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Non-invasive brain stimulation over the orbital prefrontal cortex maintains endurance performance in mentally fatigued swimmers

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Abstract

Background: Using anodal transcranial direct current stimulation (a-tDCS) on frontal brain areas might be a promising strategy to mitigates mental fatigue and maintain endurance performance swimmers. **Objective:** The objective was to analyze the effect of a-tDCS over the orbital prefrontal cortex (oPFC) on endurance performance of mentally fatigued female amateur swimmer. **Methods:** Nineteen female amateur swimmers participated in this study. In two experimental visits, the swimmers completed the 3-min all-out tethered swimming after performing a 30-min Stroop test with a-tDCS or placebo (Sham) stimulation over the left-oPFC. The brain stimulation conditions (i.e., a-tDCS and Sham) were performed in a double-blinded and counterbalanced order. **Results:** It was found lower critical force, mean force, force minimum, fatigue index, and aerobic impulse for Sham than a-tDCS ($p<0.05$). There was no main effect of condition for peak force ($p> 0.05$). **Conclusion:** We concluded that a-tDCS applied over the left-oPFC in female amateur swimmers mentally fatigued maintained endurance performance. From a practical point of view, the use of a-tDCS should be considered to counteract harmful cognitive effects and maintain endurance performance during competitive race events.

Keywords: Neuroscience, transcranial direct current stimulation, swimming, mental fatigue, cognitive fatigue.

Introduction

Mental fatigue is a psychobiological state that results in tiredness, lack of energy sensation, and attentional/alertness reduction after prolonged high cognitive demand activity (Tran et al., 2020; Wascher et al., 2014). Studies have shown that at least 30-min of high cognitive demand might cause mental fatigue in athletes (Gantois et al., 2020; Penna et al., 2018). Mental fatigue state increases subjective lack of energy sensation (Filipas et al., 2019; Fortes, Lima-Junior, et al., 2020), impairs response time throughout cognitive tasks (Gantois et al., 2019; Martin et al., 2016), and augments theta band for frontal brain area and low alpha band for central brain area in electroencephalogram (Tran et al., 2020).

Mental fatigue also impairs selective attention which is the function of the prefrontal cortex (PFC) and anterior cingulate cortex (ACC) (Boksem et al., 2005). The orbital PFC (oPFC) also shows an essential role throughout cognitive tasks. A recent study in healthy adults has shown repeated cognitive tasks involving response inhibition through activation of the oPFC (Huang et al., 2020). Repeated response inhibition overtime may lead to mental fatigue (Gantois et al., 2019; Smith et al., 2016).

Mental fatigue caused by prolonged response inhibition overtime can decreases physical (i.e., endurance, isometric resistance, and dynamic resistance) and sport-specific performance subsequent (Brown et al., 2020; Van-Cutsem et al., 2017), but not change short-duration all-out neuromuscular performance (Brown et al., 2020; Pageaux et al., 2013; Silva-Cavalcante et al., 2018). Endurance performance is one of the main parameters affected by mental fatigue, probably due to increased perception of effort (Filipas et al., 2019; Marcora et al., 2009; Penna et al., 2018; Smith et al., 2016; Van-Cutsem et al., 2017). One possible neurophysiological explanation is the increase in extra-cephalic adenosine concentration and reduced dopamine activity in the frontal brain area after prolonged cognitive exertion (Martin et al., 2018; Smith et al., 2018). However, McMorris (2020) contested this idea because research conducted in rodents showed different results on neurotransmissors. In addition, increases in adenosine due to dopamine activation during prolonged cognitive tasks are phasic, not tonic, and are induced when dopamine is phasically released (McMorris, 2020). Then, the claim about increased extracefalic adenosine concentration and reduced dopamine activity in the frontal brain following prolonged cognitive exertion should be analyzed with caution.

The frontal brain area, especially the oPFC, has been shown to play an important role in exercise regulation. The oPFC regulate effort tolerance (Robertson & Marino, 2016), is also involved in motivation (Szatkowska et al., 2008), suggesting this brain area has a fundamental role in endurance performance (Marcora & Staiano, 2010). In addition, the oPFC activities depend on interaction with many other parts of the brain, for example, in the lateral PFC, anterior insula, and ACC (Craig, 2002). So, once impaired oPFC, for example, the oPFC deactivation (Tran et al., 2020) or reduced dopamine activity on ACC (McMorris, 2020) caused by mental fatigue, could impair endurance performance.

A number of interventions have been suggested to reduce the negative impact of mental fatigue on human performance (Pires et al., 2018; Van-Cutsem et al., 2018). Some different acute ergogenic strategies have been proposed to counteract the adverse effects of mental fatigue on physical performance, including acute caffeine consumption (Azevedo, Silva-Cavalcante, Gualano, Lima-Silva, & Bertuzzi, 2016; Franco-Alvarenga et al., 2019). Notably, these studies have shown that caffeine attenuated the abnormal increase in rated perceived exertion (RPE) under mentally fatiguing conditions. In addition to caffeine, other strategies or ergogenic resources that might change or revert the harmful effects of mental fatigue on human performance are essential. Among the strategies to counteract mental fatigue, transcranial direct current stimulation (tDCS) might play an important role.

tDCS is a non-invasive brain stimulation, portable, feasible, safe, and well-tolerated (Edwards et al., 2017; Machado et al., 2019). Two types of active stimulation are possible: anodal (i.e., a-tDCS) and cathodal (i.e., c-tDCS), which aim to increase and decrease neuronal excitability, respectively (Nitsche et al., 2003). The potential mechanism underlying the ergogenic effect of tDCS could be increased cortical excitability in specific brain areas targeted by a-tDCS. Studies have been showing that when applied over oPFC or dorsolateral PFC (dlPFC), a-tDCS improves executive functions (e.g., inhibitory control or attention) (Colzato, Stern, & Kibele, 2016; Borducchi et al., 2016) and endurance performance (Angius et al., 2019; Edwards et al., 2017). For example, Angius et al. (2019) found an improvement in Stroop task (i.e., improved accuracy) and endurance performance (i.e., increased time to exhaustion) following a-tDCS over the left-dlPFC. Recent interests in the use of tDCS as a novel technique for reduction of mental fatigue and enhancement of endurance performance in swimmers shows an upward trend (Penna et al., 2021; Salehi, Fard, Jaberzadeh, & Zoghi, 2021). However, the results are controversial. Salehi et al. (2021) applied a-tDCS over the left-dlPFC per 20-min in mentally fatigued professional swimmers and found improved 50-m freestyle performance, although the tDCS presented no changes in the mental fatigue induced by prolonged cognitive task (i.e., 60-min of Stroop task). Penna et al. (2021) no found effect on 800-m freestyle performance in mentally fatigued male amateur swimmers after a-tDCS online (i.e., during the cognitive task) applied over the left temporal cortex during 30-min. Both scientific investigations utilized physical tasks that do not measure endurance performance (e.g., 50-m freestyle performance) or a controlled endurance task (i.e., 800-m freestyle performance), which pace's strategy may influence.

Also, it is important to highlight that none of the swimmers' scientific investigations above revealed a-tDCS as an ergogenic resource to counteract mental fatigue. Neuroimaging studies investigating the neural basis of mental fatigue found a reduction of functional connectivity between the left and right oPFC in mentally fatigued individuals (Sun, Lim, Kwok, & Bezerianos, 2014; Tran et al., 2020). A tDCS montage that maintain the functional connectivity between the left and right oPFC maybe be an ergogenic resource to counteract mental fatigue and maintain subsequent endurance performance. Thus, new scientific studies could test different montages for tDCS over the oPFC throughout prolonged repetitive cognitive inhibitory tasks to remove the harmful effects of mental fatigue on endurance performance. Here, we proposed the tDCS online (i.e., during cognitive task) with anodal electrode positioned over the left-oPFC (i.e., Fp1), while the cathodal electrode placed over the right-oPFC (i.e., Fp2) for counteract mental fatigue induced by prolonged cognitive task (i.e., incongruent stroop task) and maintain subsequent endurance performance in female amateur swimmers.

It seems there is a clear potential for the use of tDCS to reduce the negative impact of mental fatigue on athletes' performance. Considering the scope of the effectiveness of brain stimulation to improve cognitive and endurance performance and adding the necessity to test ergonomic tools to counteract mental fatigue in athletes, tDCS seems to be an interesting strategy in sports performance. Thus, we aimed to analyze the effect of a-tDCS over the left-oPFC on endurance performance of mentally fatigued female amateur swimmers. We hypothesized that using a-tDCS over the left-oPFC during high cognitive demand tasks could counteract mental fatigue and maintain swimmers' endurance performance.

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 factors using the option "ANOVA: repeated measures, within factors” for endurance performance in mentally fatigued swimmers (Fortes et al., 2021), including the following criteria: (a) power = 0.80; (b) medium ES ($\eta p^2 = .08$ or $f = 0.29$); (c) $\alpha = .05$; (d) the number of groups (i.e., number of experimental conditions) = 2; (e) number of measurements = 4; (f) correlation among repeated measures = 0.5; and (g) nonsphericity correction = 1. Results indicated that eighteen subjects would be necessary for the study. Using the non-probabilistic method for sample recruitment, nineteen female amateur swimmers (age = 20.2 ± 1.5 years; height = 174.2 ± 0.07 cm; body mass = 64.1 ± 6.7 kg) participated in this study. They were recruited from two swimming teams competing at the regional level (International points score = 628.3 ± 77.5) and have at least five years of experience in swimming. The exclusion criteria were the following: a) present any medical condition; and b) present injury that restrains the participants from completing physical and cognitive components of the study. All participants provided written informed consent before participation. This study was approved by the local Ethics and Research Committee and followed the ethical principles in the Declaration of Helsinki.

Experimental design

The design of the present study encompassed five sessions, as seen in Figure 1A. In the preliminary session, the swimmers were familiar with a short version (~ 5-min) of the Stroop test and psychological scales. Then, they attended four more sessions (i.e., two baseline visits and two experimental visits). In the baseline visits, the swimmers performed a 10-min of Stroop task and 3-min all-out tethered swimming. These two sessions were designed to provide tethered swimming performance and the Stroop task reliability measurements. In the experimental visits, the swimmers completed the 3-min all-out tethered swimming after performing a 30-min Stroop test with anodal (i.e., a-tDCS) or placebo (Sham) stimulation over the left-oPFC. These sessions were designed to investigate the effect of tDCS over the left-oPFC on tethered swimming performance in mentally fatigued swimmers. The brain stimulation conditions (i.e., a-tDCS and Sham) were performed in a double-blinded and counterbalanced order.

The experimental sessions were interspersed by a 96-h washout period, performed at the same time of the day (i.e., 8 to 10-h a.m.), under controlled temperature (~24°C) and humidity (50–60%). The motivation, subjective rating mental fatigue, and the electroencephalogram (EEG) were obtained before (pre-treatment), immediately after the Stroop test (post-treatment), and immediately after tethered swimming (post-physical task), as seen in Figure 1A.

*****Insert Figure 1 here*****

Mental fatigue protocol

The computerized version of the Stroop task (Graf et al., 1995) induced mental fatigue in the experimental conditions. Participants performed the task 30 minutes before the physical swimming task. The task was performed in a silent and illuminated room, with the participants sat comfortably on a chair in front of a 21 inches monitor wearing an earphone damper auditive to avoid noise distractions.

The participants answered the word color or according to its name, since the color of the words might be different from what is typed (e.g., the word "blue" might show up in "red" color, the word "green" in "blue," and so on). The participants were given a list of 50 incongruent stimuli. The test was paced with an interval of 250 ms between the response and a new stimulus. The same stimuli (50 words) were randomly shown every time, repeated for 30-min to avoid the learning effect. When the answer was correct, the stimulus disappeared, and a new one was set. A letter “X” appeared on the screen in incorrect answers, and a new stimulus subsequently appeared. The behavioral performance was measured as response time (ms) and percentage of accurate answers. The response time was measured on each 10-min to identify the mental fatigue process. The intraclass coefficient (ICC) was 0.94 ($CI_{95\%}$ = 0.90 to 0.99) and 0.97 ($CI_{95\%}$ = 0.92 to 0.99) for accuracy and response time, respectively.

tDCS configuration

The brain stimulation was applied using an automated tDCS device (MicroEstim, NKL®, São Paulo, Brazil). The anodal electrode was positioned over the left oPFC (i.e., Fp1), while the cathodal electrode was placed over the right oPFC (i.e., Fp2) (see Figure 1B). All electrodes-position were placed according to the 10–20 EEG international system. The previous findings reported by a recent meta-analysis found that tDCS durations longer than 10-min and current intensity of 2.0 mA produced the best results (Alix-Fages et al., 2019). So, the tDCS was applied with 2.0 mA for 30-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 tDCS for 30-s. The impedance was kept below 10 Kohm during tDCS. The same montage was used for the sham condition, 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. The tDCS intervention was performed in a double-blind, randomized, and counterbalanced order. The computational modelling (SimNIBS 2.1, USA) was performed to illustrate the location of the electrical current in the brain (see Figure 1B).

Cognitive manipulation checks

Electroencephalogram (EEG). oPFC and primary motor cortex (M1) activity were continuously obtained using an EEG unit with a 500 Hz sampling frequency, with active electrodes (Ag-AgCl) placed on Fp1 and Cz according to the international EEG 10–20 system, and with resistance kept ∼10 Kohm. These brain areas were chosen why previous EEG studies have suggested that alpha and theta bands over the Cz and Fp1, respectively, might be altered in humans mentally fatigued (Notturno et al., 2014; Spitoni et al., 2013; Wilson et al., 2018). The electrodes were fixed with a conductive gel, adhesive tape, and medical strips. The data were obtained for five minutes with closed eyes (pre-and post-treatment). The surface signal was amplified (gain of 1.000) and treated with a notch (60 Hz) and a 1–30 Hz bandpass filter. The EEG data were analyzed in frequency domains through a fast-Fourier transformation (FFT). The area under the alpha (8-12 Hz) and theta (4-7 Hz) bands power-spectrum were calculated over a 10-s window.

Subjective mental fatigue. The subjective rating of mental fatigue was assessed using the 100 mm Visual Analogue Scale (VAS). This scale has two extremities anchored from 0 (none at all) to 100 (maximal). The participants were required to answer, "How mentally fatigued you feel now?". The definition of MF was provided to participants, and examples of "none at all" (no feelings of tiredness and lack of energy) and "maximal" (maximum feelings of tiredness and lack of energy) MF was explained based on tasks of prolonged periods of demanding cognitive activity. Participants were oriented to drawing a single horizontal line to reflect MF throughout the 100 mm scale according to their perceived status. To quantify values, we measured distance in millimeters from 0 to 100, indicated by the participant.

Subjective motivation. The subjective rating of motivation was assessed using the 100 mm VAS. This scale has two extremities anchored from 0 (none at all) to 100 (maximal). The participants were required to answer, "How motived you feel now?". Participants were oriented to drawing a single vertical line to reflect motivation throughout the 100 mm scale according to their perceived status. To quantify values, we measured distance in millimeters from 0 to 100, indicated by the participant.

Measures

Tethered swimming. Tethered swimming test was used to evaluate the force applied during swimming. The force was measured using a dynamometer (EMG System, São Paulo, Brazil) equipped with a load cell (500-kg capacity primary weighing sensor) for 3-minute all-out test. The load cell was attached to the starting block, and the swimmers were connected to it using a 6-m cord (No. 204; Auriflex, São Paulo, Brazil). Data from the load cell were registered every 5-seconds and recorded using specific software (Lutron SW-U801, Taipei, Taiwan). Subsequently, force data were expressed as every 15-second means. Before the beginning of the test, a 5-min warm-up with moderate intensity was performed by the swimmers. A 5-min rest interval was conceived between warm-up and starting tethered swimming. During the test, swimmers were clearly instructed to keep the cord as extended as possible. No feedback was provided about elapsed or remaining time until completion. The variables collected were peak force (PF) and mean force, and from these data, the fatigue index (FI) {FI [%] = ([PF - minimal force] x 100) x PF} was calculated. Regarding aerobic performance indicators, critical force (CF) and aerobic impulse were used. CF corresponded to the mean force for the last 30 seconds of exercise, while the aerobic impulse was assumed as the area that theoretically represents the total force sustained by the aerobic metabolism during the entire test (Kalva-Filho et al., 2015). The swimmers were familiarized with a 3-minute all-out tethered swimming test. The ICC was 0.92 ($CI_{95\%}$ = 0.89 to 0.95), 0.90 ($CI_{95\%}$ = 0.87 to 0.96) and 0.95 ($CI_{95\%}$ = 0.92 to 0.99) for PF, mean force and CF, respectively, indicating good reproducibility of the tethered swimming performance.

Statistical analysis

The Shapiro-Wilk test was used to evaluate the distribution of data. A two-way ANOVA with repeated measures was used to compare the VAS (i.e., mental fatigue and motivation) and EEG bands (i.e., theta and alpha) using the condition (a-tDCS vs. Sham) and time (pre-treatment vs. post-treatment vs. post-physical task) as factors fixed and subjects as factor random. A two-way ANOVA with repeated measures also was used to analyzing a condition (a-tDCS vs. Sham) x time (pre-treatment vs post-treatment vs post-physical task) interaction for EEG measures (alpha and theta waves), adopting condition and time as factors fixed and subjects as factor random. The same statistical test (i.e., a two-way ANOVA) was used to analyzing a condition (a-tDCS vs. Sham) x time (1st 10-min vs. 2nd 10-min vs. 3rd 10-min) interaction for Stroop task (i.e., accuracy and response time), utilizing condition and time as factors fixed and subjects as factor random. A Bonferroni post-hoc test was used to identify possible statistical differences. Partial eta squared (ηp^2) was used to determine the effect size (ES) and was interpreted using the following cutoff's (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, $\eta p^2 \geq 0.20$. The sphericity assumption was assessed using the Mauchly test, and Greenhouse-Geiser correction was used when needed. The one-way ANOVA with repeated measures was used to compare tethered swimming performance (i.e., force minimum, peak force, mean force, fatigue index, critical force, and aerobic impulse) between experimental conditions (a-tDCS vs. Sham vs. Baseline). The within-group ES was interpreted qualitatively using the following thresholds (Hopkins et al., 2009): <0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; 2.0–4.0, very large. 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). A significance level of 5% was adopted.

Results

Cognitive manipulation checks

Response time Stroop task. There was a significant main effect of condition for response time [$F_{(1, 18)} = 29.1$; $p = 0.001$ (CI$_{95\%}$ = 0.001 to 0.01); $\eta p^2 = 0.11$ (CI$_{95\%}$ = 0.08 to 0.17); ES = large]. It was found impair response time for Sham than a-tDCS ($p<0.05$). There was a significant main effect of time for response time [$F_{(2, 36)} = 4.43$; $p = 0.02$ (CI$_{95\%}$ = 0.01 to 0.05); $\eta p^2 = 0.06$ (CI$_{95\%}$ = 0.03 to 0.09); ES = moderate]. Follow-up tests revealed an increase in response time from 2nd 10-min for 3th 10-min ($p<0.05$). Also, there was a significant main effect of condition x time interaction for response time [Figure 2; $F_{(2, 36)} = 18.54$; $p = 0.001$ (CI$_{95\%}$ = 0.001 to 0.004); $\eta p^2 = 0.16$ (CI$_{95\%}$ = 0.12 to 0.19); ES = large). It was found impair response time for Sham than a-tDCS in 3th 10-min ($p<0.05$).

Accuracy Stroop task. There was no a main effect of condition [$F_{(1, 18)} = 0.35$; $p = 0.69$ (CI$_{95\%}$ = 0.58 to 0.84); $\eta p^2 = 0.02$ (CI$_{95\%}$ = 0.004 to 0.03); ES = small], time [$F_{(2, 36)} = 0.42$; $p = 0.64$ (CI$_{95\%}$ = 0.49 to 0.74); $\eta p^2 = 0.02$ (CI$_{95\%}$ = 0.004 to 0.03); ES = small], and condition vs time interaction [$F_{(2, 36)} = 0.24$; $p = 0.82$ (CI$_{95\%}$ = 0.67 to 0.93); $\eta p^2 = 0.01$ (CI$_{95\%}$ = 0.0001 to 0.02); ES = small] for accuracy.

*****Insert Figure 2 here*****

EEG. There was a significant main effect for condition, time, and condition x time interaction for both theta and alpha bands (Table 1). We found a higher amplitude for Sham than a-tDCS and increased theta amplitude from pre-treatment to post-treatment and post-physical task. Also, only the Sham condition increased theta and alpha amplitude in post-treatment and post-physical tasks.

VAS Mental fatigue. There was a significant main effect of condition, time, and condition x time interaction for subjective mental fatigue (Table 1). Higher subjective mental fatigue was found for Sham than a-tDCS, increasing subjective mental fatigue from pre-treatment for post-treatment and pre-treatment for the post-physical task. Also, higher subjective mental fatigue for Sham than a-tDCS in post-treatment and post-physical tasks were found.

VAS Motivation. There was no main effect of time, condition, and condition x time interaction for motivation (Table 1).

*****Insert Table 1 here*****

Tethered swimming

Force minimum. There was a significant main effect of condition for force minimum [Table 2; $F_{(1, 18)} = 8.42$; $p = 0.02$ ($CI_{95\%}$ = 0.01 to 0.05); $d = 0.43$ ($CI_{95\%}$ = 0.32 to 0.49); ES = small]. It was found lower force minimum for Sham and Baseline than a-tDCS ($p<0.05$). There was no difference for force minimum between Sham and Baseline.

Peak force. There was no main effect of condition for peak force [Table 2; $F_{(1, 18)} = 1.67$; $p = 0.25$ ($CI_{95\%}$ = 0.18 to 0.34); $d = 0.16$ ($CI_{95\%}$ = 0.11 to 0.23); ES = trivial].

*****Insert Table 2 here*****

Mean force. There was a significant main effect of condition for mean force [Figure 3; $F_{(1, 18)} = 13.50$; $p = 0.01$ ($CI_{95\%}$ = 0.003 to 0.04); $d = 0.69$ ($CI_{95\%}$ = 0.53 to 0.75); ES = moderate]. It was found lower mean force for Sham than a-tDCS and Baseline ($p<0.05$). There was no difference for mean force between a-tDCS and Baseline ($p>0.05$).

Fatigue index. There was a significant main effect of condition for fatigue index [Figure 3; $F_{(1, 18)} = 6.51$; $p = 0.04$ ($CI_{95\%} = 0.01$ to 0.05); $d = 0.34$ ($CI_{95\%} = 0.22$ to 0.39); ES = small]. It was found higher fatigue index for Sham than a-tDCS ($p<0.05$). There was no difference for fatigue index between Sham and Baseline neither between a-tDCS and Baseline ($p>0.05$).

Critical force. There was a significant main effect of condition for critical force [Figure 3; $F_{(1, 18)} = 17.61$; $p = 0.004$ ($CI_{95\%} = 0.001$ to 0.02); $d = 0.73$ ($CI_{95\%} = 0.60$ to 0.79); ES = moderate]. It was found lower critical force for Sham than a-tDCS and Baseline ($p<0.05$). There was no difference for critical force between a-tDCS and Baseline ($p>0.05$).

Aerobic impulse. There was a significant main effect of condition for aerobic impulse [Figure 3; $F_{(1, 18)} = 14.30$; $p = 0.02$ ($CI_{95\%} = 0.01$ to 0.05); $d = 0.63$ ($CI_{95\%} = 0.51$ to 0.74); ES = moderate]. It was found lower aerobic impulse for Sham than a-tDCS and Baseline ($p<0.05$). There was no difference for aerobic impulse between a-tDCS and Baseline ($p>0.05$).

*****Insert Figure 3 here*****

Discussion

This study aimed to analyze the effect of a-tDCS over the left-oPFC on endurance performance in mentally fatigued female amateur swimmers. The main findings showed a better endurance performance (i.e., critical force, aerobic impulse, and mean force) in tethered swimming for a-tDCS than Sham, but no difference was found for the peak force following the use of tDCS. Moreover, response time was worsened in Sham condition but sustained in a-tDCS in the last 10-minutes of the mental fatigue task. Then, the hypothesis was partially confirmed.

It has been suggested that athletes submitted to ~30-min of high cognitive demanding lead them to mental fatigue state (Gantois et al., 2020; Penna et al., 2018; Smith et al., 2016), which might be revealed through subjective (e.g., VAS), behavioral (e.g., response time), and physiological (e.g., EEG) measures. In addition to the worsening in the aforementioned behavioral results, a substantial increase in VAS and EEG the Sham condition after mental fatigue induction was found. On the opposite, was demonstrated maintenance in all parameters for a-tDCS. Previous studies also revealed impairment of response time (Gantois et al., 2020; Martin et al., 2016), an increase of theta band amplitude over Fp1 (Jacquet et al., 2021; Pires et al., 2018), an increase in rating subjective mental fatigue (Fortes, Nakamura, et al., 2020; Smith et al., 2016), and no changes in subjective motivation (Martin et al., 2016; Smith et al., 2016) after 30-min or more of high cognitive demand task. It seems that the a-tDCS applied over the frontal brain area can improve attentional resources (Angius et al., 2019), which can reduce the feeling of mental fatigue (McIntire et al., 2017). Although the oPFC could be involved in motivation (Szatkowska et al., 2008), neither mental fatigue nor non-invasive brain stimulation altered the motivation scores in the present study. More studies should investigate to clarify the relationship between oPFC, mental fatigue, tDCS, and motivation.

The effectiveness of a-tDCS to modulate cognitive performance and brain oscillations have been well-demonstrated. For instance, McIntire et al. (2017) maintained sustained attention for 24-h in the mentally fatigued military after applying a-tDCS over left-DLPFC. Di Giacomo et al. (2018) found no change of theta band on the Fp1 channel when non-invasive brain stimulation was applied over the brain front-parietal area in subjects performing cognitive demand tasks. Lee et al. (2020) maintained the amplitude of the low alpha band on left-dlPFC when a-tDCS was applied for 20-min over the F3 channel in subjects performing dual-task. These findings suggest that a-tDCS might counteract to harmful effects of high cognitive demand for a prolonged period, explaining the maintenance of theta and alpha bands and the behavioral results for a-tDCS experimental condition during the 30-min Stroop task. However, considering the lack of information about how mental fatigue affects each brain area, more studies are recommended to confirm a-tDCS effectiveness against mental fatigue states.

Our study did not find a difference in peak force between experimental conditions. This result corroborated previous studies, which no found an effect of mental fatigue (Fortes, Nakamura, et al., 2020; Pageaux et al., 2013) or a-tDCS (Alix-Fages et al., 2021) on short-duration all-out neuromuscular performance in athletes. For example, Pageaux et al. (2013) did not find any change in the maximal voluntary contraction torque of the knee extensor muscles during the high mental exertion task in healthy active males. Similarly, Fortes et al. (2020) found no changes for countermovement jump (CMJ) performance in mentally fatigued high-level swimmers. Regarding tDCS, Alix-Fages et al. (2021) applied a-tDCS over left-dlPFC and did not found changes for a force-velocity profile in physically active healthy males. Also, applying a-tDCS over the M1 area (i.e., C3 and C4 channels) showed no improvement on CMJ in high-level taekwondo athletes (Mesquita et al., 2019). One possible explanation is that the fatigue on short-term neuromuscular performance seems to be regulated for peripheral fatigue pathways without the necessity of high cognitive processes (Brown et al., 2020b; Pageaux et al., 2013; Silva-Cavalcante et al., 2018). Taken together, these pieces of evidence might explain the peak force results found in the present study.

The present study results demonstrated better endurance performance for a-tDCS than Sham condition in female amateur swimmers. Impaired endurance performance in mentally fatigued swimming athletes has been shown in previous studies (Fortes et al., 2021; Penna et al., 2018). For example, Penna et al. (2018) revealed poor 1.500-m freestyle performance in young swimmers mentally fatigued, while Fortes et al. (2021) found impaired 100 and 200-m freestyle performance in high-level swimmers after 30-min using social media on a smartphone. Considering the behavioral (i.e., response time) and physiological (i.e., EEG) measures, the a-tDCS over left-oPFC counteract to mental fatigue negative effect and was able to keep the endurance performance (i.e., aerobic impulse, minimum, mean, and critical force). The a-tDCS applied over brain frontal areas can increase the attentional resources (Angius et al., 2019; McIntire et al., 2017), delaying the increase of RPE during endurance exercise (Okano et al., 2015), and increase the tolerance for long-duration exercise. This result was shown by Angius et al. (2019), which found an delay for fatigue and increased endurance performance after a-tDCS. Lattari et al. (2018) also found an increased endurance performance after a-tDCS in healthy women physically active. Futures investigations should try to reproduce the positive effect of a-tDCS for counteract mental fatigue and maintaining athletes' endurance performance.

Although the present study revealed results that might add to the scientific literature, it presents some limitations. We cannot exclude the possibility that the current stimulation affected the oPFC cortex adjacent areas. Also, only female swimmers participated in the study, so generalizations should be made with caution. Also, we lack equalization for cognitive load during mental fatigue tasks. Thus, we recommend caution in generalizing these findings.

Conclusion

We concluded that a-tDCS applied over the left-oPFC in mentally fatigued female amateur swimmers-maintained endurance performance. Thus, the perspective that a-tDCS applied over the frontal brain areas may translate into competitive advantages for amateur or professional swimmers mentally fatigued should not be ignored in the field of sports. From a practical point of view, the use of a-tDCS should be considered to counteract harmful cognitive effects and maintain endurance performance during competitive race events. The a-tDCS over the oPFC could be used immediately before race events per at least 20-min (e.g., before the athlete puts on the cap while waiting for the race).

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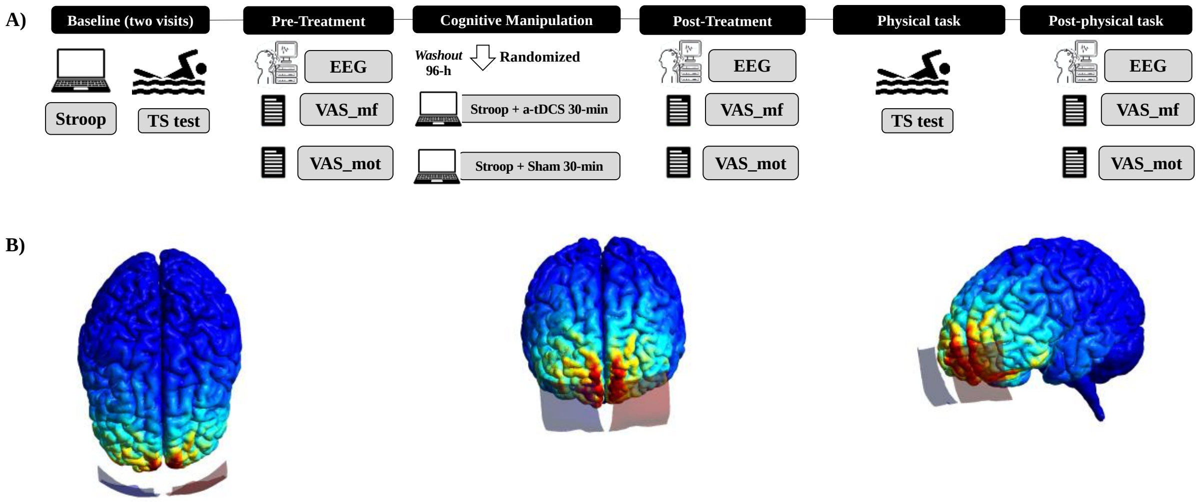

Figure 1

Experimental design of the study (A) and computational modelling of brain-stimulating (B).

Note. TS = tethered swimming; EEG = electroencephalogram; VAS_mf = subjective mental fatigue; VAS_mot = subjective motivation; a-tDCS = anodal transcranial direct current stimulation.

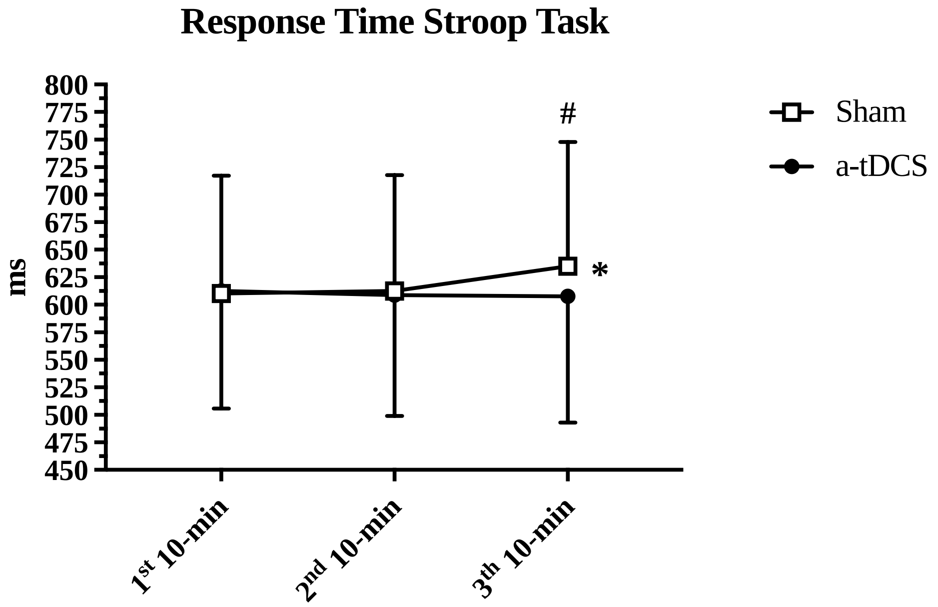

Figure 2

Response time during 30-min of Stroop task in experimental conditions (a-tDCS and Sham) in amateur swimmers.

Note. *$p<0.05$ difference for 2nd 10-min; #$p<0.05$ difference between a-tDCS and Sham condition.

Table 1

VAS (mental fatigue and motivation) and EEG waves (theta and alpha) for both experimental conditions (a-tDCS and Sham) in amateur swimmers.

Variables	**a-tDCS**	**Sham**	**Effect**	***F***	***p***	**CI$_{95\%}$**	**ηp^2 (CI$_{95\%}$)**	**ES**
Theta Fp1 (μV^2)								
Pre-treatment	2.6 ± 0.7	2.7 ± 0.8						
Post-treatment	2.6 ± 0.6$^{\#}$	2.9 ± 0.5*	Time	8.27	0.001	0.001-0.02	0.10 (0.001-0.02)	Large
Post-physical task	2.7 ± 0.6$^{\#}$	2.8 ± 0.6*	Condition	16.49	0.001	0.001-0.01	0.12 (0.09-0.16)	Large
Δ% (pre-vs post-treatment)	0.9 ± 0.4	4.5 ± 1.8	Interaction	10.01	0.001	0.001-0.004	0.15 (0.10-0.17)	Large
Alpha Cz (μV^2)								
Pre-treatment	4.7 ± 1.1	4.7 ± 0.9						
Post-treatment	4.7 ± 1.0$^{\#}$	4.9 ± 0.8*	Time	5.81	0.007	0.001-0.02	0.09 (0.06-0.12)	Moderate
Post-physical task	4.8 ± 0.7$^{\#}$	5.0 ± 1.0*	Condition	6.11	0.03	0.01-0.06	0.05 (0.03-0.08)	Moderate
Δ% (pre-vs post-treatment)	0.5 ± 0.2	3.7 ± 0.8	Interaction	7.66	0.02	0.01-0.04	0.07 (0.04-0.10)	Moderate
VAS mental fatigue (mm)								
Pre-treatment	14.1 ± 5.6	10.9 ± 4.5						
Post-treatment	60.2 ± 12.5$^{\#}$ *	68.9 ± 13.4*	Time	203.00	0.001	0.001-0.01	0.61 (0.53-0.67)	Very large
Post-physical task	63.3 ± 13.8$^{\#}$ *	71.1 ± 16.0*	Condition	2.34	0.04	0.02-0.05	0.05 (0.03-0.09)	Moderate
Δ% (pre-vs post-treatment)	291.1 ± 90.3	314.5 ± 87.6	Interaction	6.92	0.003	0.01-0.05	0.08 (0.04-0.11)	Moderate
VAS motivation (mm)								
Pre-treatment	94.0 ± 7.2	97.8 ± 8.1						
Post-treatment	96.0 ± 4.3	98.9 ± 2.5	Time	1.53	0.14	0.08-0.20	0.02 (0.01-0.03)	Small
Post-physical task	97.5 ± 2.6	98.3 ± 1.2	Condition	0.08	0.77	0.62-0.84	0.01 (0.003-0.02)	Small
Δ% (pre-vs post-treatment)	3.7 ± 2.0	2.6 ± 1.5	Interaction	0.46	0.63	0.50-0.77	0.01 (0.004-0.02)	Small

Note. VAS = Visual Analogue Scale; Δ% = percent delta from pre-to post-treatment; *p<0.05 difference for pre-treatment; $^{\#}$p<0.05 difference for sham.

Table 2

Comparison of minimum and peak force in tethered swimming between experimental conditions (a-tDCS vs. Sham vs. Baseline) in female amateur swimmers.

Variables	**a-tDCS**	**Sham**	**Baseline**	**Effect**	***F***	***p***
Force minimum (N)	55.0 ± 8.3$^{\#}$	52.6 ± 7.1	53.8 ± 5.8	Condition	8.42	0.02
Δ% (difference)		4.0 ± 1.3				
Peak force (N)	97.4 ± 12.5	96.3 ± 10.7	97.7 ± 9.2	Condition	1.67	0.25
Δ% (difference)		2.1 ± 1.0				

Note. Δ% = difference between experimental conditions; $^{\#}$p<0.05 difference for sham and baseline.

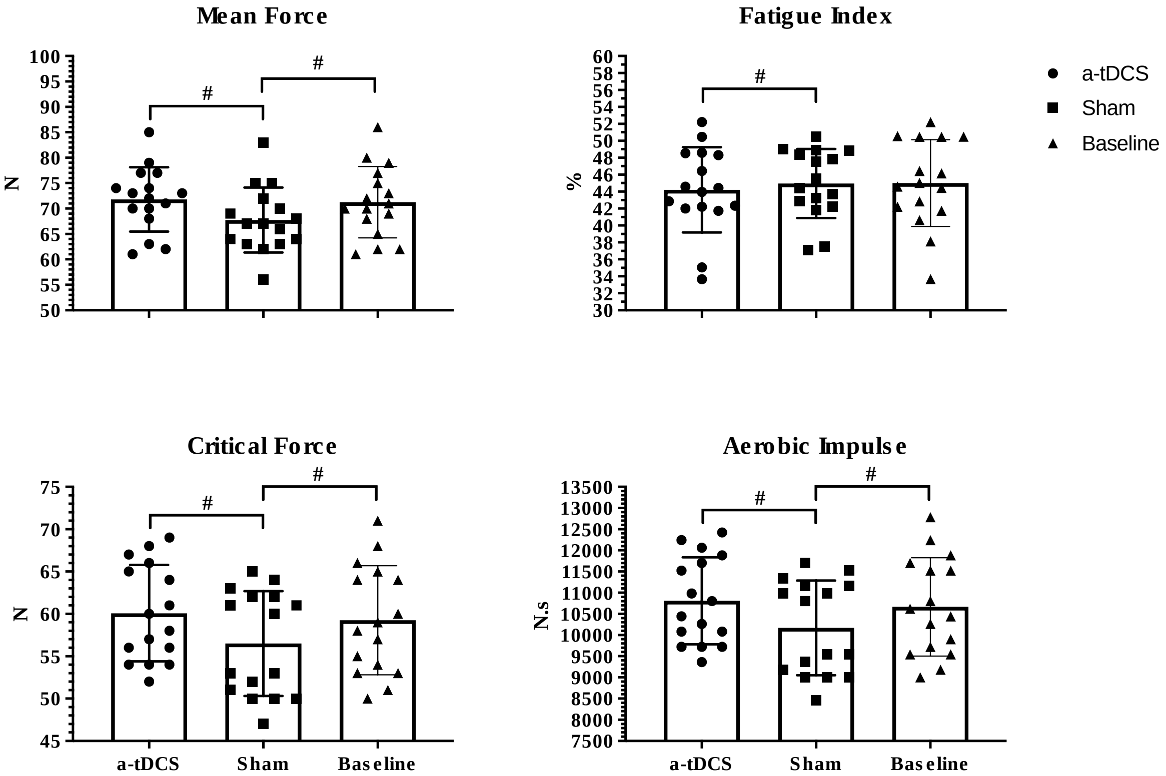

Figure 3

Mean force, fatigue index, critical force, and aerobic impulse according to the experimental condition (a-tDCS vs. Sham vs. Baseline) in female amateur swimmers.

Note. $^{\#}p<0.05$ difference for a-tDCS and Baseline.