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

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1 Non-invasive brain stimulation over the orbital prefrontal cortex maintains endurance
2 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 mitigate 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.

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Introduction

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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).

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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).

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Mental fatigue caused by prolonged response inhibition overtime can decrease 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

63 et al., 2018; Smith et al., 2018). However, McMorris (2020) contested this idea because
64 research conducted in rodents showed different results on neurotransmitters. In addition,
65 increases in adenosine due to dopamine activation during prolonged cognitive tasks are
66 phasic, not tonic, and are induced when dopamine is phasically released (McMorris, 2020).
67 Then, the claim about increased extracellular adenosine concentration and reduced
68 dopamine activity in the frontal brain following prolonged cognitive exertion should be
69 analyzed with caution.

70 The frontal brain area, especially the oPFC, has been shown to play an important role
71 in exercise regulation. The oPFC regulate effort tolerance (Robertson & Marino, 2016), is
72 also involved in motivation (Szatkowska et al., 2008), suggesting this brain area has a
73 fundamental role in endurance performance (Marcora & Staiano, 2010). In addition, the
74 oPFC activities depend on interaction with many other parts of the brain, for example, in the
75 lateral PFC, anterior insula, and ACC (Craig, 2002). So, once impaired oPFC, for example,
76 the oPFC deactivation (Tran et al., 2020) or reduced dopamine activity on ACC (McMorris,
77 2020) caused by mental fatigue, could impair endurance performance.

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

88 tDCS is a non-invasive brain stimulation, portable, feasible, safe, and well-tolerated
89 (Edwards et al., 2017; Machado et al., 2019). Two types of active stimulation are possible:
90 anodal (i.e., a-tDCS) and cathodal (i.e., c-tDCS), which aim to increase and decrease
91 neuronal excitability, respectively (Nitsche et al., 2003). The potential mechanism underlying
92 the ergogenic effect of tDCS could be increased cortical excitability in specific brain areas
93 targeted by a-tDCS. Studies have been showing that when applied over oPFC or dorsolateral
94 PFC (dlPFC), a-tDCS improves executive functions (e.g., inhibitory control or attention)
95 (Colzato, Stern, & Kibele, 2016; Borducchi et al., 2016) and endurance performance (Angius
96 et al., 2019; Edwards et al., 2017). For example, Angius et al. (2019) found an improvement
97 in Stroop task (i.e., improved accuracy) and endurance performance (i.e., increased time to
98 exhaustion) following a-tDCS over the left-dlPFC. Recent interests in the use of tDCS as a
99 novel technique for reduction of mental fatigue and enhancement of endurance performance
100 in swimmers shows an upward trend (Penna et al., 2021; Salehi, Fard, Jaberzadeh, & Zoghi,
101 2021). However, the results are controversial. Salehi et al. (2021) applied a-tDCS over the
102 left-dlPFC per 20-min in mentally fatigued professional swimmers and found improved 50-m
103 freestyle performance, although the tDCS presented no changes in the mental fatigue induced
104 by prolonged cognitive task (i.e., 60-min of Stroop task). Penna et al. (2021) no found effect
105 on 800-m freestyle performance in mentally fatigued male amateur swimmers after a-tDCS
106 online (i.e., during the cognitive task) applied over the left temporal cortex during 30-min.
107 Both scientific investigations utilized physical tasks that do not measure endurance
108 performance (e.g., 50-m freestyle performance) or a controlled endurance task (i.e., 800-m
109 freestyle performance), which pace's strategy may influence.

110 Also, it is important to highlight that none of the swimmers' scientific investigations
111 above revealed a-tDCS as an ergogenic resource to counteract mental fatigue. Neuroimaging
112 studies investigating the neural basis of mental fatigue found a reduction of functional

113 connectivity between the left and right oPFC in mentally fatigued individuals (Sun, Lim,
114 Kwok, & Bezerianos, 2014; Tran et al., 2020). A tDCS montage that maintain the functional
115 connectivity between the left and right oPFC maybe be an ergogenic resource to counteract
116 mental fatigue and maintain subsequent endurance performance. Thus, new scientific studies
117 could test different montages for tDCS over the oPFC throughout prolonged repetitive
118 cognitive inhibitory tasks to remove the harmful effects of mental fatigue on endurance
119 performance. Here, we proposed the tDCS online (i.e., during cognitive task) with anodal
120 electrode positioned over the left-oPFC (i.e., Fp1), while the cathodal electrode placed over
121 the right-oPFC (i.e., Fp2) for counteract mental fatigue induced by prolonged cognitive task
122 (i.e., incongruent stroop task) and maintain subsequent endurance performance in female
123 amateur swimmers.

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

132

133 **Materials and Methods**

134 ***Participants***

135 A priori sample size calculation was performed using G*Power software version
136 3.1.9.2 (Universität Kiel, Kiel, Germany), for an analysis of variance (ANOVA) with
137 repeated measures within factors using the option "ANOVA: repeated measures, within

138 factors” for endurance performance in mentally fatigued swimmers (Fortes et al., 2021),
139 including the following criteria: (a) power = 0.80; (b) medium ES ($\eta^2 = .08$ or $f = 0.29$); (c)
140 $\alpha = .05$; (d) the number of groups (i.e., number of experimental conditions) = 2; (e) number of
141 measurements = 4; (f) correlation among repeated measures = 0.5; and (g) nonsphericity
142 correction = 1. Results indicated that eighteen subjects would be necessary for the study.
143 Using the non-probabilistic method for sample recruitment, nineteen female amateur
144 swimmers (age = 20.2 ± 1.5 years; height = 174.2 ± 0.07 cm; body mass = 64.1 ± 6.7 kg)
145 participated in this study. They were recruited from two swimming teams competing at the
146 regional level (International points score = 628.3 ± 77.5) and have at least five years of
147 experience in swimming. The exclusion criteria were the following: a) present any medical
148 condition; and b) present injury that restrains the participants from completing physical and
149 cognitive components of the study. All participants provided written informed consent before
150 participation. This study was approved by the local Ethics and Research Committee and
151 followed the ethical principles in the Declaration of Helsinki.

152

153 *Experimental design*

154 The design of the present study encompassed five sessions, as seen in Figure 1A. In
155 the preliminary session, the swimmers were familiar with a short version (~ 5-min) of the
156 Stroop test and psychological scales. Then, they attended four more sessions (i.e., two
157 baseline visits and two experimental visits). In the baseline visits, the swimmers performed a
158 10-min of Stroop task and 3-min all-out tethered swimming. These two sessions were
159 designed to provide tethered swimming performance and the Stroop task reliability
160 measurements. In the experimental visits, the swimmers completed the 3-min all-out tethered
161 swimming after performing a 30-min Stroop test with anodal (i.e., a-tDCS) or placebo
162 (Sham) stimulation over the left-oPFC. These sessions were designed to investigate the effect

163 of tDCS over the left-oPFC on tethered swimming performance in mentally fatigued
164 swimmers. The brain stimulation conditions (i.e., a-tDCS and Sham) were performed in a
165 double-blinded and counterbalanced order.

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

172

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

174

175 *Mental fatigue protocol*

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

181 The participants answered the word color or according to its name, since the color of
182 the words might be different from what is typed (e.g., the word "blue" might show up in "red"
183 color, the word "green" in "blue," and so on). The participants were given a list of 50
184 incongruent stimuli. The test was paced with an interval of 250 ms between the response and
185 a new stimulus. The same stimuli (50 words) were randomly shown every time, repeated for
186 30-min to avoid the learning effect. When the answer was correct, the stimulus disappeared,
187 and a new one was set. A letter "X" appeared on the screen in incorrect answers, and a new

188 stimulus subsequently appeared. The behavioral performance was measured as response time
189 (ms) and percentage of accurate answers. The response time was measured on each 10-min to
190 identify the mental fatigue process. The intraclass coefficient (ICC) was 0.94 ($CI_{95\%} = 0.90$ to
191 0.99) and 0.97 ($CI_{95\%} = 0.92$ to 0.99) for accuracy and response time, respectively.

192

193 *tDCS configuration*

194 The brain stimulation was applied using an automated tDCS device (MicroEstim,
195 NKL[®], São Paulo, Brazil). The anodal electrode was positioned over the left oPFC (i.e., Fp1),
196 while the cathodal electrode was placed over the right oPFC (i.e., Fp2) (see Figure 1B). All
197 electrodes-position were placed according to the 10–20 EEG international system. The
198 previous findings reported by a recent meta-analysis found that tDCS durations longer than
199 10-min and current intensity of 2.0 mA produced the best results (Alix-Fages et al., 2019).
200 So, the tDCS was applied with 2.0 mA for 30-min using rubber conductive electrodes (5 x 5
201 cm; 25 cm²; 0.08 mA/cm²) covered with sponges soaked in saline solution (0.8% NaCl). The
202 current was ramped up and down at the beginning and end of tDCS for 30-s. The impedance
203 was kept below 10 Kohm during tDCS. The same montage was used for the sham condition,
204 but the current was turned off after 30-s. The participants reported itching and tingling
205 sensation under the electrodes during tDCS but did not report any adverse effects. The tDCS
206 intervention was performed in a double-blind, randomized, and counterbalanced order. The
207 computational modelling (SimNIBS 2.1, USA) was performed to illustrate the location of the
208 electrical current in the brain (see Figure 1B).

209

210 *Cognitive manipulation checks*

211 *Electroencephalogram (EEG)*. oPFC and primary motor cortex (M1) activity were
212 continuously obtained using an EEG unit with a 500 Hz sampling frequency, with active

213 electrodes (Ag-AgCl) placed on Fp1 and Cz according to the international EEG 10–20
214 system, and with resistance kept ~ 10 Kohm. These brain areas were chosen why previous
215 EEG studies have suggested that alpha and theta bands over the Cz and Fp1, respectively,
216 might be altered in humans mentally fatigued (Notturmo et al., 2014; Spitoni et al., 2013;
217 Wilson et al., 2018). The electrodes were fixed with a conductive gel, adhesive tape, and
218 medical strips. The data were obtained for five minutes with closed eyes (pre-and post-
219 treatment). The surface signal was amplified (gain of 1.000) and treated with a notch (60 Hz)
220 and a 1–30 Hz bandpass filter. The EEG data were analyzed in frequency domains through a
221 fast-Fourier transformation (FFT). The area under the alpha (8-12 Hz) and theta (4-7 Hz)
222 bands power-spectrum were calculated over a 10-s window.

223

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

233

234 *Subjective motivation.* The subjective rating of motivation was assessed using the 100 mm
235 VAS. This scale has two extremities anchored from 0 (none at all) to 100 (maximal). The
236 participants were required to answer, “How motivated you feel now?”. Participants were
237 oriented to drawing a single vertical line to reflect motivation throughout the 100 mm scale

238 according to their perceived status. To quantify values, we measured distance in millimeters
239 from 0 to 100, indicated by the participant.

240

241 *Measures*

242 *Tethered swimming.* Tethered swimming test was used to evaluate the force applied during
243 swimming. The force was measured using a dynamometer (EMG System, São Paulo, Brazil)
244 equipped with a load cell (500-kg capacity primary weighing sensor) for 3-minute all-out
245 test. The load cell was attached to the starting block, and the swimmers were connected to it
246 using a 6-m cord (No. 204; Auriflex, São Paulo, Brazil). Data from the load cell were
247 registered every 5-seconds and recorded using specific software (Lutron SW-U801, Taipei,
248 Taiwan). Subsequently, force data were expressed as every 15-second means. Before the
249 beginning of the test, a 5-min warm-up with moderate intensity was performed by the
250 swimmers. A 5-min rest interval was conceived between warm-up and starting tethered
251 swimming. During the test, swimmers were clearly instructed to keep the cord as extended as
252 possible. No feedback was provided about elapsed or remaining time until completion. The
253 variables collected were peak force (PF) and mean force, and from these data, the fatigue
254 index (FI) $\{FI [\%] = ([PF - \text{minimal force}] \times 100) \times PF\}$ was calculated. Regarding aerobic
255 performance indicators, critical force (CF) and aerobic impulse were used. CF corresponded
256 to the mean force for the last 30 seconds of exercise, while the aerobic impulse was assumed
257 as the area that theoretically represents the total force sustained by the aerobic metabolism
258 during the entire test (Kalva-Filho et al., 2015). The swimmers were familiarized with a 3-
259 minute all-out tethered swimming test. The ICC was 0.92 ($CI_{95\%} = 0.89$ to 0.95), 0.90 ($CI_{95\%}$
260 $= 0.87$ to 0.96) and 0.95 ($CI_{95\%} = 0.92$ to 0.99) for PF, mean force and CF, respectively,
261 indicating good reproducibility of the tethered swimming performance.

262

263 *Statistical analysis*

264 The Shapiro-Wilk test was used to evaluate the distribution of data. A two-way
265 ANOVA with repeated measures was used to compare the VAS (i.e., mental fatigue and
266 motivation) and EEG bands (i.e., theta and alpha) using the condition (a-tDCS vs. Sham) and
267 time (pre-treatment vs. post-treatment vs. post-physical task) as factors fixed and subjects as
268 factor random. A two-way ANOVA with repeated measures also was used to analyzing a
269 condition (a-tDCS vs. Sham) x time (pre-treatment vs post-treatment vs post-physical task)
270 interaction for EEG measures (alpha and theta waves), adopting condition and time as factors
271 fixed and subjects as factor random. The same statistical test (i.e., a two-way ANOVA) was
272 used to analyzing a condition (a-tDCS vs. Sham) x time (1st 10-min vs. 2nd 10-min vs. 3rd 10-
273 min) interaction for Stroop task (i.e., accuracy and response time), utilizing condition and
274 time as factors fixed and subjects as factor random. A Bonferroni post-hoc test was used to
275 identify possible statistical differences. Partial eta squared (η^2) was used to determine the
276 effect size (ES) and was interpreted using the following cutoff's (Cohen, 1992): small effect,
277 $\eta^2 < 0.03$; moderate effect, $0.03 \leq \eta^2 < 0.10$; large effect, $.10 \leq \eta^2 < 0.20$; very large
278 effect, $\eta^2 \geq 0.20$. The sphericity assumption was assessed using the Mauchly test, and
279 Greenhouse-Geiser correction was used when needed. The one-way ANOVA with repeated
280 measures was used to compare tethered swimming performance (i.e., force minimum, peak
281 force, mean force, fatigue index, critical force, and aerobic impulse) between experimental
282 conditions (a-tDCS vs. Sham vs. Baseline). The within-group ES was interpreted
283 qualitatively using the following thresholds (Hopkins et al., 2009): <0.2 , trivial; 0.2–0.6,
284 small; 0.6–1.2, moderate; 1.2–2.0, large; 2.0–4.0, very large. Data were processed in the
285 Statistical Package for Social Sciences Version 21.0 (IBM Corp., Armonk, NY, USA) and
286 GraphPad Prism 8 (San Diego, CA, USA). A significance level of 5% was adopted.

287

288

Results***Cognitive manipulation checks***

290 *Response time Stroop task.* There was a significant main effect of condition for response time
291 [$F_{(1, 18)} = 29.1$; $p = 0.001$ ($CI_{95\%} = 0.001$ to 0.01); $\eta p^2 = 0.11$ ($CI_{95\%} = 0.08$ to 0.17); ES =
292 large]. It was found impair response time for Sham than a-tDCS ($p < 0.05$). There was a
293 significant main effect of time for response time [$F_{(2, 36)} = 4.43$; $p = 0.02$ ($CI_{95\%} = 0.01$ to
294 0.05); $\eta p^2 = 0.06$ ($CI_{95\%} = 0.03$ to 0.09); ES = moderate]. Follow-up tests revealed an
295 increase in response time from 2nd 10-min for 3th 10-min ($p < 0.05$). Also, there was a
296 significant main effect of condition x time interaction for response time [Figure 2; $F_{(2, 36)} =$
297 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
298 was found impair response time for Sham than a-tDCS in 3th 10-min ($p < 0.05$).

299

300 *Accuracy Stroop task.* There was no a main effect of condition [$F_{(1, 18)} = 0.35$; $p = 0.69$ ($CI_{95\%}$
301 $= 0.58$ to 0.84); $\eta p^2 = 0.02$ ($CI_{95\%} = 0.004$ to 0.03); ES = small], time [$F_{(2, 36)} = 0.42$; $p = 0.64$
302 ($CI_{95\%} = 0.49$ to 0.74); $\eta p^2 = 0.02$ ($CI_{95\%} = 0.004$ to 0.03); ES = small], and condition vs
303 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
304 0.02); ES = small] for accuracy.

305

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

307

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

313

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

319

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

322

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

324

325 *Tethered swimming*

326 *Force minimum.* There was a significant main effect of condition for force minimum [Table
327 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 =
328 small]. It was found lower force minimum for Sham and Baseline than a-tDCS ($p < 0.05$).
329 There was no difference for force minimum between Sham and Baseline.

330

331 *Peak force.* There was no main effect of condition for peak force [Table 2; $F_{(1, 18)} = 1.67$; $p =$
332 0.25 (CI_{95%} = 0.18 to 0.34); $d = 0.16$ (CI_{95%} = 0.11 to 0.23); ES = trivial].

333

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

335

336 *Mean force.* There was a significant main effect of condition for mean force [Figure 3; $F_{(1, 18)}$
337 = 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

338 was found lower mean force for Sham than a-tDCS and Baseline ($p < 0.05$). There was no
339 difference for mean force between a-tDCS and Baseline ($p > 0.05$).

340

341 *Fatigue index.* There was a significant main effect of condition for fatigue index [Figure 3;
342 $F_{(1, 18)} = 6.51$; $p = 0.04$ (CI_{95%} = 0.01 to 0.05); $d = 0.34$ (CI_{95%} = 0.22 to 0.39); ES = small]. It
343 was found higher fatigue index for Sham than a-tDCS ($p < 0.05$). There was no difference for
344 fatigue index between Sham and Baseline neither between a-tDCS and Baseline ($p > 0.05$).

345

346 *Critical force.* There was a significant main effect of condition for critical force [Figure 3;
347 $F_{(1, 18)} = 17.61$; $p = 0.004$ (CI_{95%} = 0.001 to 0.02); $d = 0.73$ (CI_{95%} = 0.60 to 0.79); ES =
348 moderate]. It was found lower critical force for Sham than a-tDCS and Baseline ($p < 0.05$).
349 There was no difference for critical force between a-tDCS and Baseline ($p > 0.05$).

350

351 *Aerobic impulse.* There was a significant main effect of condition for aerobic impulse [Figure
352 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 =
353 moderate]. It was found lower aerobic impulse for Sham than a-tDCS and Baseline ($p < 0.05$).
354 There was no difference for aerobic impulse between a-tDCS and Baseline ($p > 0.05$).

355

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

357

358 **Discussion**

359 This study aimed to analyze the effect of a-tDCS over the left-oPFC on endurance
360 performance in mentally fatigued female amateur swimmers. The main findings showed a
361 better endurance performance (i.e., critical force, aerobic impulse, and mean force) in
362 tethered swimming for a-tDCS than Sham, but no difference was found for the peak force

363 following the use of tDCS. Moreover, response time was worsened in Sham condition but
364 sustained in a-tDCS in the last 10-minutes of the mental fatigue task. Then, the hypothesis
365 was partially confirmed.

366 It has been suggested that athletes submitted to ~30-min of high cognitive demanding
367 lead them to mental fatigue state (Gantois et al., 2020; Penna et al., 2018; Smith et al., 2016),
368 which might be revealed through subjective (e.g., VAS), behavioral (e.g., response time), and
369 physiological (e.g., EEG) measures. In addition to the worsening in the aforementioned
370 behavioral results, a substantial increase in VAS and EEG the Sham condition after mental
371 fatigue induction was found. On the opposite, was demonstrated maintenance in all
372 parameters for a-tDCS. Previous studies also revealed impairment of response time (Gantois
373 et al., 2020; Martin et al., 2016), an increase of theta band amplitude over Fp1 (Jacquet et al.,
374 2021; Pires et al., 2018), an increase in rating subjective mental fatigue (Fortes, Nakamura, et
375 al., 2020; Smith et al., 2016), and no changes in subjective motivation (Martin et al., 2016;
376 Smith et al., 2016) after 30-min or more of high cognitive demand task. It seems that the a-
377 tDCS applied over the frontal brain area can improve attentional resources (Angius et al.,
378 2019), which can reduce the feeling of mental fatigue (McIntire et al., 2017). Although the
379 oPFC could be involved in motivation (Szatkowska et al., 2008), neither mental fatigue nor
380 non-invasive brain stimulation altered the motivation scores in the present study. More
381 studies should investigate to clarify the relationship between oPFC, mental fatigue, tDCS,
382 and motivation.

383 The effectiveness of a-tDCS to modulate cognitive performance and brain oscillations
384 have been well-demonstrated. For instance, McIntire et al. (2017) maintained sustained
385 attention for 24-h in the mentally fatigued military after applying a-tDCS over left-DLPFC.
386 Di Giacomo et al. (2018) found no change of theta band on the Fp1 channel when non-
387 invasive brain stimulation was applied over the brain front-parietal area in subjects

388 performing cognitive demand tasks. Lee et al. (2020) maintained the amplitude of the low
389 alpha band on left-dIPFC when a-tDCS was applied for 20-min over the F3 channel in
390 subjects performing dual-task. These findings suggest that a-tDCS might counteract to
391 harmful effects of high cognitive demand for a prolonged period, explaining the maintenance
392 of theta and alpha bands and the behavioral results for a-tDCS experimental condition during
393 the 30-min Stroop task. However, considering the lack of information about how mental
394 fatigue affects each brain area, more studies are recommended to confirm a-tDCS
395 effectiveness against mental fatigue states.

396 Our study did not find a difference in peak force between experimental conditions.
397 This result corroborated previous studies, which no found an effect of mental fatigue (Fortes,
398 Nakamura, et al., 2020; Pageaux et al., 2013) or a-tDCS (Alix-Fages et al., 2021) on short-
399 duration all-out neuromuscular performance in athletes. For example, Pageaux et al. (2013)
400 did not find any change in the maximal voluntary contraction torque of the knee extensor
401 muscles during the high mental exertion task in healthy active males. Similarly, Fortes et al.
402 (2020) found no changes for countermovement jump (CMJ) performance in mentally
403 fatigued high-level swimmers. Regarding tDCS, Alix-Fages et al. (2021) applied a-tDCS
404 over left-dIPFC and did not found changes for a force-velocity profile in physically active
405 healthy males. Also, applying a-tDCS over the M1 area (i.e., C3 and C4 channels) showed no
406 improvement on CMJ in high-level taekwondo athletes (Mesquita et al., 2019). One possible
407 explanation is that the fatigue on short-term neuromuscular performance seems to be
408 regulated for peripheral fatigue pathways without the necessity of high cognitive processes
409 (Brown et al., 2020b; Pageaux et al., 2013; Silva-Cavalcante et al., 2018). Taken together,
410 these pieces of evidence might explain the peak force results found in the present study.

411 The present study results demonstrated better endurance performance for a-tDCS than
412 Sham condition in female amateur swimmers. Impaired endurance performance in mentally

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

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

434

435

Conclusion

436

437

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

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

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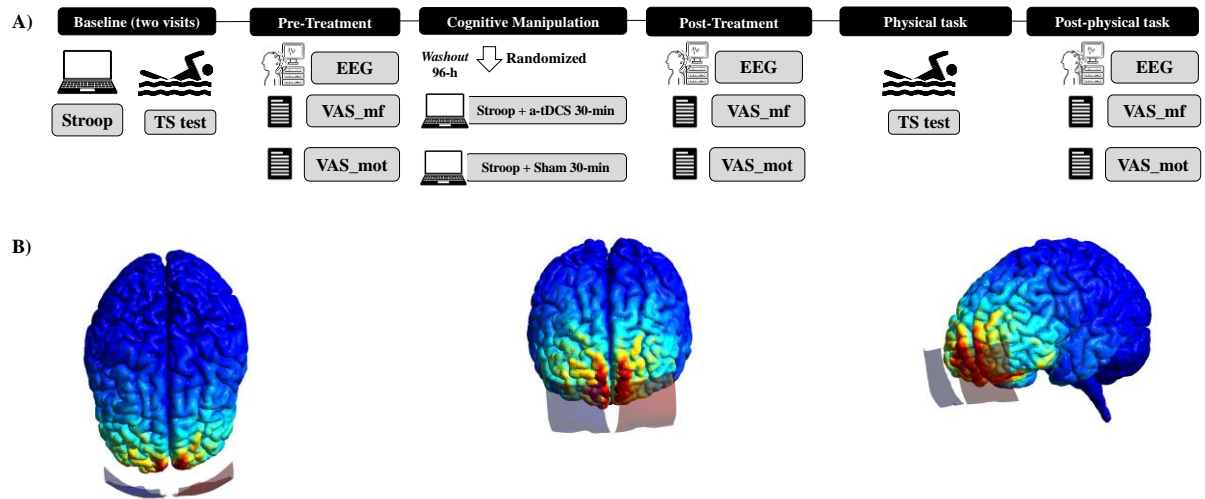
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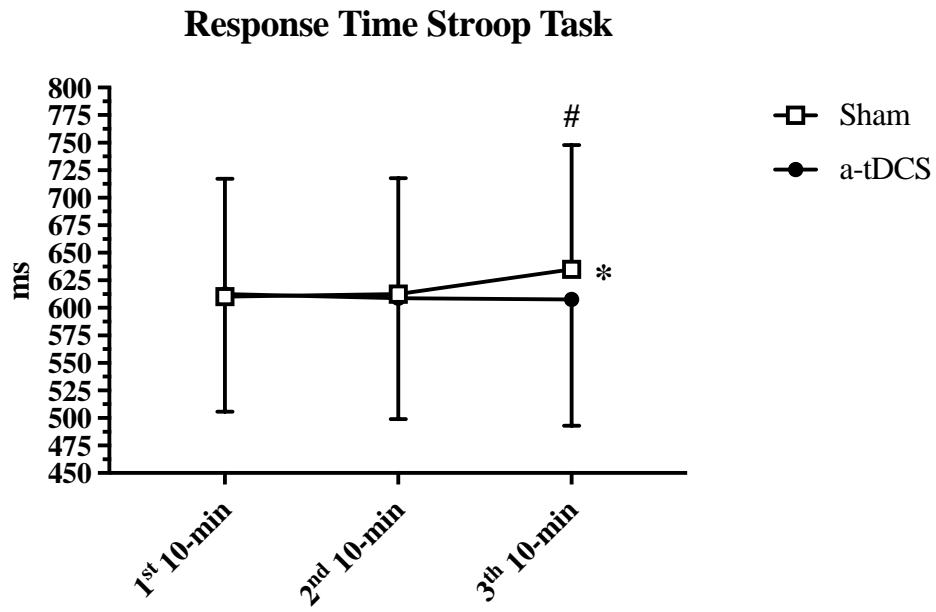
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Figure 1
Experimental design of the study (A) and computational modelling of brain-stimulating (B).
 Note. TS = tethered swimming; EEG = electroencephalogram; VAS_mf = subjective mental fatigue; VAS_mot = subjective motivation; a-tDCS = anodal transcranial direct current stimulation.



637

638 Figure 2

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

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

641 Table 1

642 *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	<i>F</i>	<i>p</i>	CI _{95%}	ηp^2 (CI _{95%})	ES
<i>Theta Fp1 (μV²)</i>								
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
<i>Alpha Cz (μV²)</i>								
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
<i>VAS mental fatigue (mm)</i>								
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
<i>VAS motivation (mm)</i>								
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

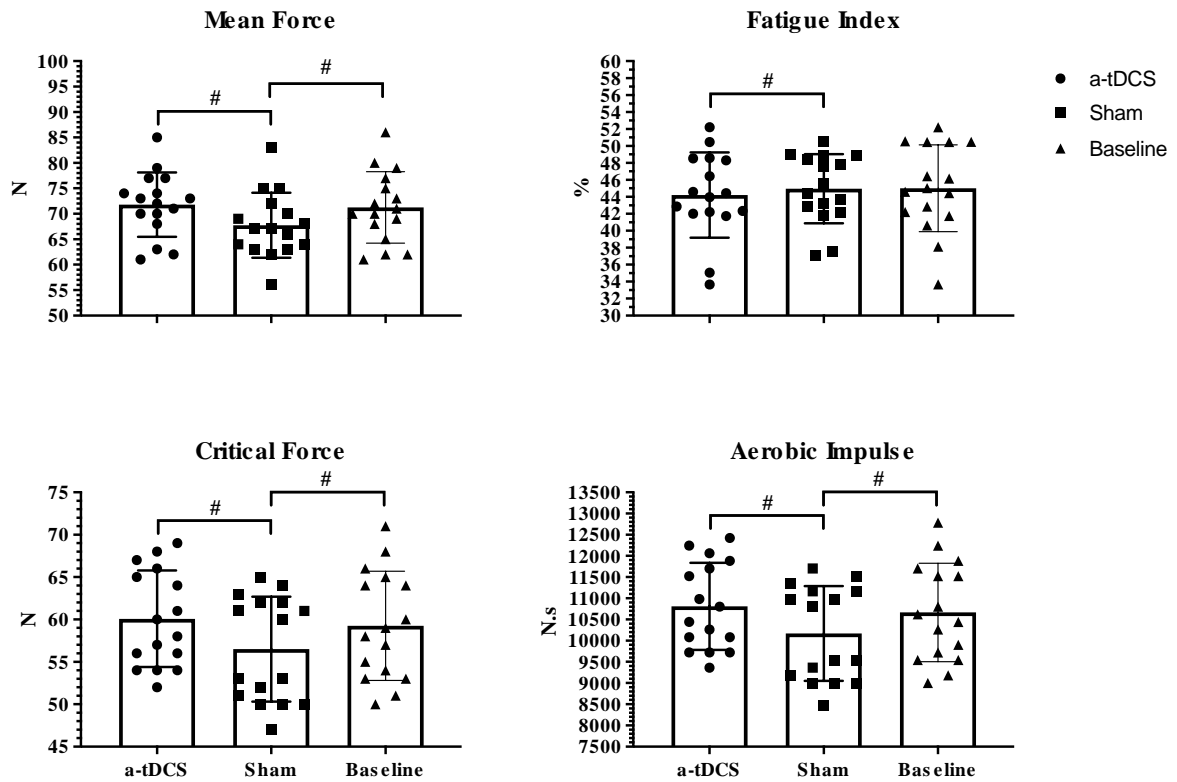
643 *Note.* VAS = Visual Analogue Scale; Δ% = percent delta from pre-to post-treatment; *p<0.05 difference for pre-treatment; [#]p<0.05 difference for sham.

644 Table 2

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

Variables	a-tDCS	Sham	Baseline	Effect	F	p
<i>Force minimum (N)</i>	55.0 ± 8.3 [#]	52.6 ± 7.1	53.8 ± 5.8	Condition	8.42	0.02
<i>Δ% (difference)</i>		4.0 ± 1.3				
<i>Peak force (N)</i>	97.4 ± 12.5	96.3 ± 10.7	97.7 ± 9.2	Condition	1.67	0.25
<i>Δ% (difference)</i>		2.1 ± 1.0				

647 *Note.* Δ% = difference between experimental conditions; [#]p<0.05 difference for sham and baseline.



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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.