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Full Length Article

The influence of transcranial direct current stimulation on pain affect and endurance exercise

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ABSTRACT

Introduction: Transcranial direct current stimulation (tDCS) is a non-invasive form of electrical brain stimulation that has been offered as a novel method to enhance endurance exercise performance. While the underlying mechanisms for these performance enhancing effects remain unclear, one explanation relates to a reduction in pain experienced during exercise. Research examining this explanation however, has failed to consider the widely recognised motivational-affective component of the pain experience.

Objectives: The present study aimed to determine whether pain experienced during exercise involves an affective component, and whether a reduction in pain affect may account for the performance-enhancing effects of tDCS.

Methods: Healthy, pain-free individuals (n = 23), including 11 males and 12 females aged 18–39 years, were recruited for participation in a randomised, placebo-controlled, participant blinded, repeated measures design study. Participants attended two testing sessions separated by at least five days. In each session, participants received either active (2 mA, 20 min) or sham (placebo control) tDCS delivered to the left dorsolateral prefrontal cortex (DLPFC). Participants then completed an endurance exercise task comprised of a sustained isometric contraction of the leg extensors performed to exhaustion at an intensity corresponding to 25% of their maximal voluntary contraction. During this task, participants provided ratings of pain intensity and pain unpleasantness at 20 s intervals.

Results: Ratings of pain intensity ($p < .001$) and pain affect ($p < .001$) increased throughout the endurance exercise task. However, the tDCS intervention did not enhance endurance exercise performance ($p > .05$), nor manipulate perceptions of pain affect ($p > .05$).

Conclusions: While the endurance exercise task induced pain affect, tDCS over the left DLPFC was not effective in reducing this component of the pain experience, nor enhancing exercise performance.

1. Introduction

The brain has emerged as the new frontier in efforts to advance human athletic potential (Park, Fairweather, & Donaldson, 2015). Non-invasive methods of brain stimulation, in particular, have proven to be popular methods in attempts to enhance endurance exercise performance (Davis, 2013). For example, publicly available electrical brain stimulation devices, such as the HaloSport (Halo Neuroscience, 2018), claim performance-enhancing (ergogenic) effects following brief periods of stimulation. However, care must be taken to not only confirm the safety of these techniques, but also to uncover the mechanisms that underlie any performance-enhancing effect (Angius, Hopker, & Mauger, 2017). Doing so may lead to the refinement and enhanced efficacy of these approaches for use in sporting contexts. One promising brain stimulation technique that has demonstrated resurgence in both scientific and public communities is transcranial direct current stimulation (tDCS; Angius et al., 2017).

This non-invasive form of electrical stimulation allows for the temporary modulation of cortical excitability (Brunoni et al., 2012). The administration of tDCS involves the delivery of a low-amplitude, constant direct current dispersed through two electrodes, an anode and a cathode (Brunoni et al., 2012). This form of neuromodulation results in polarity-dependent shifts in the resting membrane potential of underlying cortical neurons (Nitsche & Paulus, 2011), with anodal stimulation enhancing, and cathodal stimulation inhibiting, excitability (Brunoni et al., 2012). Brief stimulation periods of 10 min to the motor cortex (M1) have demonstrated sustained excitability or inhibitory effects that persist for up to 1 h, and repeated stimulation can prolong and

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List of Abbreviations

DLPFC	Dorsolateral Prefrontal Cortex
EIP	Exercise-Induced Pain
M1	Motor Cortex
mA	Milliamperes
MVC	Maximal Voluntary Contraction
Nm	Newton Meter
NRS	Numerical Rating Scale
tDCS	Transcranial Direct Current Stimulation
TTE	Time to Exhaustion

stabilise changes that last for weeks (Nitsche & Paulus, 2011).

The interest in tDCS for its performance-enhancing potential in endurance exercise has grown considerably (Angius et al., 2017). However, findings to-date have been mixed (Holgado, Vadillo, & Sanabria, 2019). For example, anodal tDCS over the temporal cortex (Okano et al., 2013) and M1 (Angius, Hopker, Marcora, & Mauger, 2015) has been reported to enhance peak power output during cycling tasks. By contrast, no improvement in cycling performance was observed by Barwood et al. (2016), who also targeted the temporal cortex with anodal stimulation. Further, while some studies (Abdelmoula, Baudry, & Duchateau, 2016; Cogiamanian, Marceglia, Ardolino, Barbieri, & Priori, 2007) have shown tDCS to enhance muscular endurance in single-limb isometric contractions, others have discerned no performance-enhancing effect (Abdelmoula, Baudry, & Duchateau, 2018; Holgado et al., 2019; Kan, Dundas, & Nosaka, 2013; Lattari et al., 2018; Muthalib, Kan, Nosaka, & Perrey, 2013; Radel, Tempest, Denis, Besson, & Zory, 2017; Valenzuela et al., 2018).

It is possible that methodological differences may account for the discrepancies in research findings. For example, while some have applied tDCS for 20 min at current intensities of 2 mA (mA; Okano et al., 2013), others have used stimulation protocols of a reduced duration and intensity (Abdelmoula et al., 2016; Cogiamanian et al., 2007), with variation also observed in targeted cortical region. Such differences have been shown to produce variability in the resulting changes in neuronal activity, and consequential task-specific outcomes (Nitsche & Paulus, 2011). These inconsistencies in methods and research findings mean that the ergogenic effects of tDCS remain unclear (Angius et al., 2017; Holgado et al., 2019). Nevertheless, tDCS remains a novel and promising avenue for performance-enhancing interventions (Angius et al., 2017).

In addition to these methodological inconsistencies, the mechanisms through which tDCS may act to enhance exercise performance remains an important area for clarification (Angius et al., 2017). A popular hypothesis attributes the ergogenic effects of tDCS to reductions in perceived pain (Cogiamanian et al., 2007). Exercise-induced pain (EIP) refers to pain that occurs naturally during exercise, typically originating from the site of muscular performance (O'Connor & Cook, 1999). It has been theorised that an athlete's ability to tolerate EIP is a critical determinant of success in endurance performance (Anshel and Russell, 1994), with EIP often characterised as an inhibiting factor during exercise (Astokorki & Mauger, 2016; Mauger, 2013). This role of EIP in fatiguing exercise is supported by both anecdotal reports of elevated pain tolerance in athletes (O'Connor & Cook, 1999; Tesarz, Schuster, Hartmann, Gerhardt, & Eich, 2012), and by the performance-enhancing effects of analgesic substances. For example, caffeine consumption, which is known to have analgesic effects, has resulted in significant increases in cycling endurance time (Gonglach, Ade, Bemben, Larson, & Black, 2015). Further, acetaminophen ingestion has facilitated significantly faster cycling time-trial completion time when compared to placebo (Mauger, Jones, & Williams, 2010).

Given the purported analgesic effects of tDCS over the M1 (Angius et al., 2015; Lefaucheur et al., 2008), it is possible that tDCS may similarly enhance exercise performance by reducing perceived pain. Angius et al. (2015) investigated this suggestion, reporting no significant change in EIP after active tDCS over the M1. Similar findings were also reported by Kan et al (2013). However, whilst these findings suggest that the ergogenic effects of tDCS are not attributable to changes in EIP, further research is needed before such an explanation can be dismissed.

One particularly important aspect that has not been considered is the multidimensional nature of pain. Specifically, the sensory-discriminative component of pain encompasses the perceived intensity, quality, and location of the sensation (pain intensity; Eisenberger, 2012), primarily projected through the somatosensory cortex (Hofbauer, Rainville, Duncan, & Bushnell, 2001). Conversely, a second, motivational-affective component relates to the unpleasant, aversive nature of the pain experience, and relies on regions of the limbic system, thalamus (pain affect; Melzack & Casey, 1968; Yen & Lu, 2013), and the dorsolateral prefrontal cortex (DLPFC; Lorenz, Minoshima, & Casey, 2003).

It is the sensory-discriminative dimension which has been assessed in research examining EIP and the performance-enhancing effects of tDCS, with existing research failing to produce changes in this dimension of the EIP experience following stimulation (Angius et al., 2015; Kan et al., 2013). In contrast, research to-date has failed to consider changes in the motivational-affective aspect. Given that the behavioural responses to escape the pain source are activated by the motivational-affective dimension (Schnitzler & Ploner, 2000), it is possible that termination or reduction of exercise relates to the motivational-affective aspect of EIP, rather than the sensory-discriminative. Although there is no definitive evidence that EIP encompasses an affective dimension, previous research has postulated this possibility (Nijs, Van De Putte, Louckx, Truijen, & De Meirleir, 2008; Stébenne et al., 2017). Thus, it is probable that this dimension of pain reflects a critical factor in determining exercise endurance capacity.

Furthermore, anodal tDCS of the left DLPFC has been shown to alleviate affective responses to experimentally-induced pain affect (Boggio et al., 2008; Maeoka, Matsuo, Hiyamizu, Morioka, & Ando, 2012). Indeed, the left DLPFC has been proposed to play a major role in the motivational-affective aspect of pain, with neuroimaging research determining a negative correlation between cortical activation of this area and perceptions of pain unpleasantness (Lorenz et al., 2003). The administration of anodal tDCS to the left DLPFC may therefore act to enhance exercise performance by reducing pain affect.

The present study first aimed to evaluate whether endurance exercise induces both sensory and affective dimensions of pain, assessed as pain intensity and unpleasantness, respectively. In addition, the study aimed to assess whether anodal tDCS over the left DLPFC would reduce pain affect induced by endurance exercise, and enhance endurance performance. It was hypothesised that a sustained isometric knee contraction would induce both pain unpleasantness and pain intensity. Further, it was hypothesised that active tDCS with the anodal electrode placed over the left DLPFC would reduce ratings of exercise-induced pain unpleasantness, but not pain intensity, and enhance muscular endurance time when compared to a placebo control.

2. Method

2.1. Participants

Participants were recruited from the local university and the broader community. To eliminate the potential impacts of age (Grashorn, Sprenger, Forkmann, Wrobel, & Bingel, 2013) and exercise engagement (Flood, Waddington, Keegan, Thompson, & Cathcart,

2017) on responses to pain, participation was restricted to healthy, pain-free individuals aged 18–40 years, who were not currently engaged in competitive sport beyond an amateur level. Individuals reporting documented contraindications for tDCS, such as neurological lesions, cardiac disorders, and intercranial pressure (Villamar et al., 2013), were also excluded.

Adhering to the recommendations of Minarik et al (2016), a priori power analysis for determining sample size was calculated. Data presented in Oki et al. (2016) was used, who similarly aimed to enhance isometric muscular endurance using active and placebo tDCS conditions. Oki et al. reported a medium effect size ($d = 0.54$) and sufficient power (0.85), with an alpha (α) level set at 0.05, and a sample size of 13. This effect size is comparable to previous research with similar sample size detecting a significant effect of tDCS (Minarik et al., 2016).

Based on this analysis, the final sample of 23 participants was deemed adequate. Participants included 11 males and 12 females. (mean ± SD: age, 26.00 ± 5.00 years, height, 174.76 ± 8.96 cm, weight 76.39 ± 15.03 kg, physical activity, 2749.87 ± 2500.86 MET-min/week). Right leg dominance was reported by 21 participants, and two reported left leg dominance. Undergraduate psychology students ($n = 3$) received 2 h research course credit for participation. All other participants ($n = 20$) were offered the opportunity to enter a draw to win one of three $30 bookshop gift cards. Participation was voluntary and anonymous, with participants maintaining the right to withdraw at any time.

2.2. Measures

Physical activity. The short, self-administered version of the International Physical Activity Questionnaire (IPAQ-SF; International Activity Questionnaire, 1998) was used to evaluate the physical activity level of participants. The measure captures self-reported physical activity levels over the preceding seven days through seven open-ended questions concerning exercise intensity (vigorous, moderate), and time spent walking and sitting (days, hours, and minutes). Responses are used to provide a global physical activity level estimate, calculated as metabolic equivalent value (MET). The IPAQ-SF is a widely used self-report tool for estimating physical activity engagement, and has demonstrated acceptable reliability ($\alpha = 0.66$ to $\alpha = 0.88$; Lee, Macfarlane, Lam, & Stewart, 2011).

Motivation. The 14-item Motivation Scale developed by Matthews, Campbell, and Faulkner (2001) was used to assess participant motivation corresponding to the physical exercise tasks. Items independently evaluate success and intrinsic motivation, with agreement to the respective item rated on a 5-point scale (0 = *not at all* and 4 = *extremely*). Higher total scores on each domain indicate stronger respective motivation. Both domains have demonstrated excellent reliability in previous research; SM $\alpha = 0.87$, IM $\alpha = 0.81$. A correlation of 0.22 (Matthews, Campbell, & Falconer, 2001), indicated discriminability between the two constructs. Adhering to the recommended scoring method (Matthews et al., 2001), composite scores for each motivation domain were computed.

Pain. Changes in pain intensity and pain affect (pain unpleasantness) during the endurance exercise task were assessed using two verbally administered Numerical Pain Rating Scales (NRS) adapted from those devised by Greenspan, Roy, Caldwell, and Farooq (2003). Both pain intensity and pain unpleasantness were assessed on a 0–100 NRS scale with descriptive anchors at 0 and 100, and numerical anchors at intervals of 10. The verbal descriptors from the original scales were removed to facilitate prompt response times. The descriptive anchors for pain intensity were 0 = *not at all intense* and 100 = *extremely intense*, while pain unpleasantness descriptors were 0 = *not at all unpleasant* and 100 = *extremely unpleasant*. Each scale was presented independently as a vertically oriented scale. Similar scales have been identified as valid and reliable tools for the assessment of pain (Ferreira-Valente, Pais-Ribero, & Jensen, 2011) and are widely used for the evaluation of both pain intensity and pain unpleasantness (e.g., Greenspan et al., 2003; Pagé et al., 2012; Rainville, Feine, Bushnell, & Duncan, 1992), with reliable discrimination between these two pain constructs (Pagé et al., 2012). Prior to obtaining pain ratings, the distinction between the intensity and unpleasantness of pain was explained, using an adapted English translation of French instructions devised by Price, McGrath, Raffi, and Buckingham (1983); the English adaptation of this tool has demonstrated efficacy in previous research (Duncan, Bushnell, & Lavigne, 1989; Rainville et al., 1992). To familiarise participants to these measures, participants were instructed to recall a recent occasion in which they experienced physical pain and provide a verbal rating of pain intensity and pain unpleasantness. This method has proven effective in previous research (Price, McGrath, Rafii, & Buckingham, 1983; Rainville et al., 1992).

2.3. Physical performance

Force measurement. An isokinetic dynamometer (HUMAC NORM, Computer Sports Medicine, Stoughton, MA, USA) measured force production of the knee extensors during maximal voluntary contractions (MVC) and endurance tasks.

All tasks were completed in the same position, with participants seated upright, perpendicular to the dynamometer. Adjustments to the dynamometer and seating position were made to ascertain the correct alignment of the lateral femoral epicondyle of the dominant leg with the dynamometer axis of rotation. To minimise trunk movement during force production, participants were secured to the chair at the hip, shoulders, and thigh of the operating leg using stabilising straps. Force was applied through the stationary padded arm of the dynamometer, fastened slightly above the medial malleolus of the dominant leg positioned with 90° knee flexion.

Maximal force production. Three submaximal familiarisation contractions at 25%, 50%, and 75% of maximal effort were conducted 60 s prior to the MVC trials. Each familiarisation trial lasted 5 s and was separated by 20 s. The MVC assessment comprised two trials separated by 60 s, in which participants were instructed to maximally contract their dominant leg for 5 s. The researcher provided scripted verbal encouragement during both trials. Elapsed time and visual feedback corresponding to force production were presented to participants on a computer monitor parallel to the isokinetic dynamometer. Peak torque (newton meter; Nm) achieved from the superior of the two trials was used to calculate the target force for the endurance task.

Endurance task. Endurance time was evaluated in a submaximal isometric contraction. Participants were required to maintain an isometric contraction of the knee extensors at or above 25% of their previous best MVC for as long as possible. Time to exhaustion (TTE) was recorded as the time until either volition exhaustion, or the production of force deviated below the target value for three consecutive seconds. Current and target force (Nm) was displayed visually to enable participants to monitor their force production. The researcher provided scripted verbal encouragement at 15 s intervals throughout the trial. No feedback regarding elapsed time was provided to participants throughout the task.

2.4. Transcranial direct current stimulation

A TCT 1ch tDCS stimulator (Research Version, TCT Research Limited, Hong Kong) was used to deliver direct current stimulation through two rubber electrodes enclosed in 35 cm^2 (5 cm × 7 cm) saline-soaked sponges. Using the international 10/20 electroencephalography system, the anode electrode was placed on the scalp, overlying the left DLPFC (F3). The cathode electrode was placed over the contralateral supraorbital area (Fp2). The electrodes were secured in place with a Velcro strap with the long axis positioned parallel to the horizontal line; this montage is similar to previous investigations into the effect of tDCS on pain affect (Boggio, Zaghi, & Fregni, 2009; Maeoka et al., 2012). The

employed stimulation parameters of 2 mA for 20 min are consistent with similar experimental protocols achieving significant reductions in pain (DaSilva et al., 2012; Valle et al., 2009).

The active tDCS condition involved a 30 s ramp up from 0 mA to the target intensity of 2 mA, where this intensity was maintained for the desired stimulation time. At the end of this period, the current gradually decreased from 2 mA to 0 mA, ending the stimulation. The sham condition (a placebo control) comprised the same protocol as the active condition, however stimulation intensity ramped up to 2 mA over 30 s, and was then immediately ramped back down to 0 mA for the remainder of the 20 min. No current was applied in the interim. This stimulation level is not sufficient to produce meaningful neuromodulation, and previous research has shown this protocol to effectively blind participants to the experimental condition (Borckardt et al., 2012).

Electrode conductivity was monitored by the stimulation device throughout the stimulation protocol to ensure satisfactory stimulation intensity. Adjustments, including electrode placement and saline application, were made as necessary to ensure satisfactory electrode resistance.

Participants were asked to remain seated, calm, and relaxed during both stimulation conditions to avoid any confounding influences. The same researcher conducted all sessions.

2.5. Procedure

This research obtained approval from the local human research ethics committee. A repeated-measures, within-subjects, randomised crossover design, with a single-blinded placebo control was employed.

Recruitment. Upon expression of interest via email, volunteers were provided an information form outlining the exclusion criteria based on the contraindications of tDCS, safe engagement in exercise, and confounding factors for exercise performance and pain responses. Once deemed eligible for participation, volunteers were requested to select suitable times to complete two testing sessions. Eight volunteers did not meet the inclusion criterion and were excluded from participation. All correspondence was conducted over email.

Experimental sessions. Testing was conducted between June and August 2018 between the hours of 08:30 and 18:00, in a temperature-controlled laboratory. Sessions were separated by at least five days (maximum of ten days) to reduce any carry-over effects relative to the tDCS or exercise tasks, and each participant attended the laboratory at the same time of day for both sessions.

Participants were instructed to abstain from illicit drugs and analgesic substances for one week, strenuous exercise and alcohol for 12 h, and caffeine and smoking for 6 h prior to the experimental sessions. This was to ensure a well-rested sample, and to eliminate the effects of these factors on exercise performance and pain responses. Adherence to these requests was confirmed on arrival to both sessions.

Upon arrival to their first session, participants were provided with a hard copy information form providing an overview of the requirements for participation and the study aims. The procedure was then described in full to enable participants to ask questions prior to commencement. The protocol is depicted in Figure 1.

Following this, participants' written informed consent, age, height, weight, and physical activity habits were obtained. Participants were then positioned on the isokinetic dynamometer, and underwent the three familiarisation contractions and two MVC trials. Participants remained seated during all rest intervals. MVC was measured prior to tDCS stimulation to ensure that any influence of the stimulation on MVC capacity did not impact on the target force for the endurance task. Next, participants rated their level of motivation for the muscular endurance task before receiving 20 min of tDCS according to their assigned condition. Motivation corresponding to the endurance task was then assessed again to uncover changes resulting from the stimulation. The scripted conceptual definitions of pain intensity and pain unpleasantness were then delivered. Participants then performed the TTE task, where ratings of pain intensity and pain unpleasantness were reported at 20-s intervals, and at task exhaustion. The second session followed identical procedures to that of the first, differing only in that participants received the opposite stimulation protocol, and collection of demographic data was omitted. Additionally, a comprehensive debrief was administered at the conclusion of the final session.

2.6. Data analysis

The nature of the endurance task resulted in individual differences in TTE, and consequential variation of data point frequency across participants. To account for this, statistical analysis for the comparison of pain intensity and pain unpleasantness ratings was conducted using a combination of intra-individual *iso-times* and percentage of TTE. In this method, the participant's shortest TTE over their two trials was identified as 100% iso-time. This value was compared against the corresponding time value in the participants' longer trial, such that 100% iso-time in both trials reflected the same endurance time (seconds). Data points at 25% intervals from their 100% iso-time were then calculated. Additionally, the values at exhaustion for each trial were included. This approach provided five data points for each participant for both trials (25% iso, 50% iso, 75% iso, 100% iso, exhaustion), with the pain rating closest to the calculated iso-time percentage used for statistical comparison across trials. Previous research has employed this method to assess changes in perceptual experiences during endurance tasks (Angius et al., 2015; Marcora, Staiano, & Manning, 2009).

Data was analysed on SPSS statistics software (Version 23, IBM Corp, Armonk, NY) with a critical alpha of .05 considered statistically significant for all analyses. There was no missing data. Preliminary data screening for statistical outliers and erroneous or out-of-range values was conducted prior to analysis. Minor deviations from normality were indicated upon observations of significant Shapiro-Wilk statistics for several variables (active MVC, active pain intensity at 75% and100% iso, sham pain intensity at 100% iso, active pain unpleasantness at 75% and100% iso, sham pain unpleasantness at 75% iso). However, the

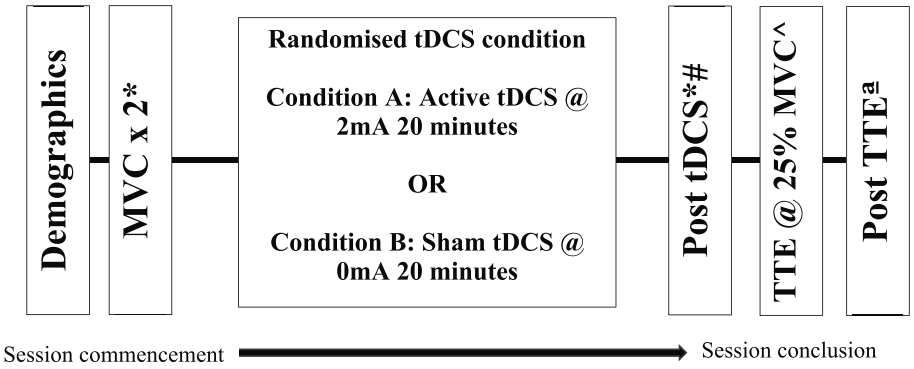

Fig. 1. Graphic depiction of experimental protocol. *Motivation questionnaire administered (post MVC, prior to tDCS, and post tDCS, prior to TTE); #pain intensity and pain unpleasantness conceptual definitions provided prior to TTE task; ^pain intensity and pain unpleasantness ratings obtained at 20-s intervals during TTE task. The order of tDCS condition was randomised. Exhaustion is defined as the deviation below target force for > 3 s, or volition exhaustion; [a] Study debrief (second session only). Each session was approximately 1 h in duration.

assumption of normality was assumed following inspection of histograms and Q-Q plots across all variables. Significant Mauchly's test statistics indicated that the assumption of sphericity was violated for both time ($p < .001$) and the time by condition interaction ($p < .001$) across both pain intensity and pain unpleasantness variables. The Huynh-Feldt epsilon correction was consequently employed in both analyses.

Two, 2 × 2 repeated-measures ANOVAs evaluated levels of intrinsic motivation and success motivation across condition (active vs. sham) and time (pre- and post-tDCS stimulation). Changes in pain intensity and pain unpleasantness were assessed using two, 2 × 5 repeated measures ANOVAs (condition x time). Paired samples *t*-tests were conducted to compare MVC force and TTE in the endurance performance task between the two tDCS conditions.

3. Results

Motivation. The assessment of the internal consistency of the motivation measure used in the present study confirmed adequate reliability for both success motivation and intrinsic motivation ranging from $\alpha = 0.79$ to $\alpha = 0.90$, and $\alpha = 0.59$ to $\alpha = 0.70$, respectively. Levels of success motivation did not differ significantly over time $F(1, 22) = 2.48$, $p = .130$, or between conditions $F(1, 22) = 1.80$, $p = .193$ (Pre-tDCS: active, 15.26 ± 6.02; sham, 15.61 ± 4.99. Post-tDCS: active, 14.17 ± 5.38; sham, 15.74 ± 6.44). Likewise, intrinsic motivation did not significantly differ over time $F(1, 22) = 0.09$, $p = .773$, or between conditions, $F(1, 22) = 0.06$, $p = .804$ (Pre-tDCS: active, 23.54 ± 3.25; sham, 23.39 ± 3.22. Post-tDCS: active, 23.43 ± 3.16; sham, 23.39 ± 3.08). Finally, there was no significant time by condition interaction for success $F(1, 22) = 2.95$, $p = .100$, or intrinsic $F(1, 22) = 0.04$, $p = .843$, motivation.

Maximal force production. No significant difference in MVC between active (204.04 ± 87.37 Nm) and sham (205.91 ± 90.20 Nm) conditions was observed; $t(22) = -0.319$, $p = .753$.

Pain Unpleasantness. Statistical analysis revealed a significant main effect for time, $F(2.00, 43.90) = 122.96$, $p < .001$, $\eta\rho^2 = 0.85$, but no significant main effect for condition, $F(1.00, 22.00) = 2.57$, $p = .123$. The time by condition interaction was also not significant, $F(2.93, 64.55) = 1.51$, $p = .220$, see Figure 2. The significant main effect of time was further investigated utilising pairwise comparisons and a Bonferroni correction factor ($\alpha = 0.05$), revealing that all five time intervals of 25% iso ($M = 38.00$, $SE = 2.93$), 50% iso ($M = 52.78$, $SE = 2.80$), 75% iso ($M = 69.78$, $SE = 2.67$), 100% iso ($M = 78.91$, $SE = 2.64$) and exhaustion ($M = 88.89$, $SE = 2.56$) significantly differed from each other ($p < .001$).

Pain Intensity. Statistical analysis revealed no significant main effect for condition, $F(1.00, 22.00) = 4.26$, $p = .051$, and no significant interaction between time and condition, $F(2.79, 61.31) = 1.01$, $p = .390$, for pain intensity ratings, as depicted in Figure 3. However, a significant main effect for time was uncovered, $F(2.12, 46.55) = 126.21$, $p < .001$, $\eta\rho^2 = 0.85$. The main effect of time was investigated, using pairwise comparisons and employing a Bonferroni correction factor ($\alpha = 0.05$), revealing significant differences in pain intensity between all five time intervals ($p < .001$); 25% iso ($M = 35.50$, $SE = 2.70$), 50% iso ($M = 51.26$, $SE = 2.53$), 75% iso ($M = 66.41$, $SE = 2.59$), 100% iso ($M = 76.52$, $SE = 2.53$) and exhaustion ($M = 86.37$, $SE = 2.17$).

Endurance Performance. The analysis revealed no significant difference in TTE between active (173.30 ± 56.68 s) and sham (182.17 ± 74.77 s) tDCS conditions; $t(22) = -0.773$ $p = .448$.

4. Discussion

The present study aimed to investigate whether EIP has an affective dimension, and whether anodal tDCS over the left DLPFC would reduce EIP affect, and enhance endurance performance. It was hypothesised that active tDCS over the left DLPFC would reduce pain unpleasantness, but not pain intensity, and enhance endurance performance in an isometric contraction of the knee extensors.

Mean intrinsic motivation and success motivation were consistent with levels observed in previous research (Flood et al., 2017; Marcora et al., 2009) suggesting that participants were adequately motivated to complete the TTE task. An increase in reported pain unpleasantness and intensity throughout the TTE task was observed, with significant differences between ratings of both pain dimensions across each iso-time interval. This is consistent with previous research demonstrating that EIP increases as a function of task duration (Angius et al., 2015; Gonglach et al., 2015; Mauger et al., 2010; Weiser, Kinsman, & Stamper, 1973). However, while existing research has demonstrated that endurance exercise produces pain (Astokorki & Mauger, 2016), these findings are restricted to perceived pain intensity (Angius et al., 2015; Kan et al., 2013; Mauger et al., 2010). Therefore, the current study presents novel findings by demonstrating that EIP also encompasses an affective component, and the magnitude of this pain

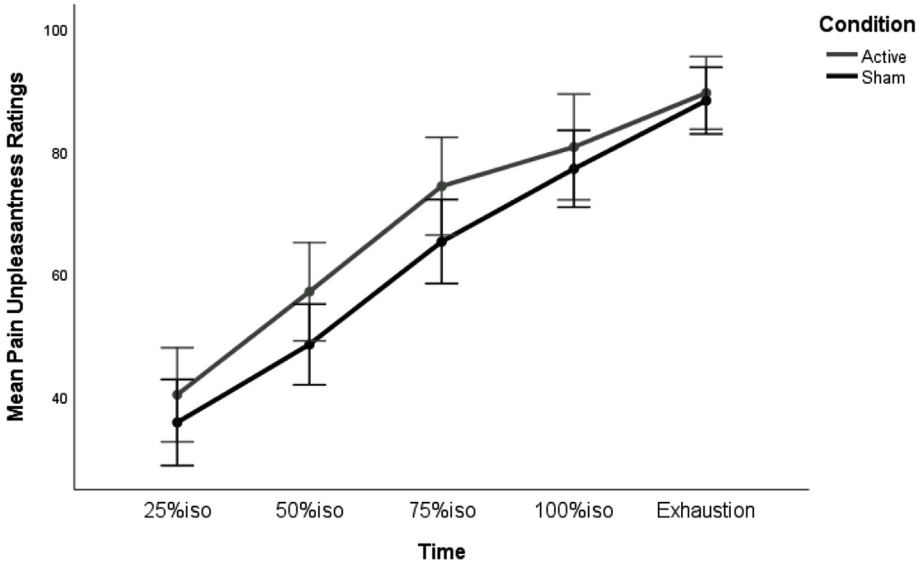

Fig. 2. The effect of tDCS condition (active vs. sham) on pain unpleasantness ratings across time interval (25% iso, 50% iso, 75% iso, 100% iso, exhaustion). No significant difference in mean pain unpleasantness ratings were found between the active and sham tDCS conditions. Error bars represent 95% confidence intervals.

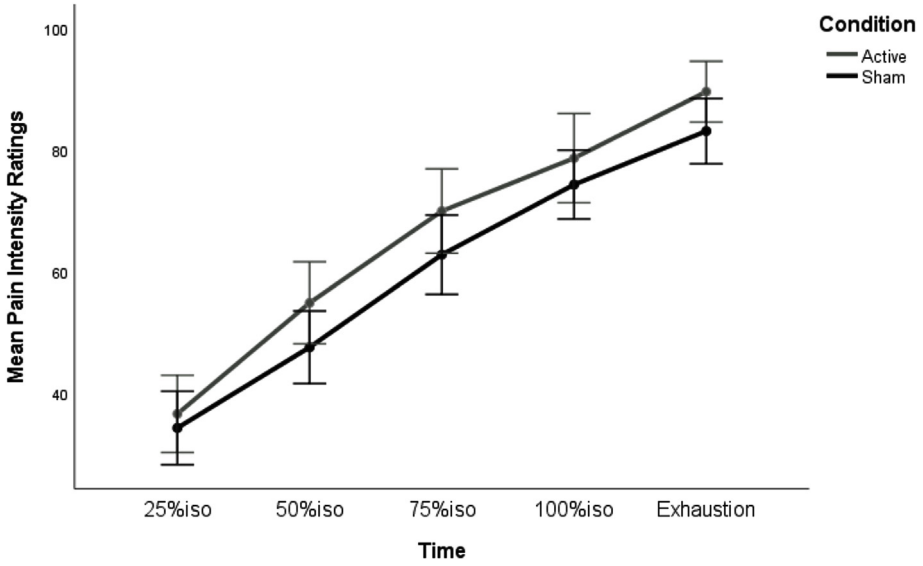

Fig. 3. The effect of tDCS condition (active vs. sham) on pain intensity ratings across time interval (25% iso, 50% iso, 75% iso, 100% iso, exhaustion). No significant difference in mean pain intensity ratings were found between the active and sham tDCS conditions. Error bars represent 95% confidence intervals.

dimension increases with task duration.

Although both pain intensity and pain unpleasantness increased throughout the sustained contraction, active tDCS delivered to the left DLPFC failed to attenuate this increase. Angius et al. (2015) and Kan et al. (2013) reported similar findings of no change in exercise-induced pain intensity following tDCS. This is in contrast to previous findings of the analgesic effects of tDCS in clinical settings, including fibromyalgia (Valle et al., 2009) and spinal cord injury (Fregni et al., 2006). This difference in the nature of pain is notable, given that EIP is comprised of unique processing pathways to other noxious stimuli (Millan, 2002). Specifically, Angius et al. (2015) reported that active tDCS over the M1 reduced pain intensity induced by cold-water immersion; however pain intensity corresponding to a cycling endurance task remained unchanged following the same tDCS intervention. The authors concluded the processing and modulatory pathways for exercise-induced pain intensity likely differ from pain intensity induced by thermal stimuli (Angius et al., 2015).

In relation to pain unpleasantness, active tDCS over the left DLPFC has elicited significant reductions in pain unpleasantness ratings towards a series of aversive images depicting human pain (Boggio, Zaghi, & Fregni, 2009; Maeoka et al., 2012). No such analgesic effect was observed in the current study, suggesting that the left DLPFC is not an effective stimulation site for the reduction of pain unpleasantness induced by endurance exercise. As appears to be the case for pain intensity, such findings may indicate that EIP produces different affective responses to those evoked by viewing unpleasant stimuli. These results support the possibility of anatomically distinct pathways involved in the processing of EIP, highlighting the need for caution when generalising tDCS-induced analgesic effects across pain modalities.

The active tDCS intervention also failed to influence TTE when compared to the sham condition. Such findings align with the absence of a performance enhancing effect observed by others following tDCS stimulation (Abdelmoula et al., 2018; Barwood et al., 2016; Kan et al., 2013; Lattari et al., 2018; Lampropoulou & Nowicky, 2013; Muthalib et al., 2013; Radel et al., 2017; Valenzuela et al., 2018). EIP is proposed to be involved in the regulation of fatiguing exercise, with EIP suggested to contribute to alterations in exercise intensity by influencing adjustments to work-rate (Mauger, 2013). Therefore, reducing this conscious perception of EIP should facilitate improvements in performance (Angius et al., 2015; Mauger, 2013). The ergogenic effects of analgesic substances such as acetaminophen (Foster, Taylor, Chrismas, Watkins, & Mauger, 2014; Mauger et al., 2010) uphold this theoretical standpoint. Due to a failure to reduce perceptions of EIP in the present study, this manipulation of work-rate regulation would not have occurred, thereby producing no alteration in exercise output. Similar findings have also been reported in other studies of tDCS, where unchanged EIP was associated with unchanged endurance performance, observed in both isometric (Kan et al., 2013) and whole-body dynamic (Angius et al., 2015) tasks. However, others have reported increases in exercise performance following tDCS without accompanying changes in pain (Angius, Pageaux, Hopker, Marcora, & Mauger, 2016). The present findings do not necessarily preclude the proposed involvement of sensory and affective dimensions of EIP in the regulation of exercise performance; rather, they indicate further research is required to determine appropriate alternative methods, such as mindfulness-based psychological interventions (Brown & Jones, 2010; Perlman, Salomons, Davidson, & Lutz, 2010), to effectively manipulate EIP.

4.1. Strengths and limitations

The primary strength of the present study resides in its theory-driven methodology. While the functions of EIP have received considerable research attention, this topic is still subject to ongoing investigations (Mauger, 2013). Despite the well-documented empirical support denoting pain as a complex, multidimensional experience (e.g., Melzack & Casey, 1968; Moayedi & Davis, 2013; Perl, 2007), research into EIP has only considered the sensory dimension of pain. However, the motivational nature of pain affect (Melzack & Casey, 1968; Schnitzler & Ploner, 2000) may reflect an important perceptual determinant within exercise regulation and performance. Nevertheless, to the author's knowledge, this is the first study to investigate this notion, and the findings and theoretical standpoints therefore offer unique contributions to the exercise performance, psychology, and tDCS literature.

There are several limitations of the current study that should also be considered. The endurance task required participants to monitor and maintain a specific torque target displayed on the computer monitor, while simultaneously providing two conceptually distinct pain ratings. These cognitive demands may have inhibited participant performance and ability to provide accurate ratings. This potential cognitive burden may have increased the level of measurement error and directly impacted the results. Yet, in-task measurements are commonly used to quantify perceptual changes during endurance exercise, and are considered an appropriate method to depict an individual's experience

(Angius et al., 2015; Vitor-Costa et al., 2015; Okano et al., 2013; Williams, Hoffman, & Clark, 2013). Indeed, the measurement of pain during exercise was necessary to achieve the aims of the current study.

The scales utilised within the present study to assess exercise induced pain intensity and pain unpleasantness were initially developed to measure thermally induced pain (Greenspan et al., 2003). While validated in that domain, they have not been used in the context of exercise performance, and may not be appropriate for the measurement of EIP. Importantly, while Cook, O'Connor, Eubanks, Smith, and Lee (1997) emphasised the unique psychophysiological considerations required for developing reliable and valid measures of exercise-induced pain intensity, such considerations have not been made for the assessment of pain unpleasantness, underscoring the need for a specialised and validated measurement tool for pain unpleasantness during exercise.

Performance was assessed in the current study using a sustained isometric contraction. While this enabled an isolated and controlled evaluation of perceptual responses to endurance performance, it is argued that whole-body, dynamic exercises provide a more accurate depiction of real-world performance tasks (Angius et al., 2017). The external validity of isometric task performance is routinely questioned (Kordi et al., 2017; Wilson & Murphy, 1996), with ongoing dispute surrounding conclusions on the determinants of dynamic task performance based on isometric tests (Angius et al., 2017; Wilson & Murphy, 1996). It has also been argued that the factors that govern exercise regulation may be task-specific (Abbiss & Laursen, 2008). Caution should therefore be taken when interpreting and generalising the current findings.

The left DLPFC plays a fundamental role in a range of processes, including higher order cognitive functioning and emotional control (Diamond, 2013; Mohanty et al., 2007). However, the optimal tDCS montage for this area remains undefined (Seibt, Brunoni, Huang, & Bikson, 2015). Further, the efficacy of tDCS for the enhancement of physical performance is largely impacted by tDCS montage (Angius et al., 2016; Angius et al., 2017). Given this methodological uncertainty, the failure to utilise neurophysiological measures of the changes induced by tDCS in the left DLPFC presents as a limitation of the current study. Nonetheless, the employed montage is similar to previous research that has targeted the left DLPFC and observed significant reductions in pain affect (Boggio, Zaghi, & Fregni, 2009; Maeoka et al., 2012).

The use of tDCS has proven popular in research exploring techniques for neuromodulation due, at least in part, to the availability of a placebo stimulation. Although widely used and shown to be an effective method of blinding participants to their assigned experimental condition (Borckardt et al., 2012; Gandiga, Hummel, & Cohen, 2006), some have questioned the efficacy of sham control tDCS as a placebo stimulation, particularly for higher stimulation intensities (Davis, Gold, Pascual-Leone, & Bracewell, 2013; O'Connell et al., 2012). In the current study, anecdotal reports from participants indicated that the use of sham tDCS was successful in blinding participants to their experimental condition. However, a formal examination of the efficacy of the participant blinding procedure was not conducted. Future research should assess the efficacy of the sham stimulation using established measures (O'Connell et al., 2012).

The use of a single-blinded experimental design should also be considered when drawing conclusion based on the current findings. With the experimenter aware of the participants' assigned condition, there is an increased potential for experimenter bias. In an attempt to limit this potential for bias, several methodological considerations were made to standardise the testing protocol. For example, verbal encouragement offered during the physical tasks and the explanation of the pain measurement tools were both scripted to ensure uniformity across conditions. Despite these precautions, it is possible that unconscious experimenter bias may have impacted on results. It is suggested that future research adopt a double-blinded design to reduce this potential for bias.

Future research should continue to investigate the potential mechanisms through which the ergogenic effects of tDCS are produced. Clarification of these underlying mechanisms may result in the refinement and enhanced proficiency of tDCS across a variety of exercise and sporting contexts for public, commercial, and scientific communities. These explorations should not only consider electrode montage, and stimulation parameters, but also employ additional measurements of the neurophysiological effects of stimulation, to facilitate an extensive evaluation of the relative impacts of tDCS during exercise. The current findings represent the first attempt to profile the affective properties of pain experienced during exercise. It is hoped that this greater understanding of exercise-induced pain affect will stimulate further research into the potential regulatory role played by pain in endurance exercise.

5. Conclusions

In the present study, EIP was shown to involve both an affective and sensory component. However, the administration of active anodal tDCS over the left DLPFC did not result in an increase in endurance performance (time to exhaustion), or a reduction in EIP affect and intensity.

Declarations of interest

None.

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