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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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

Abstract

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

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

Introduction

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

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

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

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

There are three theoretical frameworks to explain the decision-making in team sport athletes [e.g., processing information (cognitive knowledge), ecologic dynamic (perception-action coupling), and naturalistic] (Ashford, Abraham, & Poolton, 2021), which are from inherently different views of human behavior (Cotterill & Discombe, 2016). It is important, at this point, to clarify the focus on decision-making adopted in the present paper. Decision-making is known as a deliberate process of selection. Expert players excel in their capability to extract and process cues from the environment, recognize and interpret familiar patterns of play, and form expectations by computing situational probability (Ashford, Abraham, & Poolton, 2021). These selection processes are an intermediate agent between what a player perceives and how a player responds to the play unfolding about them. In that sense, the present study utilizes processing information and naturalistic approaches to explain decision-making. The processing information perspective defines decision-making as a structured and higher cognitive process (Cotterill & Discombe, 2016).

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

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

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

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

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

According to the identical elements' theory (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008), perceptual-cognitive skills, as decision-making and visual search behavior, can be improved with off-field training that stimulates similar brain areas. Therefore, it is reasonable to speculate that the a-tDCS might activate brain areas commonly stimulated in soccer games, such as the DLPFC or visuomotor system (Hülsdünker, Strüder, & Mierau, 2018). In this case, a positive cognitive-transfer effect might occur to specific perceptual-cognitive skills (e.g., visual search and decision-making task) in soccer match situations. Complexity and creative solutions in sports decision-making situations seem to recruit general-domain brain networks, supporting executive functions and semantic memory demands controlled by the frontal brain area (Fink et al. 2019), for example, the DLPFC. Thus, the objective of this study was to analyze the long-term effect of a-tDCS in DLPFC on decision-making and visual search behavior in soccer athletes. We expected that a-tDCS over the DLPFC would promote improvements in decision-making performance and changes in visual search behavior in soccer athletes.

Materials and Methods

Participants

A priori sample size calculation was performed using G*Power software version 3.1.9.2 (Universität Kiel, Kiel, Germany), for an analysis of variance (ANOVA) with repeated measures within–between groups interaction using the option "ANOVA: repeated measures, within-between factors interaction" for decision-making skill (Gantois et al., 2020), including the following criteria: (a) power = 0.8; (b) medium ES (ηp^2 =.07); (c) α =.05; (d) the number of groups = 2; (e) number of measurements = 2; (f) correlation among repeated measures = 0.5; and (g) nonsphericity correction = 1. Results indicated that twenty subjects would be necessary for the study. An additional 30% of subjects were recruited to prevent any dropout, totaling 26 participants. Using the non-probabilistic method for sample recruitment, twenty-six male soccer athletes were recruited for this investigation (M = 22.6 years, SD = 2.3; M = 76.2 kg, SD = 5.9; M = 1.75 m, SD = 0.06). They played at the third division of the Brazilian Championship of Soccer for an average of 8.5 years (SD = 2.7). They were randomly divided into two equal groups: a-tDCS and Sham groups. Three soccer athletes (one of a-tDCS and two of the Sham group) were excluded from the study because of absence in over 10% of experimental sessions and muscle-skeletal injury. All experimental sessions were conducted during the participants' in-season; therefore, they participated in team practices during the study. The local Ethics committee approved the study, and we followed all the guidelines of the Declaration of Helsinki.

Experimental design

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

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

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

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

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

*****Figure 1*****

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

Measures

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

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

Passing decision-making in SSG. The passing decision-making skill was coded using standardized coding criteria adapted from a previous study (Romeas et al., 2016). The decision component involves the selection of the skill (e.g., pass), as well as which teammate to pass. The quality of each decision was coded as 1 for an appropriate decision and 0 for an inappropriate decision according to the following criteria: 1) one point decision; the player made a good decision when the pass went to an open teammate and: a) directly or indirectly created a shot attempt, or; b) passed the ball to a teammate who was in a better position than himself; 2) zero-point decision; the player made a poor decision when the pass because: a) he passed the ball to a player who was closely guarded or when there was a defensive player positioned in the passing line, or; b) the pass was intercepted or turned over, or; c) the pass was directed to an area of the field where no teammate was positioned, or; d) he kicked the ball out of the field of play. Decisions that were neither appropriate nor inappropriate were not coded. These procedures for assessing the passing decision-making skill were similar to other studies (Gantois et al., 2020; Romeas et al., 2016). Decision-making coding was assessed by two experienced soccer coaches blinded to the experiment and trained to use the instrument for coding. Then, the total score of each player by session was converted to a percentage for analysis. Percentage accuracy values were established for each participant by dividing the number of points awarded by the total number available and then multiplying by 100. The intraclass coefficient correlation (ICC) was used to determine the inter-rater reliability of passing decision-making accuracy in baseline (ICC = 0.79, $CI_{95\%}$ = 0.72 to 0.88) and post-experiment (ICC = 0.83, $CI_{95\%}$ = 0.75 to 0.90).

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

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

Visual search behavior. The visual search data was measured using portable Eye Tracking-XG (Applied Science Laboratories, USA) equipment with a sampling frequency of 60 Hz. A second camera with a 25 Hz frequency, attached to the eye-tracking-XG glasses, recorded the game scenario. Data of both cameras were combined using the Gaze Tracker software (Applied Science Laboratories, USA). It is important to highlight that all line players used eye-tracking devices during small-sided games 5 vs. 5. Visual search data were analyzed frame-by-frame using video software (Kinovea open source project, www.kinovea.org). The number and duration of fixations were obtained, and recorded values were averaged across each participant's trials. A fixation was defined as when the individual’s gaze remained stationary at a specific location for a minimum of 100 ms or four video frames within a 3o visual angle (or less). So, the number of fixations was the sum of all fixations during the experiment. Besides, the fixation duration was defined as the mean duration of all fixations higher than 100 ms observed during the experiment. The ICC was used to determine the inter-rater reliability of duration of fixations in baseline (ICC = 0.92, $CI_{95\%}$ = 0.86 to 0.94) and post-experiment (ICC = 0.89, $CI_{95\%}$ = 0.85 to 0.92). The same test also was utilized for to determine the inter-rater reliability of number of fixations in baseline (ICC = 0.93, $CI_{95\%}$ = 0.89 to 0.97) and post-experiment (ICC = 0.92, $CI_{95\%}$ = 0.85 to 0.95).

Statistical analysis

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

Results

tDCS-induced sensations and blinding

All 23 participants received the experimental conditions according to the experimental group, and there was no dropout. No serious adverse effects were reported. The most common sensations reported were itching, burning, and pitching. At the beginning of the stimulation, the sensations were located on the head and stopped quickly after stimulation.

Passing decision-making in SSG

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

Decision-making task

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

Response time. The results showed group [Figure 2C; $F_{(1, 21)} = 3.08$; $p = 0.04$ ($CI_{95\%} = 0.02$ to 0.06); $\eta p^2 = 0.03$ ($CI_{95\%} = 0.02$ to 0.05); ES = moderate) and time effects [$F_{(1, 21)} = 2.56$; $p =$ 0.02 ($CI_{95\%} = 0.001$ to 0.003); $\eta p^2 = 0.07$ ($CI_{95\%} = 0.05$ to 0.10); ES = moderate] for response time in specific-soccer decision-making performance. Also, it was found a group x time interaction [$F_{(1, 21)}$ = 5.45; p = 0.02 ($CI_{95\%}$ = 0.01 to 0.04); ηp^2 = 0.05 ($CI_{95\%}$ = 0.04 to 0.08); ES = moderate; Sham: 647.14 ± 116.35 ms and 653.28 ± 140.98 ms for baseline and post-experiment; a-tDCS: 655.03 ± 131.68 ms and 626.39 ± 145.23 ms for baseline and post-experiment]. Only the a-tDCS group reduced response time in specific-soccer decision-making performance (p = 0.01) and showed lower response time in comparison to Sham group (p = 0.01) in post-experiment.

*****Table 1*****

*****Figure 2*****

Visual search behavior

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

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

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

*****Figure 3*****

Discussion

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

The improvement of passing, shooting towards the goal, or dribbling decision-making are perceptual-cognitive skills considered essential to succeed in a soccer match (Romeas et al., 2016; Smith et al., 2016). The soccer athletes with greater accuracy in decision-making might directly or indirectly create a shot attempt or pass the ball to a teammate who was in a better position than himself. Some brain areas involved in making decisions in a team sport are PFC, DLPFC, VMPFC, and pre-supplementary motor area (Qiu et al., 2019). Considering the tDCS's physiological mechanisms (Angius et al., 2019; Lo et al., 2019), the tDCS applied to those brain areas could increase the attentional resources and improve the accuracy of decision-making performance. A recent study presented improvements in decision-making only when the a-tDCS was applied on the DLPFC right side (Edgcumbe et al., 2019). However, the findings of the present study were divergent when tDCS was applied over the left DLPFC. Following the logic of an inverted U-shaped dose-effect relationship between neural excitation/inhibition and cognitive performance (Colzato, Hommel, & Beste, 2020), the administration of a-tDCS might produce a neural hyperexcitation and related cognitive costs in people with elevated regional excitability (e.g., soccer players). In sum, it seems that cognitive enhancement and cognitive impairment might occur simultaneosly. The equilibrium between the two relies on individual biological traits (Colzato et al., 2020), which would explain the findings for decision-making accuracy in the present study. Thus, more studies are suggested to analyze the effect of a-tDCS on soccer athletes' decision-making accuracy.

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

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

Our findings present relevant implications for coaches and those involved in developing perceptual-cognitive skill training programs. The study's strengths are the ecological validity (i.e., experimental design close to what happens in sport training centers), originality (i.e., the first study that analyzed the long-term effect of a-tDCS on decision-making performance and visual search behavior in athletes), and measures with good reproducibility. Although the present study revealed results that might add to the scientific literature, it presents some limitations. It was a single-blind investigation (i.e., only athletes did not know if it was a-tDCS or Sham intervention). Also, we did not control the training sessions that involved physical, technical, and tactical skills. Then, we might not be sure whether the changes in visual search behavior and improvement for response time in decision-making were caused only by the tDCS or the combination between tDCS and physical, technical, and tactical skills. In addition, the player position was not controlled (e.g., soccer players were required to imagine themselves as offensive midfielders). We did not measure cortical excitability changes. So, we cannot exclude the possibility that the current stimulation affected the DLPFC cortex adjacent areas. Thus, more studies with neuroimaging (e.g., fMRI, EEG) are recommended to monitor the effect of the a-tDCS. In other words, our results may be attributed to the modulation of neuronal activation of the DLPFC and other adjacent areas that we could not predict.

Even though e we do not deny that positive enhancement effects exist for decision-making response time after repeated a-tDCS over left DLPFC, they are likely to be accompanied by negative aspects. It seems that tDCS may cause a trade-off between enhancing some cognitive functions and impairing others, depending on individual differences. Considering individual differences is crucial because, as proposed by Colzato et al. (2020), the critical equilibrium between neural excitation and inhibition, and corresponding cognitive enhancement or impairment, varies between specific brain regions and individual factors. Therefore, the results should be interpreted cautiously, and future research should investigate the effects of long-term tDCS intervention on perceptual-cognitive skills in team sports using other neuroimaging techniques and considering individual factors.

Conclusion

In conclusion, our results showed no changes in decision-making accuracy but demonstrated a reduction in the response time in a specific decision-making task in the a-tDCS group. Also, the findings showed changes in visual search behavior during the decision-making screen task. In sum, the findings of this study support the effectiveness of using a-tDCS over left-DLPFC to changes visual search behavior and improve the response time of decision-making skills in soccer athletes, which confirm the value of this noninvasive ergogenic resource. Besides, the more significant gains obtained post-tDCS is a very appealing strategy to further optimize perceptual-cognitive skills in soccer athletes. However, it is important to keep in mind that different brain regions can display different kinds of equilibrium between neural excitation and inhibition (Colzato et al., 2020) so that identical stimulation parameters in another brain area might produce opposite cognitive outcomes.

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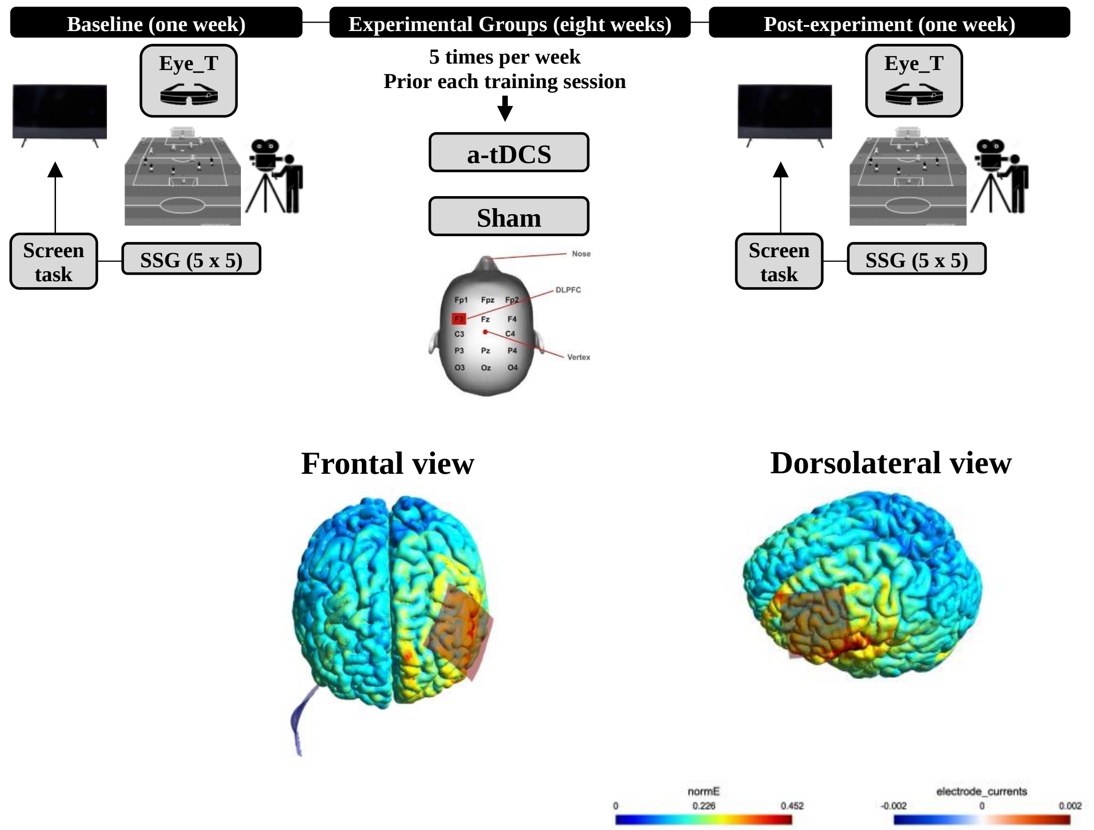

Figure 1

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.

Table 1

Decision-making skill and visual search behavior according to experimental group (a-tDCS and Sham) in soccer players.

Variables	**a-tDCS**	**Sham**	**Effect**	***p***	***ηp²***	**ES**
Passing decision-making (%)						
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
Accuracy decision-making (%)						
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
RT decision-making (ms)						
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
Number of fixations (n.s^{-1})						
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
Duration of fixations (ms)						
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

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

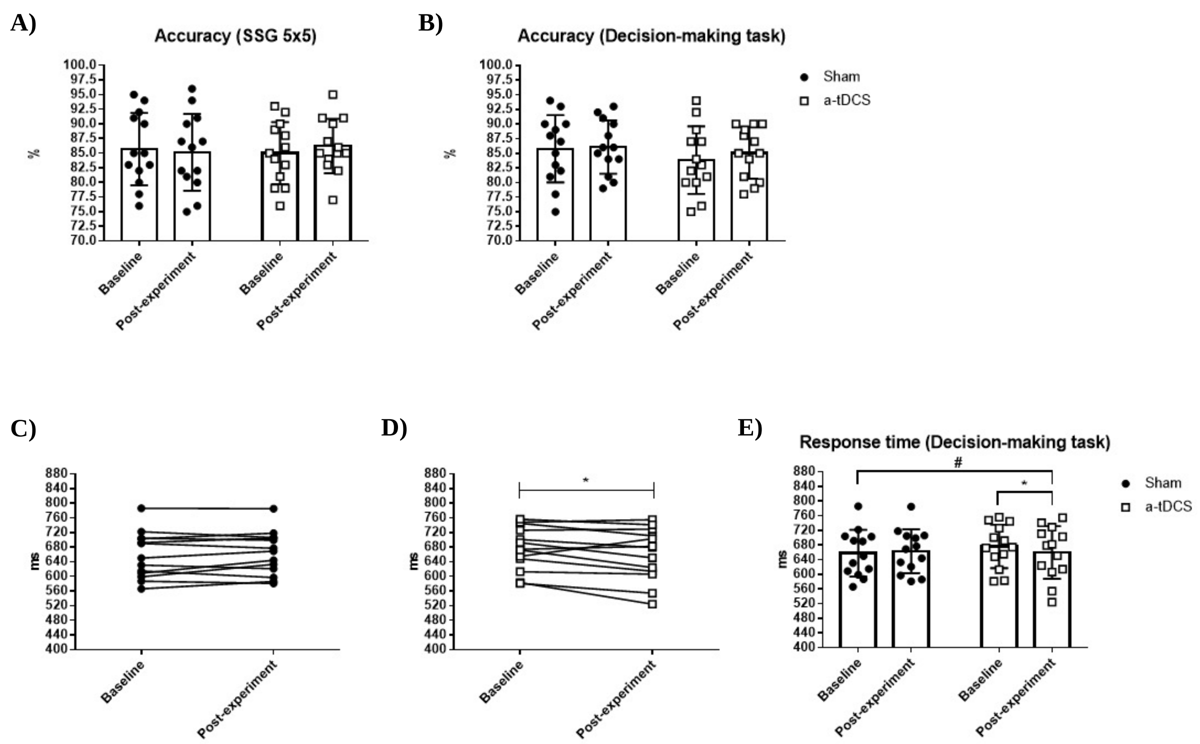

Figure 2

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 ($p<0.05$).*

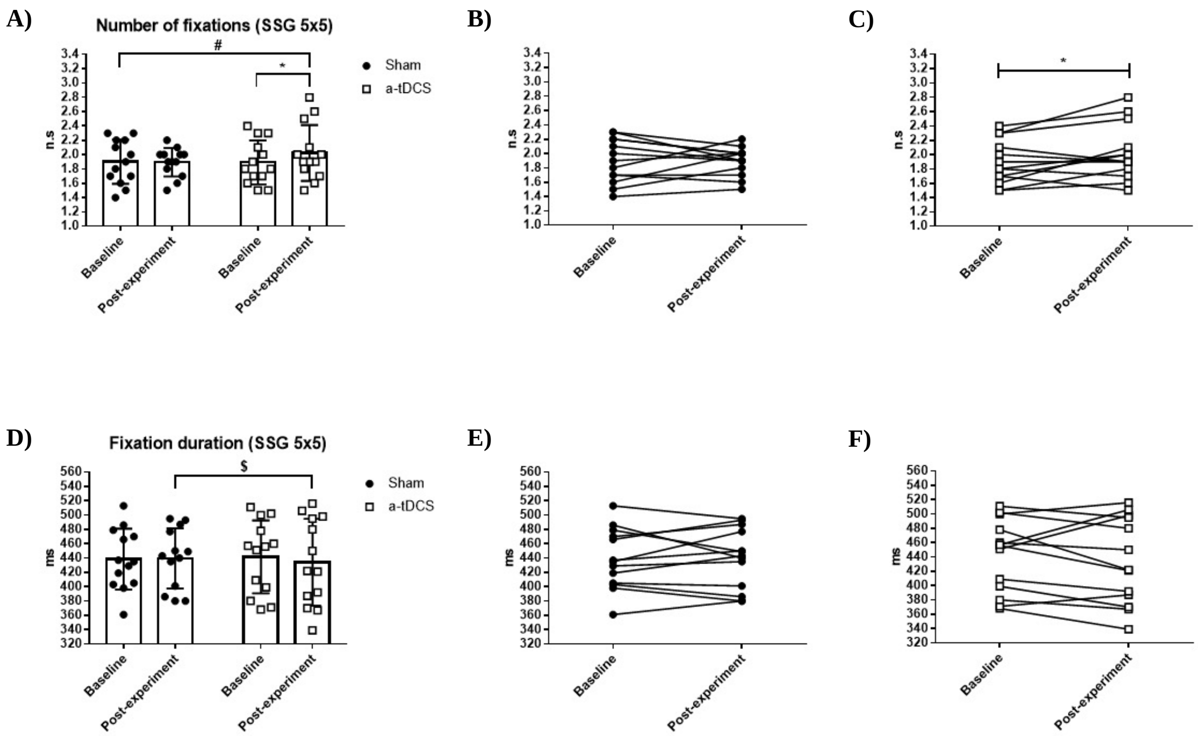

Figure 3

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).*