  ms and  $439.72 \pm 81.64$  for baseline and post-experiment; a-tDCS:  
349  $438.32 \pm 81.57$  ms and  $426.06 \pm 72.83$  ms for baseline and post-experiment]. The a-tDCS  
350 group showed lower fixations duration in comparison to Sham group ( $p = 0.01$ ) in post-  
351 experiment.

352

353 **\*\*\*Figure 3\*\*\***

354

355

### Discussion

356 The present study aimed to analyze long-term a-tDCS on DLPFC on soccer athletes'  
357 visual search behavior and decision-making. In summary, our results showed no changes in  
358 decision-making accuracy but demonstrated a reduction in the response time in a specific  
359 decision-making task in the a-tDCS group. Also, the results indicated changes in visual  
360 search behavior only for the a-tDCS group. Therefore, the results partially corroborate our  
361 hypotheses.

362 The improvement of passing, shooting towards the goal, or dribbling decision-making  
363 are perceptual-cognitive skills considered essential to succeed in a soccer match (Romeas et  
364 al., 2016; Smith et al., 2016). The soccer athletes with greater accuracy in decision-making  
365 might directly or indirectly create a shot attempt or pass the ball to a teammate who was in a  
366 better position than himself. Some brain areas involved in making decisions in a team sport  
367 are PFC, DLPFC, VMPFC, and pre-supplementary motor area (Qiu et al., 2019). Considering  
368 the tDCS's physiological mechanisms (Angius et al., 2019; Lo et al., 2019), the tDCS applied  
369 to those brain areas could increase the attentional resources and improve the accuracy of  
370 decision-making performance. A recent study presented improvements in decision-making

371 only when the a-tDCS was applied on the DLPFC right side (Edgcumbe et al., 2019).  
372 However, the findings of the present study were divergent when tDCS was applied over the  
373 left DLPFC. Following the logic of an inverted U-shaped dose-effect relationship between  
374 neural excitation/inhibition and cognitive performance (Colzato, Hommel, & Beste, 2020),  
375 the administration of a-tDCS might produce a neural hyperexcitation and related cognitive  
376 costs in people with elevated regional excitability (e.g., soccer players). In sum, it seems that  
377 cognitive enhancement and cognitive impairment might occur simultaneously. The equilibrium  
378 between the two relies on individual biological traits (Colzato et al., 2020), which would  
379 explain the findings for decision-making accuracy in the present study. Thus, more studies  
380 are suggested to analyze the effect of a-tDCS on soccer athletes' decision-making accuracy.

381         Regardless, our findings showed an attenuation on response time in the specific-  
382 soccer decision-making task only for the a-tDCS group, with a moderate difference to the  
383 Sham group in post-experiment. The ability to respond quickly to a stimulus is essential to an  
384 excellent performance in soccer because some perceptual-cognitive skills enable players to  
385 catch up, identify, and select relevant information from the game environment, which makes  
386 the players faster, increasing appropriate tactical decisions and motor responses (Vaeyens,  
387 Lenoir, Williams, & Philippaerts, 2007). Therefore, when the time available for decision-  
388 making motor and technical action is restricted in soccer, players need to answer correctly  
389 and quickly (Kunrath et al., 2020). Thus, players need to present well-developed cognitive  
390 abilities to perform motor and tactical behaviors as quickly as possible (Kunrath et al., 2020;  
391 Smith et al., 2016). Based on the importance of soccer's cognitive abilities, the intervention  
392 with 40 sessions of 2.0 mA of a-tDCS during 15 min in DLPFC was enough to cause  
393 improvements. Although the possible mechanisms involved are still unclear, the result is  
394 quite promising because this type of intervention is feasible in the athlete's day-to-day.

395           Regarding the visual search behavior, the results indicated a higher number of  
396 fixations and lower fixations duration for a-tDCS than the Sham group after eight weeks of  
397 intervention. These findings corroborate previous investigations that found the same effect  
398 compared to elite and sub-elite soccer athletes to novice or amateur (Vaeyens, Lenoir,  
399 Williams, Mazyn, et al., 2007; Williams, 2000). It seems that such changes in visual search  
400 behavior during game scenarios can indicate improved perceptual-cognitive skills. Perhaps  
401 the a-tDCS in DLPFC improves attention focus in multiple objects in-game contexts, such as  
402 teammates, balls, empty spaces, and opponents. Also, some researches have indicated that  
403 tDCS might modulate the network between PFC and other brain areas (Huang et al., 2019;  
404 Steinberg et al., 2019). The contribution of other brain areas as the occipital cortex is  
405 possible, even indirectly, whether activated by the a-tDCS, which could explain the changes  
406 to the visual search behavior. Future research might focus on analyzing the effect of the a-  
407 TDCS on soccer athletes' visual search behavior.

408           Our findings present relevant implications for coaches and those involved in  
409 developing perceptual-cognitive skill training programs. The study's strengths are the  
410 ecological validity (i.e., experimental design close to what happens in sport training centers),  
411 originality (i.e., the first study that analyzed the long-term effect of a-tDCS on decision-  
412 making performance and visual search behavior in athletes), and measures with good  
413 reproducibility. Although the present study revealed results that might add to the scientific  
414 literature, it presents some limitations. It was a single-blind investigation (i.e., only athletes  
415 did not know if it was a-tDCS or Sham intervention). Also, we did not control the training  
416 sessions that involved physical, technical, and tactical skills. Then, we might not be sure  
417 whether the changes in visual search behavior and improvement for response time in  
418 decision-making were caused only by the tDCS or the combination between tDCS and  
419 physical, technical, and tactical skills. In addition, the player position was not controlled (e.g.,



445 ergogenic resource. Besides, the more significant gains obtained post-tDCS is a very  
446 appealing strategy to further optimize perceptual-cognitive skills in soccer athletes. However,  
447 it is important to keep in mind that different brain regions can display different kinds of  
448 equilibrium between neural excitation and inhibition (Colzato et al., 2020) so that identical  
449 stimulation parameters in another brain area might produce opposite cognitive outcomes.

450 **References**

- 451 Afonso, J., Garganta, J., McRobert, A., Williams, A., M., Mesquita, I. (2012). The Perceptual  
452 Cognitive Processes Underpinning Skilled Performance in Volleyball: Evidence from  
453 Eye-Movements and Verbal Reports of Thinking Involving an in Situ Representative  
454 Task. *Journal of Sports Science and Medicine*, 11, 339–345.
- 455 Adelhöfer, N., Mückschel, M., Teufert, B., Ziemssen, T., Beste, C. (2019). Anodal tDCS  
456 affects neuromodulatory effects of the norepinephrine system on superior frontal theta  
457 activity during response inhibition. *Brain Structured Functioning*, 224(3), 1291–300.  
458 <https://doi.org/10.1007/s00429-019-01839-3>
- 459 Angius, L., Hopker, J., & Mauger, A. R. (2017). The ergogenic effects of transcranial direct  
460 current stimulation on exercise performance. *Frontiers in Physiology*, 8, 90.  
461 <https://doi.org/10.3389/fphys.2017.00090>
- 462 Angius, L., Santarnecchi, E., Pascual-Leone, A., & Marcora, S. M. (2019). Transcranial  
463 Direct Current Stimulation over the Left Dorsolateral Prefrontal Cortex Improves  
464 Inhibitory Control and Endurance Performance in Healthy Individuals. *Neuroscience*,  
465 419, 34–45. <https://doi.org/10.1016/j.neuroscience.2019.08.052>
- 466 Ashford, M., Abraham, A., & Poolton, J. (2021). Understanding a Player's Decision-Making  
467 Process in Team Sports: A Systematic Review of Empirical Evidence. *Sports*, 9, 65.  
468 <https://doi.org/10.3390/sports9050065>
- 469 Bar-Eli, M., Plessner, H., & Raab, M. (2011). Judgement, Decision Making and Success in  
470 Sport. In *Judgement, Decision Making and Success in Sport*.  
471 <https://doi.org/10.1002/9781119977032>
- 472 Borducchi, D. M. M., Gomes, J. S., Akiba, H., Cordeiro, Q., Borducchi, J. H. M., Valentin, L.  
473 S. S., Borducchi, G. M., & Dias, Á. M. (2016). Transcranial direct current stimulation  
474 effects on athletes' cognitive performance: An exploratory proof of concept trial.

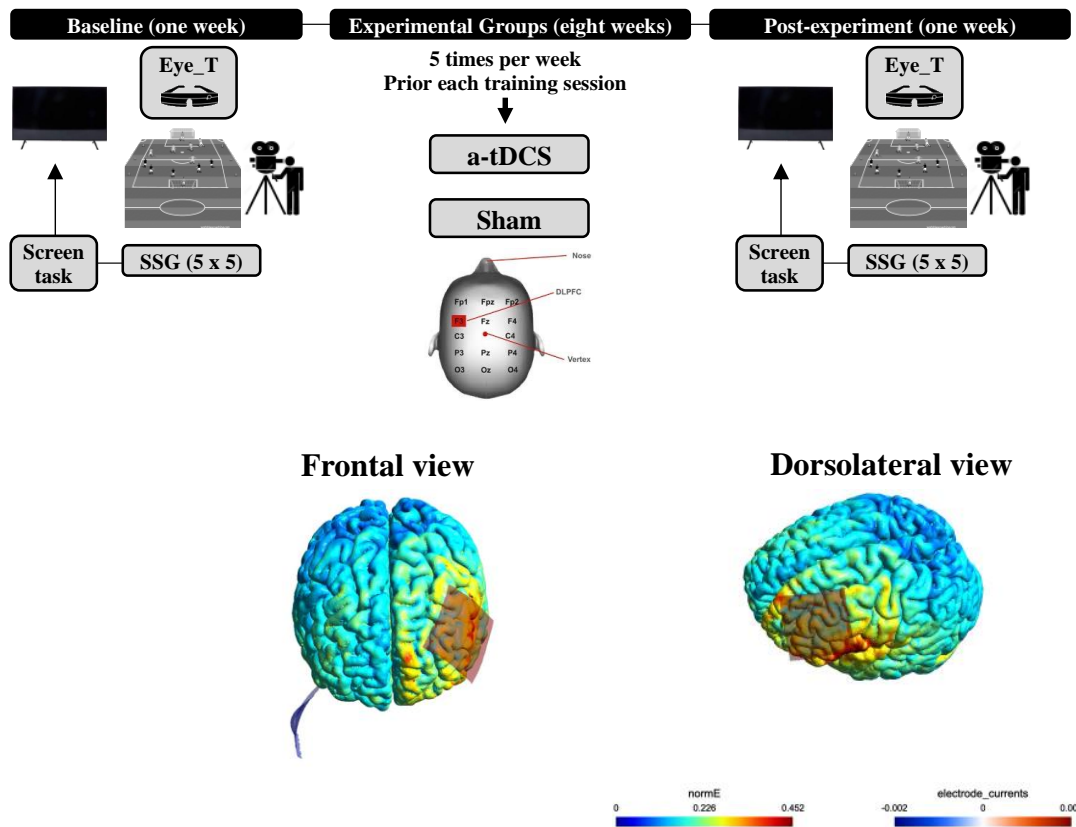
- 475 *Frontiers in Psychiatry*, 7, 183. <https://doi.org/10.3389/fpsy.2016.00183>
- 476 Colzato, L. S., Hommel, B., & Beste, C. (2020). The Downsides of Cognitive Enhancement.  
477 *The Neuroscientist*, 00(0), 1-9. <https://doi.org/10.1177/107385842095971971>
- 478 Cotterill, S., & Discombe, R. (2016). Enhancing decision-making during sports performance:  
479 Current understanding and future directions. *Sport and Exercise Psychology Review*,  
480 12(1), 54-68.
- 481 Dahlin, E., Neely, A. S., Larsson, A., Bäckman, L., & Nyberg, L. (2008). Transfer of learning  
482 after updating training mediated by the striatum. *Science*, 320(5882), 1510-1512.  
483 <https://doi.org/10.1126/science.1155466>
- 484 Edgcumbe, D. R., Thoma, V., Rivolta, D., Nitsche, M. A., & Fu, C. H. Y. (2019). Anodal  
485 transcranial direct current stimulation over the right dorsolateral prefrontal cortex  
486 enhances reflective judgment and decision-making. *Brain Stimulation*, 12(3), 652–658.  
487 <https://doi.org/10.1016/j.brs.2018.12.003>
- 488 Edwards, D. J., Cortes, M., Wortman-Jutt, S., Putrino, D., Bikson, M., Thickbroom, G., &  
489 Pascual-Leone, A. (2017). Transcranial direct current stimulation and sports  
490 performance. *Frontiers in Human Neuroscience*, 11, 243.  
491 <https://doi.org/10.3389/fnhum.2017.00243>
- 492 Faubert, J., & Sidebottom, L. (2012). Perceptual-cognitive training of athletes. *Journal of*  
493 *Clinical Sport Psychology*, 6(1), 85–102. <https://doi.org/10.1123/jcsp.6.1.85>
- 494 Fink, A., Bay, J. U., Koschutnig, K., Prettenthaler, K., Rominger, C., Benedek, M., Papousek,  
495 I., Weiss, E. M., Seidel, A., & Memmert, D. (2019). Brain and soccer: Functional  
496 patterns of brain activity during the generation of creative moves in real soccer decision-  
497 making situations. *Human Brain Mapping*, 40(3), 755–764.  
498 <https://doi.org/10.1002/hbm.24408>
- 499 Fortes, L. S., Almeida, S. S., Praça, G. M., Nascimento-Júnior, J. R. A., Lima-Junior, D.

- 500 Barbosa, B. T., & Ferreira, M. E. C. (2021). Virtual reality promotes greater  
501 improvements than video-stimulation screen on perceptual-cognitive skills in young  
502 soccer athletes. *Human Movement Science, 79*, 102856,  
503 <https://doi.org/10.1016/j.humov.2021.102856>
- 504 Gantois, P., Caputo Ferreira, M. E., Lima-Junior, D. de, Nakamura, F. Y., Batista, G. R.,  
505 Fonseca, F. S., & Fortes, L. de S. (2020). Effects of mental fatigue on passing decision-  
506 making performance in professional soccer athletes. *European Journal of Sport Science,*  
507 *20(4)*, 534–543. <https://doi.org/10.1080/17461391.2019.1656781>
- 508 Grandperrin, Y., Grosprêtre, S., Nicolier, M., Gimenez, P., Vidal, C., Haffen, E., & Bennabi,  
509 D. (2020). Effect of transcranial direct current stimulation on sports performance for two  
510 profiles of athletes (power and endurance) (COMPETE): a protocol for a randomised,  
511 crossover, double blind, controlled exploratory trial. *Trials, 21*, e461.  
512 <https://doi.org/10.1186/s13063-020-04412-0>
- 513 Hadlow, S. M., Panchuk, D., Mann, D. L., Portus, M. R., & Abernethy, B. (2018). Modified  
514 perceptual training in sport: A new classification framework. *Journal of Science and*  
515 *Medicine in Sport, 21(9)*, 950–958. <https://doi.org/10.1016/j.jsams.2018.01.011>
- 516 Harris, D. J., Wilson, M. R., Buckingham, G., & Vine, S. J. (2019). No effect of transcranial  
517 direct current stimulation of frontal, motor or visual cortex on performance of a self-  
518 paced visuomotor skill. *Psychology of Sport and Exercise, 43*, 368-373. [https://sci-](https://sci-hub.se/10.1016/j.psychsport.2019.04.014)  
519 [hub.se/10.1016/j.psychsport.2019.04.014](https://doi.org/10.1016/j.psychsport.2019.04.014)
- 520 Huang, L., Deng, Y., Zheng, X., & Liu, Y. (2019). Transcranial direct current stimulation  
521 with halo sport enhances repeated sprint cycling and cognitive performance. *Frontiers in*  
522 *Physiology, 10*, 118. <https://doi.org/10.3389/fphys.2019.00118>

- 523 Hülzdünker, T., Strüder, H. K., & Mierau, A. (2018). The athletes' visuomotor system -  
524 Cortical processes contributing to faster visuomotor reactions. *European Journal of*  
525 *Sport Science, 18(7): 955-964.* <https://doi.org/10.1080/17461391.2018.1468484>
- 526 Kunrath, C. A., Nakamura, F. Y., Roca, A., Tessitore, A., & Teoldo Da Costa, I. (2020). How  
527 does mental fatigue affect soccer performance during small-sided games? A cognitive,  
528 tactical and physical approach. *Journal of Sports Sciences, 1-11.*  
529 <https://doi.org/10.1080/02640414.2020.1756681>
- 530 Lex, H., Essig, K., Knoblauch, A., Schack, T. (2015). Cognitive Representations and  
531 Cognitive Processing of Team-Specific Tactics in Soccer. *PLoS ONE, 10,* e0118219.  
532 <https://doi.org/10.1371/journal.pone.0118219>
- 533 Li, N., Wang, Y., Jing, F., Zha, R., Wei, Z., Yang, L., Geng, X., Tanaka, K., & Zhang, X.  
534 (2021). A role of the lateral prefrontal cortex in the congruency sequence effect revealed  
535 by transcranial direct current stimulation. *Psychophysiology, 58(5),* e13784.  
536 <https://doi.org/10.1111/psyp.13784>
- 537 Lo, O. Y., van Donkelaar, P., & Chou, L. S. (2019). Effects of transcranial direct current  
538 stimulation over right posterior parietal cortex on attention function in healthy young  
539 adults. *European Journal of Neuroscience, 49(12),* 1623–1631.  
540 <https://doi.org/10.1111/ejn.14349>
- 541 McMorris, T. (2020). Cognitive Fatigue Effects on Physical Performance: The Role of  
542 Interoception. *Sports Medicine, 50(10),* 1703–1708. [https://doi.org/10.1007/s40279-020-](https://doi.org/10.1007/s40279-020-01320-w)  
543 [01320-w](https://doi.org/10.1007/s40279-020-01320-w)
- 544 McRobert, A. P., Ward, P., Eccles, D.W., & Williams, A. M. (2011). The effect of  
545 manipulating context-specific information on perceptual-cognitive processes during a  
546 simulated anticipation task. *British Journal of Psychology, 102,* 519–534.  
547 <https://doi.org/10.1111/j.2044-8295.2010.02013.x>

- 548 Minati, L., Campanhã, C., Critchley, H. D., & Boggio, P. S. (2012). Effects of transcranial  
549 direct-current stimulation (tDCS) of the dorsolateral prefrontal cortex (DLPFC) during a  
550 mixed-gambling risky decision-making task. *Cognitive Neuroscience*, 3(2), 80-88,  
551 <https://doi.org/10.1080/17588928.2011.628382>
- 552 Moreira, A., Machado, D. G. S., Moscaleski, M., Bikson, M., Unal, G., Bradley, P. S.,  
553 Baptista, A. F., Morya, E., Cevada, T., Marques, L., Zanetti, V., & Okano, A. H. (2021).  
554 Effect of tDCS on wellbeing and autonomic function in professional male players after  
555 official soccer matches. *Physiology & Behavior*, 233, 113351.  
556 <https://doi.org/10.1016/j.physbeh.2021.113351>
- 557 Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor  
558 cortex by weak transcranial direct current stimulation. *Journal of Physiology*, 527(3),  
559 633. <https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x>
- 560 North, J. S., & Williams, M. A. (2008). Identifying the critical time period for information  
561 extraction when recognizing sequences of play. *Research Quarterly for Exercise and*  
562 *Sport*, 79(2), 268–273. <https://doi.org/10.1080/02701367.2008.10599490>
- 563 Prete, G., Bertollo, M., & Tommasi, L. (2020). *Brain stimulation techniques and sports*  
564 *performance*. In M. Bertollo, E. Filho, & P. C. Terry (Eds.), *Advancements in mental*  
565 *skills training* (pp. 166–177). Routledge.
- 566 Qiu, F., Pi, Y., Liu, K., Zhu, H., Li, X., Zhang, J., & Wu, Y. (2019). Neural efficiency in  
567 basketball players is associated with bidirectional reductions in cortical activation and  
568 deactivation during multiple-object tracking task performance. *Biological Psychology*,  
569 144, 28–36. <https://doi.org/10.1016/j.biopsycho.2019.03.008>
- 570 Roca, A., Ford, P., R., McRobert, A., P., & Williams, A., M. (2013). Perceptual-Cognitive  
571 Skills and Their Interaction as a Function of Task Constraints in Soccer. *Journal of*  
572 *Sport and Exercise Psychology*, 35, 144–155. <https://doi.org/10.1123/jsep.35.2.144>

- 573 Romeas, T., Guldner, A., & Faubert, J. (2016). 3D-Multiple Object Tracking training task  
574 improves passing decision-making accuracy in soccer players. *Psychology of Sport and*  
575 *Exercise*, 22, 1–9. <https://doi.org/10.1016/j.psychsport.2015.06.002>
- 576 Smith, M. R., Zeuwts, L., Lenoir, M., Hens, N., De Jong, L. M. S., & Coutts, A. J. (2016).  
577 Mental fatigue impairs soccer-specific decision-making skill. *Journal of Sports*  
578 *Sciences*, 34(14), 1297–1304. <https://doi.org/10.1080/02640414.2016.1156241>
- 579 Steinberg, F., Pixa, N. H., & Fregni, F. (2019). A Review of Acute Aerobic Exercise and  
580 Transcranial Direct Current Stimulation Effects on Cognitive Functions and Their  
581 Potential Synergies. *Frontiers in Human Neuroscience*, 12, 534.  
582 <https://doi.org/10.3389/fnhum.2018.00534>
- 583 Vaeyens, R., Lenoir, M., Williams, A. M., Mazyn, L., & Philippaerts, R. M. (2007). The  
584 effects of task constraints on visual search behavior and decision-making skill in youth  
585 soccer players. *Journal of Sport and Exercise Psychology*, 29(2), 147–169.  
586 <https://doi.org/10.1123/jsep.29.2.147>
- 587 Vaeyens, R., Lenoir, M., Williams, A. M., & Philippaerts, R. M. (2007). Mechanisms  
588 underpinning successful decision making in skilled youth soccer players: An analysis of  
589 visual search behaviors. *Journal of Motor Behavior*, 39(5), 395–408.  
590 <https://doi.org/10.3200/JMBR.39.5.395-408>
- 591 Zwierko, T., Jedziniak, W., Florkiewicz, B., Stępiński, M., Buryta, R., Kostrzewa-Nowak,  
592 D., Nowak, R., Popowczak, M., & Woźniak, J. (2019). Oculomotor dynamics in skilled  
593 soccer players: The effects of sport expertise and strenuous physical effort. *European*  
594 *Journal of Sport Science*, 19(5), 612–620.  
595 <https://doi.org/10.1080/17461391.2018.1538391>  
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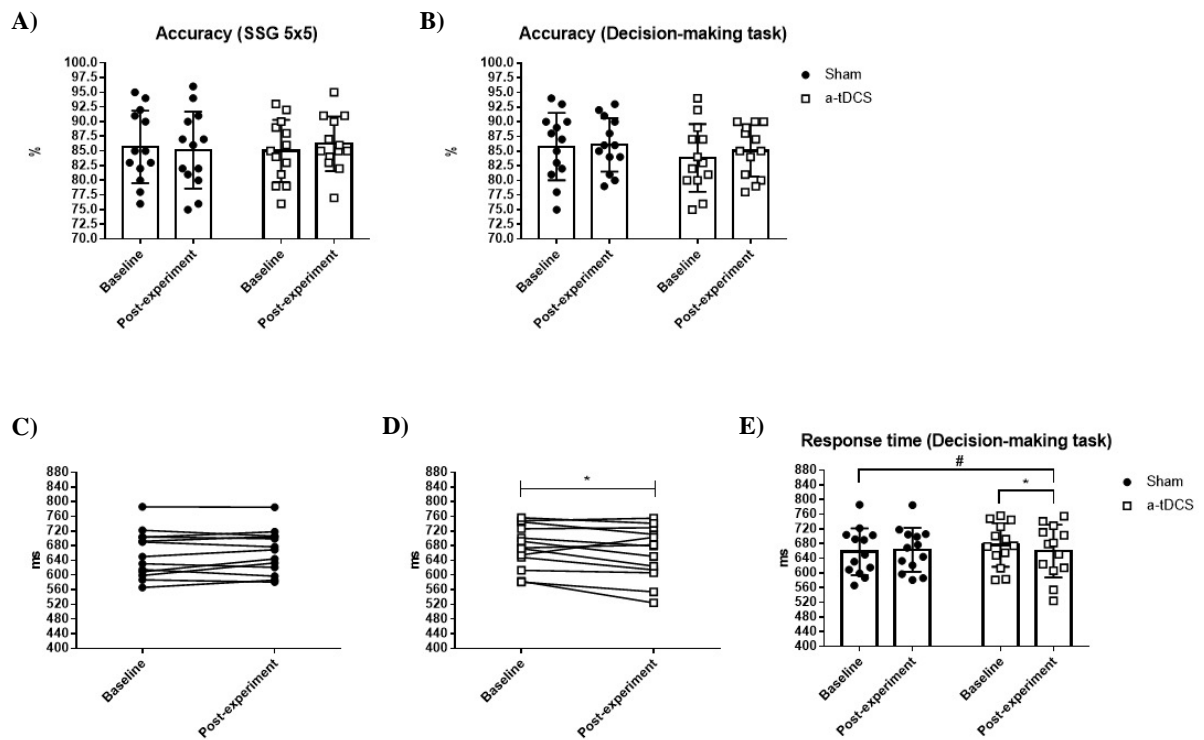
Figure 1  
*Experimental design of the study and computational modelling*  
Note. SSG = small-sided game; Eye\_T = Eye-tracker; a-tDCS = anodal transcranial direct current stimulation; DLPFC = dorsolateral prefrontal cortex.

603 Table 1  
 604 *Decision-making skill and visual search behavior according to experimental group (a-tDCS and Sham) in*  
 605 *soccer players.*

<b>Variables</b>	<b>a-tDCS</b>	<b>Sham</b>	<b>Effect</b>	<b><i>p</i></b>	<b><math>\eta p^2</math></b>	<b>ES</b>
<i>Passing decision-making (%)</i>						
Baseline	85.00 ± 5.09	85.69 ± 5.92	Time	0.62	0.01	Small
Post-treatment	86.23 ± 4.47	85.15 ± 6.27	Group	0.92	0.01	Small
Δ% (baseline-vs post-experiment)	2.3 ± 1.4	2.0 ± 1.2	Interaction	0.22	0.02	Small
<i>Accuracy decision-making (%)</i>						
Baseline	83.84 ± 5.53	85.76 ± 5.50	Time	0.33	0.01	Small
Post-treatment	85.07 ± 4.21	86.02 ± 4.35	Group	0.43	0.01	Small
Δ% (baseline-vs post-experiment)	2.8 ± 1.5	2.4 ± 1.3	Interaction	0.56	0.02	Small
<i>RT decision-making (ms)</i>						
Baseline	676.46 ± 57.25	658.00 ± 61.28	Time	0.02	0.07	Moderate
Post-treatment	659.46 ± 68.93	663.15 ± 57.56	Group	0.04	0.03	Moderate
Δ% (baseline-vs post-experiment)	-4.1 ± 2.0	1.6 ± 0.9	Interaction	0.02	0.05	Moderate
<i>Number of fixations (n.s<sup>-1</sup>)</i>						
Baseline	1.89 ± 0.29	1.91 ± 0.30	Time	0.04	0.04	Moderate
Post-treatment	2.02 ± 0.37	1.89 ± 0.18	Group	0.03	0.04	Moderate
Δ% (baseline-vs post-experiment)	7.8 ± 3.3	-1.0 ± 0.5	Interaction	0.02	0.05	Moderate
<i>Duration of fixations (ms)</i>						
Baseline	441.69 ± 48.94	438.53 ± 40.56	Time	0.56	0.01	Small
Post-treatment	434.07 ± 58.17	439.69 ± 40.44	Group	0.02	0.04	Moderate
Δ% (baseline-vs post-experiment)	-2.6 ± 1.6	1.7 ± 1.1	Interaction	0.44	0.008	Small

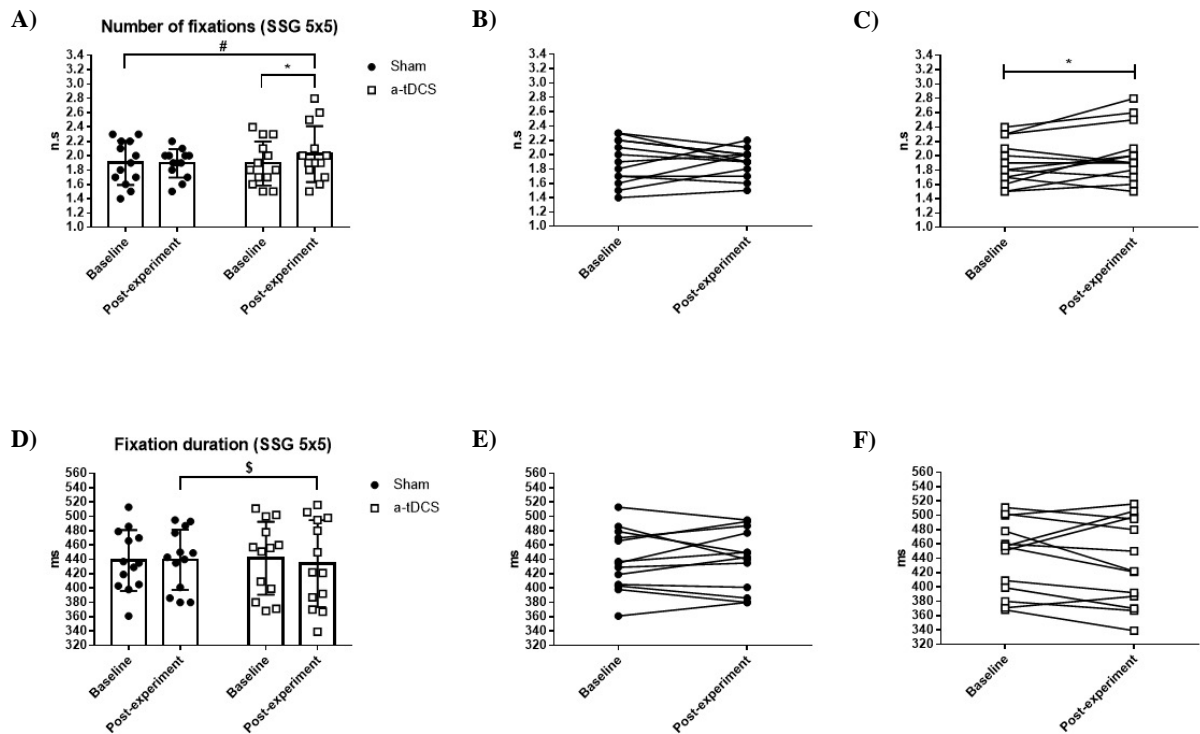
606 Note. Δ% = percent delta from baseline-to post-treatment; RT = response time; \*p<0.05 difference for baseline within-  
 607 group; #p<0.05 difference for between-group in post-experiment.

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Figure 2  
 Passing decision-making in small-sided game 5vs5 (A), specific-soccer decision-making task [accuracy (B), and  
 response time (C, D, and E)] according to group (a-tDCS and Sham) in soccer athletes.  
 Note. \*difference baseline-vs post-experiment intra-group ( $p < 0.05$ ); #main effect group vs. time interaction ( $p < 0.05$ ).



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Figure 3  
The number of fixations (A, B, and C) and fixation duration in small-sided game 5vs5 (D, E, and F) according to group (a-tDCS and Sham) in soccer athletes.  
Note. \*difference baseline-vs post-experiment intra-group ( $p < 0.05$ ); #main effect group vs. time interaction ( $p < 0.05$ ); §difference between groups in post-experiment ( $p < 0.05$ ).