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ORIGINAL INVESTIGATION

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Prior brain endurance training improves endurance exercise performance

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ABSTRACT

Mental fatigue (MF) impairs endurance exercise performance. Brain endurance training (BET) describes the systematic repetition of mentally-fatiguing cognitive tasks designed to build resilience to MF and improve endurance performance. Evidence to date shows that mental training *during* physical training can benefit post-training exercise performance, however, this concurrent BET approach may not be practical for all settings. Therefore, the current study evaluated the effects of mental training *before* physical training (*prior BET*) on exercise performance. A randomised control trial design: pre-test, training (BET, control), post-test. During the pre-test and post-test sessions, participants performed a 5-min rhythmic handgrip task requiring the generation of as much force as possible, a 20-min 2-back working memory task, and another 5-min rhythmic handgrip task. Participants were randomly assigned to a BET ($n = 12$) or control group ($n = 12$). Both groups completed the same submaximal rhythmic handgrip training for five weeks (four sessions per week). The BET group also completed 20-min cognitive training (2-back working memory task, incongruent colour-word Stroop task) before each submaximal exercise training session. Endurance performance improved more ($p < 0.05$) following BET (24%) than physical training alone (12%). Compared to the control group, the BET group showed higher prefrontal oxygenation during the post-test exercise tasks ($p < 0.05$). Both groups were characterised by the same exertion, motivation, heart rate, and heart rate variability. Mental training before physical training improves endurance performance greater than physical training alone. The benefits of p*rior BET* may be explained, at least in part, by improved prefrontal oxygenation.

Highlights

- This study provides further evidence that brain endurance training (BET) improves performance over matched physical training.
- Prior BET (i.e. engaging in mentally demanding cognitive tasks before physical training) offers another option to enhance fatigue resilience, which expands the use of BET to more sports and potentially higher intensity training where concurrent BET will not be practical.
- The benefits of prior BET may be explained, at least in part, by improved prefrontal oxygenation.

KEYWORDS
Mental fatigue; muscle fatigue; prefrontal cortex; attention; psychobiological model; near infrared spectroscopy

1. Introduction

Mental fatigue is a psychobiological state that individuals may experience during and after prolonged periods of mentally demanding cognitive activities (Marcora et al., 2009) that is marked by feelings of tiredness and often exhaustion (Boksem et al., 2005; Boksem & Tops, 2008). The negative effects of mental fatigue on cognition are well established, including impairments in sustained attention, cognitive function, and executive control (Hopstaken et al., 2015), and are manifested as psychological, physiological, or subjective responses (Cutsem et al., 2017). Marcora and colleagues examined the effects of mental fatigue, induced by a 90-min cognitive task, on whole-body endurance performance, and demonstrated impairment in a subsequent submaximal cycle exercise test to exhaustion (Marcora et al., 2009). This effect was accompanied by higher ratings of perceived exertion (RPE) but no differences in cardiorespiratory activity. A series of replications and extensions followed this seminal study which have provided substantial evidence that a state of mental fatigue can induce elevated perception of effort during submaximal whole body exercise and impair performance (Cutsem et al., 2017). In addition, a state of mental

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fatigue has been shown to impair sub-maximal isometric knee extensor exercise until exhaustion (Pageaux et al., 2013), and engagement in a response inhibition cognitive task has shortened time to exhaustion during sub-maximal isometric handgrip exercise (Bray et al., 2008). Collectively, these findings suggest that mental fatigue negatively impacts endurance performance, regardless of the types of contractions and muscles active during exercise.

Given that mental fatigue impairs sub-maximal endurance performance, it is possible that physical training while mentally fatigued builds resilience to withstand its negative impact and thereby improves subsequent performance. This possibility was proposed by Marcora (Marcora et al., 2014) who coined the phrase *brain endurance training* (*BET*). It is based on two principles. First, that endurance performance is limited by perception of effort in highly motivated individuals (Marcora, 2008; Marcora et al., 2010). Second, that mental fatigue increases perception of effort and impairs sub-maximal endurance performance (Cutsem et al., 2017). Accordingly, increasing resilience to withstand mental fatigue should reduce perception of effort and thereby improve endurance performance. In sum, BET is the combination of mentally-fatiguing cognitive tasks coupled with exercise that aims to improve endurance performance.

To date, few studies have investigated BET (Dallaway et al., 2021; Marcora et al., 2014). Marcora and colleagues (Marcora et al., 2014) compared the effects of BET and control training on cycling performance. Both groups trained for 1-hour on a cycle ergometer at 65% $\dot{V}{\cdot}O_2$max three times a week for 12 weeks, and the BET group concurrently performed a cognitive task whilst cycling, which required sustained attention, working memory and response inhibition. Following training, $\dot{V}{\cdot}O_2$max increased in both groups, and, crucially, time to exhaustion increased more in the BET group (126%) than the control group (42%).

We recently reported similar findings in a study that compared the effects of concurrent BET and control training on dynamic rhythmic handgrip performance (Dallaway et al., 2021). Both groups trained for 15 min on a handgrip task four times a week for 6 weeks, and the BET group concurrently performed cognitive tasks (2-back, incongruent word Stroop) that demanded attention, memory, and response inhibition. Following training, force production improved more in the BET group (32%) than the control group (12%). Moreover, prefrontal cortex (PFC) oxygenation during exercise, measured via near infrared spectroscopy (NIRS), was stable in the BET group but lower in the control group, which suggests less mental effort for a greater force production during exercise for BET relative to control (as reflected by the attenuated drop in PFC tissue oxygenation during this task relative to the control group). Additionally, increased heart rate variability characterised the BET group during the post-training physical tasks. This suggests increased parasympathetic and/or decreased sympathetic nervous system activity and indicates that the BET participants found the physical tasks less demanding.

The abovementioned BET studies showed that *concurrent BET* can improve exercise performance compared to standard physical training. However, concurrent mental and physical training is impracticable for sports where athletes cannot attend to, process, and respond to stimuli displayed on a screen while exercising. To overcome difficulties associated with dual-task situations, it is possible to complete the mentally-fatiguing cognitive training prior to the physical training element. The effectiveness of this *prior BET*, or pre-fatigue method, has yet to be investigated.

Our study purposes were twofold. First, we investigated whether *prior BET* improves maximal rhythmic handgrip performance compared to physical training alone. We hypothesised that the BET group would perform better on the handgrip task than the control group following training. Second, we explored prefrontal cortical haemodynamics and cardiac mechanisms underlying the BET effect. In line with past research (Dallaway et al., 2021), we hypothesised that the BET group would exhibit stable PFC oxygenation and decreased parasympathetic and/or increased sympathetic nervous system activity for a higher force output than controls.

2. Materials and methods

We employed a mixed model experimental design, with group (BET, control) as the between-participant factor, and test (pre-test, post-test) and task (solo, subsequent) as within-participant factors. Participants attended 22 sessions over seven weeks, consisting of a pre-test (week one), 20 training sessions (weeks two to six) and post-test (week seven).

Participants were 24 (13 females, 11 males) healthy undergraduate students aged 20 ± 2 years. Exclusion criteria included dominant hand injury and changes in habitual exercise during the study. Participants were requested to sleep for 7 h and abstain from vigorous exercise and alcohol consumption (24 h), food (1 h), and caffeine (3 h) before every session. Participants were randomly assigned, by a chance procedure, to either a control group ($n = 12$) or BET group ($n = 12$). Power calculations using GPower (Faul et al., 2007) indicated that with a sample size of 24, our study was powered at 80% to detect significant ($p < .05$) between (group) by within (test) interaction effects ($f = .30$, $\eta^2 = .08$) corresponding to a small-to-medium effect size by analysis of variance (Cohen, 1992). Ethical approval was obtained from the University of Birmingham Research Ethics committee. Informed consent was obtained from participants. Each received a £20 voucher and course credit.

Pre- and Post-Testing: Following instrumentation, determination of MVC (Cooke et al., 2011), and 1-min familiarisation of the upcoming task, participants completed a 5-min endurance task under two conditions (solo, subsequent). In each condition, participants were asked to generate as much force as possible by squeezing a handgrip dynamometer with their dominant hand once per second cued by a metronome. The task was completed for the first time (solo) at the start of the session and for the second time (subsequent) following 1200 s of a 2-back (Braver et al., 1997) working memory task. The cognitive and physical tasks were separated by 5-min each, during which participants completed self-report questionnaires and physiological measures recorded. To increase task engagement and motivation, participants had a chance to win a further £20 voucher for the best physical and cognitive performance in their group.

The 2-back task presented a random consonant in the centre of a computer monitor for 500 ms, followed by a blank display for 3000 ms before the presentation of the next consonant. Participants were required to respond by indicating if the current letter displayed was the same (target) or different (non-target) as the letter displayed two previously using a computer keyboard with their non-dominant hand. Letters were displayed with a 1:2 target to non-target ratio. Performance was determined by the percentage of correct responses. Participants were verbally briefed on the task and presented with written instructions prior to the familiarisation period and performance task. All cognitive tasks were implemented using E-Studio (Psychology Software Tools, USA).

Force (N) was recorded continuously throughout all sessions. In the pre-test and post-test tasks, physical performance was calculated from the peak force (N) generated each squeeze per second. An electrocardiogram was recorded using surface electrodes in a modified chest configuration and an amplifier (509, Morgan, USA). Heart rate variability (HRV) measures were used as an indicator of physiological demands (Mulder, 1992). HRV was calculated from the R-to-R wave interval period for each minute of the pre-test and post-test tasks. The root mean square of the successive differences (RMSSD) and the standard deviation (SDNN) of the R-to-R wave interval were calculated (for further detail see Cooke et al Cooke et al., 2011).

Prefrontal cortical haemodynamics were assessed using near infra-red spectroscopy (NIRS; NIRO-200NX, Hamamatsu Photonics KK, Japan). The NIRO-200NX device measures changes in chromophore concentrations of oxyhaemoglobin and deoxyhaemoglobin (ΔO2Hb and ΔHHb) via the modified Beer–Lambert law and provides depth-resolved measures of tissue O_2 saturation [total oxygenation index (TOI)] and tissue Hb content (i.e. relative value of the total haemoglobin normalised to the initial value, nTHI) using the spatially resolved spectroscopy (SRS) method. The SRS-derived NIRS parameters limit contamination from superficial tissue via depth-resolved algorithmic methods, providing an index of targeted local tissue saturation (TOI) and perfusion (nTHI), see Davies et al. (Davies et al., 2015) for a recent review. Probes were enclosed in light-shielding rubber housing that maintained emitter-to-detector optode spacing (4 cm), positioned over the right prefrontal electrode site (Fp2 in 10–20 system). Before each task, participants were instructed to sit still, relax, clear their mind, and look at a fixation cross for 2 min (Gusnard & Raichle, 2001). Measures of TOI, nTHI, O_2Hb and HHb were averaged over 30-s calculated relative to the last 30 s of the prior baseline. To examine changes as a function of time, the value during first 30-s interval was subtracted from the value during final 30-s interval, for each measure during the physical tasks.

All signals were acquired via a Power 1401 (Cambridge Electric Design Limited, UK) digital-to-analogue convertor (16-bit resolution, 2.5 kHz sample rate) running Spike2 (version 6.06) software. Physiological measures were recorded only in the testing sessions.

Success motivation (Matthews et al., 2001) was measured prior to each task using a 5-point scale with anchors of "0 = not at all" and "4 = extremely"; example items included "I will be disappointed if I fail to do well on this task" and "I am eager to do well". Exertion and fatigue were measured following each task using 11-point scales: the mental exertion (ME) scale had anchors of "0 = nothing at all" and "10 = maximal mental exertion", whereas the mental fatigue (MF) scale had anchors of "0 = nothing at all" and "10 = totally exhausted". A baseline measure of MF was also taken. Following each task, interest and enjoyment (McAuley et al., 1989) were measured using a 7-point scale with anchors of "1 = not true at all" and "7 = very true", with example items including "I enjoyed doing this activity very much" for enjoyment and "I would describe this activity as very interesting" for interest. RPE (Borg, 1982) was measured every minute during the physical tasks and after the training sessions.

Training: The physical task required participants to squeeze the handgrip dynamometer once per second (cued by an audio metronome) at approximately 30% MVC until they reached a pre-determined cumulative force production target. Target attainment was calculated by summing the force generated, normalised to MVC, every second. In line with our past research (Dallaway et al., 2021), the initial target was 12000 (1 unit representing 1% MVC per second), which incremented 1000 points every week (every fifth session) to account for training-related improvements in strength. In all physical training sessions, visual feedback was provided throughout to help ensure participants squeezed at the required force level. The BET group completed the computer-based cognitive tasks prior to physical training. No performance feedback was provided to participants.

The cognitive tasks during the training period for the BET group consisted of the pre-test concurrent 2-back (sessions 1-4, 9-12, 17-20) and colour-word incongruent Stroop (sessions 5-8, 13-16). The 2-back test had a letter refresh rate of 3000 ms (sessions 1-4), 2500 ms (sessions 9-12) and 2000ms (sessions 17-20). The colour-word Stroop (Macleod, 1991) required participants to indicate the font colour (red, yellow, green, blue) of a colour word from two possible answers displayed in a black font in the bottom left and right corners of the display. Participants received verbal and written instructions prior to the training task. The Stroop test requires response inhibition and working memory. The stimulus was presented for 2500 ms or until a response was given, followed by a fixation cross for 500 ms. The sequence and increasing difficulty of the cognitive tasks were designed to mitigate any learning effects.

Statistical analysis. To test the study hypotheses, and to account for any baseline differences, we used mixed model analysis of covariance (ANCOVA) to examine the effects on our performance and physiological measures (described above) of group (BET, control), our between-participants factor, together with test (pre, post), and task (solo, subsequent), as our within-participants factors. For the self-report psychological measure of RPE given during testing, mixed model analysis of variance (ANOVA) tests were used, with the addition of time (5 min) as a within-participant factor. Where interaction effects occurred follow up pairwise comparisons were conducted using least significant difference (LSD) tests. A series of independent samples t-tests were used to compare training metrics (training time, MF, ME, interest/enjoyment, and RPE) between groups. These analyses were performed using SPSS (v27, IBM, United States). The multivariate approach to the ANOVA and ANCOVA tests has been reported. Significance was set at $p < 0.05$, with data expressed as mean ± standard deviation, unless otherwise stated. Partial eta-squared ($\eta_p{}^2$) was reported as a measure of effect size, with values of .02, .13 and .26 representing small, medium, and large effect sizes, respectively (Cohen, 1992).

3. Results

Training Measures: There was no significant difference in training time between the Control, 978 ± 163 s and the BET group 989 ± 153 s ($t_{11} = 0.77$ $p = .27$), or baseline MF with Control reporting a rating of 1.9 ± 1.2 and the BET group 2.1 ± 1.3 s ($t_{11} = 1.88$, $p = .06$). However, following the 20-min cognitive task the BET group increased their rating of MF to 3.8 ± 1.7, resulting in a significant difference ($t_{11} = 13.73$, $p < .001$) prior to the physical training relative to the Control group whose rating was 1.9 ± 1.2. The BET group reported higher ($t_{11} = 3.57$, $p < .001$) RPE during the matched (intensity and duration) physical training of 4.9 ± 1.6 compared to 4.3 ± 2.0 in the Control group. Additionally, during the physical tasks there were no differences in ratings of interest/enjoyment and ME between the groups.

Performance Measures: A 2 group (BET, control) by 2 test (pre, post) ANCOVA on MVC revealed no main effect for test ($F_{1,21} = 0.23$, $p = .64$, $\eta_p^2 = .01$), with the average MVC increasing from 382 ± 101 N to 404 ± 109 N (5.4%) from pre-test to post-test. A pair of 2 group (BET, control) by 2 test (pre, post) ANCOVAs were performed on the average peak force produced per second during the 2 physical tasks (Figure 1). These yielded a main effect for test on the solo task ($F_{1,21} = 5.13$, $p < .05$, $\eta_p^2 = .19$) and subsequent task ($F_{1,21} = 5.13$, $p < .05$, $\eta_p^2 = .20$), and a test-by-group interaction effect on the solo task ($F_{1,21} = 5.01$, $p < .05$, $\eta_p^2 = .19$) and subsequent task ($F_{1,21} = 5.13$, $p < .05$, $\eta_p^2 = .20$). Overall force production increased more from pre-test to post-test in the BET group (24%) than the control group (12%). A 2 group (BET, control) by 2 test (pre, post) ANCOVA on the number of correct responses during the 20-min 2-back cognitive task found no group or test main effects.

Physiological Measures: A series of 2 group (BET, control) by 2 test (pre, post) ANCOVAs were conducted on the changes in prefrontal cortical haemodynamic responses (TOI, nTHI, O_2Hb and HHb) during the two physical tasks (Figure 2), revealing a group-by-test interaction for nTHI ($F_{1.15} = 5.63$, $p < 0.05$, $\eta^2 = .27$) and a main effect for test on TOI ($F_{1.15} = 39.38$, $p < 0.001$, $\eta^2 = .72$), O_2Hb ($F_{1.15} = 42.62$, $p < 0.001$, $\eta^2 = .74$) and HHB ($F_{1.16} = 5.62$, $p < 0.05$, $\eta^2 = .26$). Pairwise comparisons revealed post-test differences between groups for THI. A series of 2 group (BET, control) by 2 test (pre, post) ANCOVAs

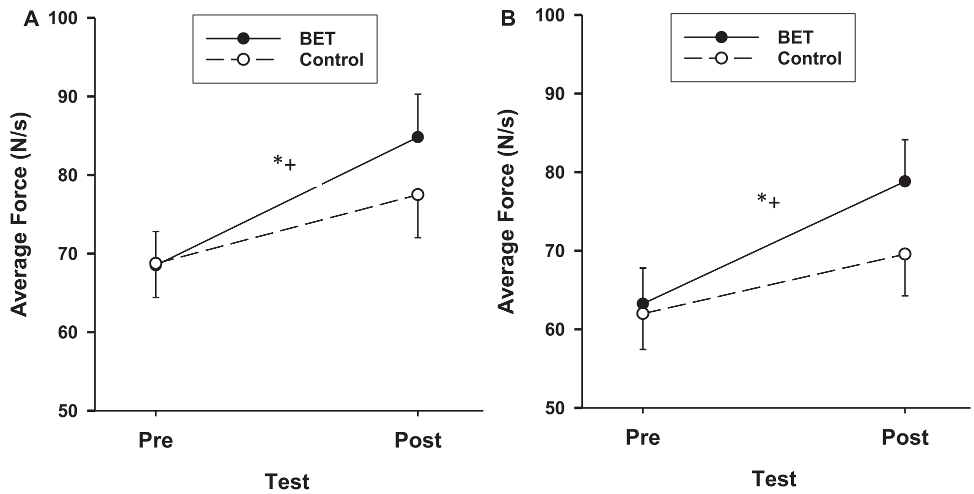

Figure 1. Effect of brain endurance and physical training on the relative physical performance for the solo (A) and subsequent (B) physical task . + Significant ($p < 0.0$) main effect of training. * Significant ($p < 0.05$) interaction effect of group by training. Data presented as M ± SEM.

examined the cardiac responses (HR, RMSSD, SDDN) during the physical tasks. These analyses yielded a main effect on test for HR ($F_{1,21} = 6.17, p < .05$, $\eta^2 = .23$) (Figure 3(A)), SDNN ($F_{1,21} = 23.94, p < .001$, $\eta^2 = .53$) (Figure 3(B)) and RMSSD ($F_{1,21} = 10.69, p < .05$, $\eta^2 = .34$) (Figure 3(C)). Further analyses of the physiological measures over time during the physical tasks are presented in the Supplementary Material.

Psychological Measures: A pair of 2 group (BET, control) by 2 test (pre, post) ANOVAs were performed on RPE that revealed a main effect for time ($F_{4.19} = 28.18$ $p < 0.001$, $\eta^2 = .86$) for the solo task (Figure 4(A, B)) and subsequent task (Figure 4(C,D)) ($F_{4.19} = 26.75$ $p < 0.001$, $\eta^2 = .85$), which increased from start to finish during both physical tasks. A 2 group (BET, control) by 2 test (pre, post) ANCOVA on success motivation (across the three tasks) yielded a main effect for test ($F_{1.21} = 4.70$ $p < 0.05$, $\eta^2 = .18$), with pre-test motivation reported as 2.45 ± 0.16 and post-test motivation reported as 2.32 ± 0.12. There were no group differences for both RPE and success motivation.

4. Discussion

The present study investigated the effects of *prior BET* on endurance exercise performance. In support of our first hypothesis, we found that a 5-week *prior BET* protocol improved maximal handgrip endurance performance more than physical training alone, whereby training increased force production by 24% versus 12%, respectively. This finding is consistent with the notion that systematic repetition of mentally-fatiguing cognitive tasks before exercise can help build resilience to withstand the negative effects of mental fatigue on performance and thereby help maintain or improve endurance performance. Ours is the first study, to our knowledge, to investigate the efficacy of BET using the prior (pre-fatigue) method. We confirmed that participants in the BET group completed their physical training with higher ratings of MF than control. It is worth noting that baseline MF ratings were the same for both BET and control groups, demonstrating that the cognitive tasks (Stroop, 2-back) were sufficiently demanding to induce a state of mental fatigue before the onset of physical training. This impacted perceived exertion during the handgrip tasks, with RPE being 12% higher in the BET group relative to the control group for the same submaximal physical training.

The abovementioned performance improvements following *prior BET* are in broad agreement, albeit smaller, with previous research using the concurrent BET method. Marcora (Marcora et al., 2014) showed that 12-week BET combined with physical training, improved cycling time to exhaustion by 126% compared to 42% with physical training alone. In the present study, participants completed only five weeks of training. Therefore, the additional seven weeks of training in the Marcora study, which incorporated whole-body endurance training, is likely to have produced more physiological adaptation and as well as more exposure to cognitive tasks, which alone or together may account for the greater improvement in endurance performance. The 6-week training protocol and handgrip endurance task used in a previous concurrent BET training study (Dallaway et al., 2021) offers a closer comparison with the current study. That study showed that dynamic rhythmic muscular endurance improved more following concurrent BET (32%) than control (12%).

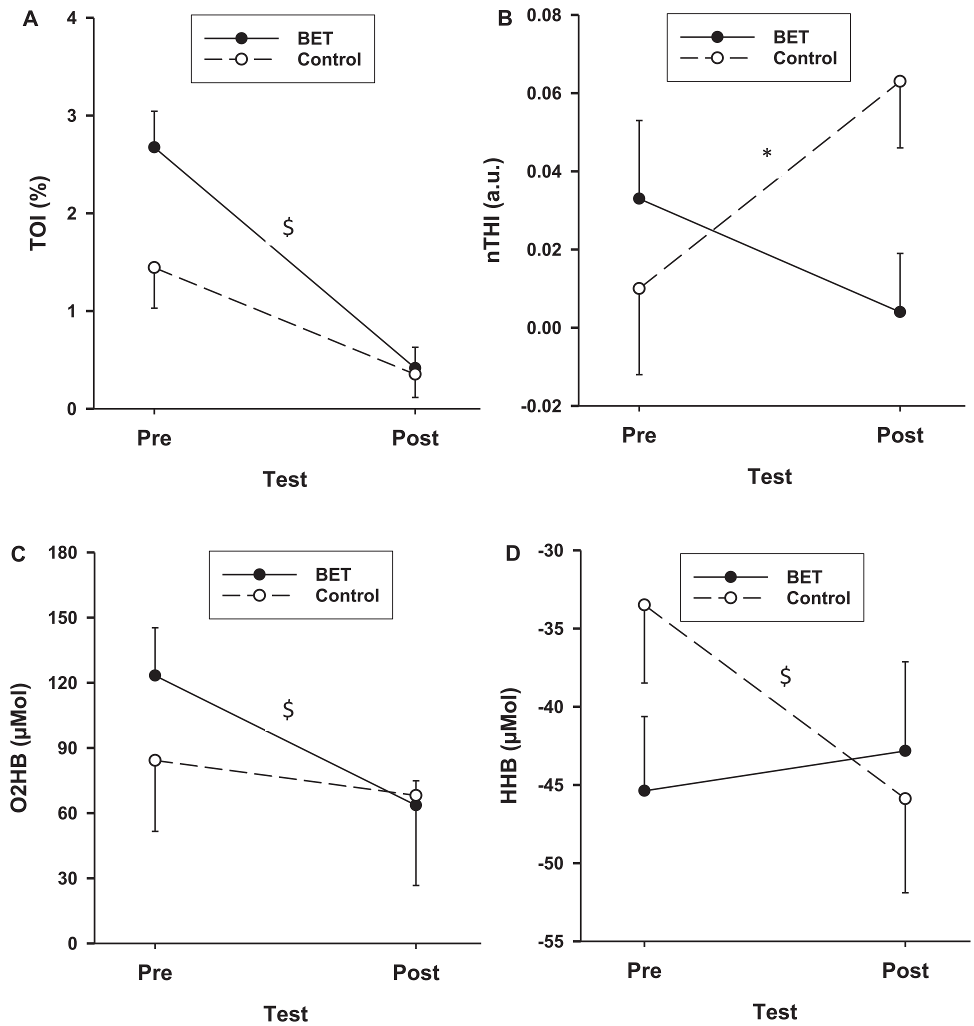

Figure 2. Effect of brain endurance and physical training on prefrontal cortical hemodynamics (FP2) for TOI (A), nTHI (B), O2HB (C) and HHB (D) during the two physical tasks. $ Significant ($p < 0.05$) main effect for test. * Significant ($p < 0.05$) group-by-test interaction effect. Data presented as M ± SEM.

The somewhat greater improvement in performance following concurrent compared to prior BET (32% versus 24%) could be due to the additional week of training, the use of concurrent versus prior cognitive tasks, and/or the greater number of task-based assessments. Specifically, the BET group trained using an extra physical task in the previous study (concurrent cognitive and physical handgrip test), which resulted in greater improvements relative to the control group and therefore contributing to the higher overall performance improvements relative to our current findings. Finally, the present study found no group differences in cognitive performance after training during the 2-back task, whereas the previous study found the BET group were better than the control group. This could be due to a lower number of participants in the current study, a shorter training period, and/or the concurrent nature of the previous training.

The present study also explored candidate cerebral haemodynamic and cardiac mechanisms underlying the BET effect on performance. In contrast to our second hypothesis, we found that the improved performance of the BET group was achieved with the same HR and HRV as the control group. However, in support of our hypothesis, the BET group exhibited greater prefrontal oxygenation during both physical tasks compared to the control group. In sum, the BET group's enhanced physical performance was associated with greater PFC oxygenation but the same cardiac activity, perceived exertion and motivation during the physical tasks compared to control.

The current study found no differences in HR or HRV between BET and control groups, whereas the previous concurrent BET study (Dallaway et al., 2021) found no group differences in HR but increased HRV in the BET group. Greater HRV is suggestive of reduced

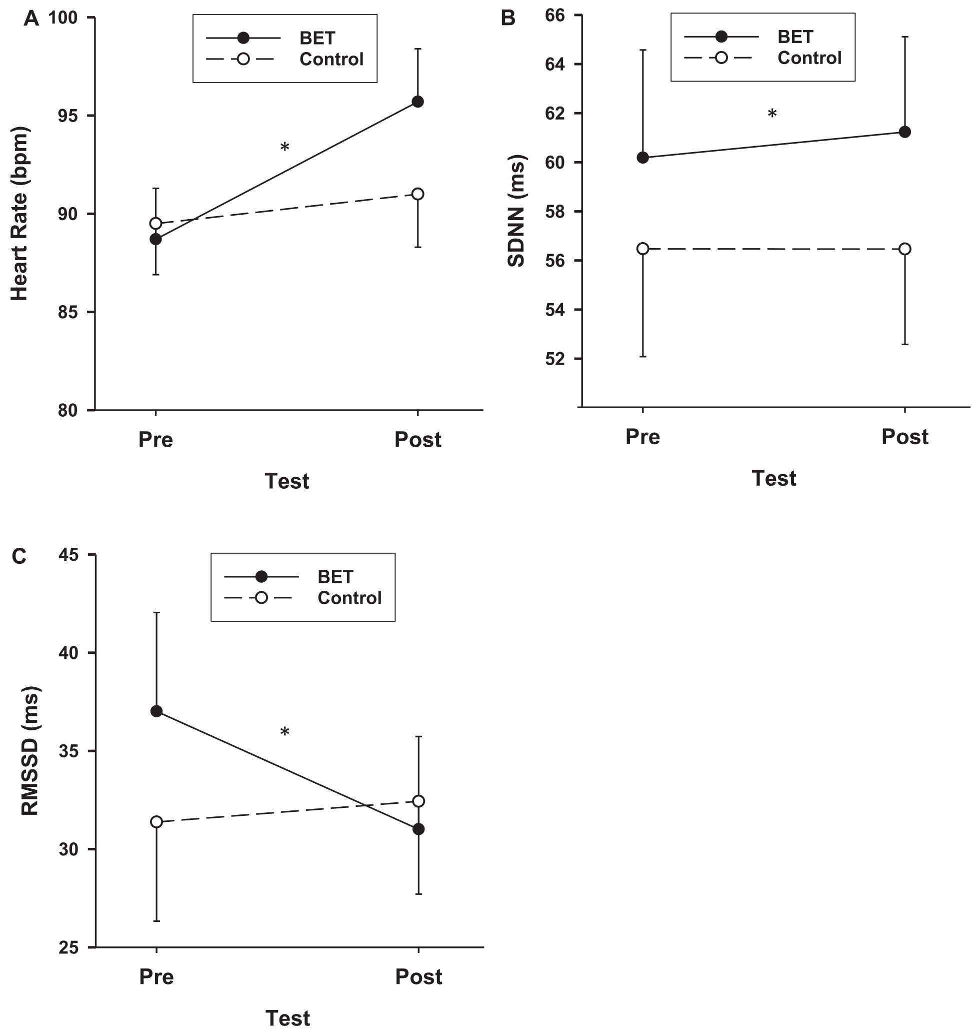

Figure 3. Effect of brain endurance and physical training on cardiac responses of heart rate (A) and measures of heart rate variability (B – RMSSD, C – SDNN) during the two physical tasks. * Significant ($p < 0.05$) test main effect. Data presented as M ± SEM.

sympathetic nervous system activation and/or augmented parasympathetic activation. Concurrent BET involves dual-tasking unlike prior BET. Research shows that 30-min of a 2-back working memory task can induce central fatigue, decrease vagal nerve activity, and increase sympathetic nervous activity (Tanaka et al., 2009). The PFC and the anterior cingulate cortex (ACC) play an important role in the regulation of the autonomic nervous system (ANS) (Tang & Posner, 2009) and abnormalities in these brain regions are associated with fatigue (Gergelyfi et al., 2014; Tajima et al., 2010). Therefore, the higher mental load required by concurrent BET may have further impacted the PFC and ACC, than that during prior BET thereby decreasing parasympathetic and increasing sympathetic nervous system activities (AMANN M, 2011).

The BET group sustained higher prefrontal oxygenation throughout the physical tasks following training compared to the control group. Maintaining PFC perfusion and oxygen extraction may have improved the BET-group's effort-based decision making (Mehta et al., 2013) during the physically demanding handgrip tasks and consequently improved endurance performance beyond physical training alone. PFC activation is influenced by demanding cognitive tasks (Boksem et al., 2005) and has been suggested to play in role in the regulation of endurance exercise (Robertson & Marino, 2016). During the post-test physical tasks, the control group's nTHI was higher than the BET group, indicating that the control group increased brain blood perfusion to extract and utilise more oxygen. In contrast, the BET group maintained prefrontal oxygenation whilst producing more force without the additional demands on the PFC, which suggests they perceived the physical tasks were less mentally demanding and is consistent with our previous concurrent BET findings (Dallaway et al., 2021). The toleration of a greater cognitive load may facilitate effort-based

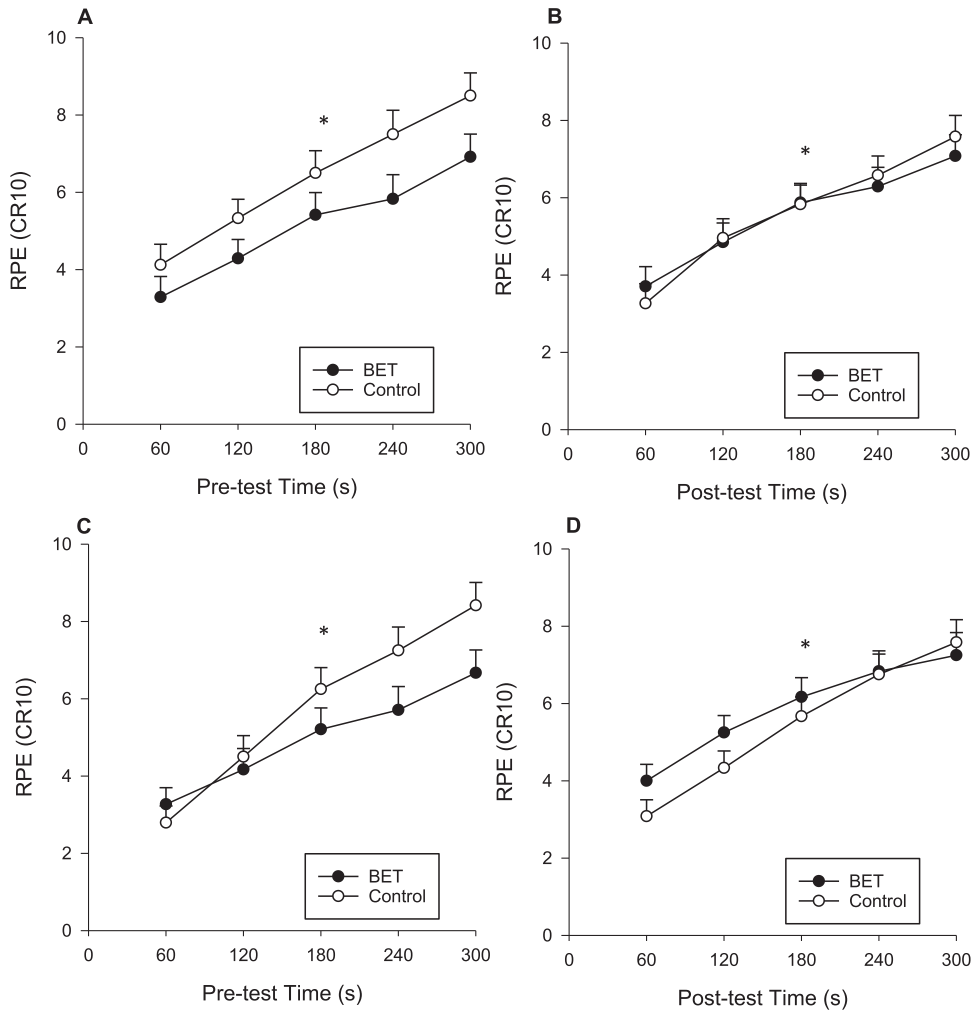

Figure 4. Effect of brain endurance (BET) and physical training (Control) on RPE during the solo physical (A & B) and subsequent physical task (C & D). * Significant ($p < 0.001$) main effect of time. Data presented as M ± SEM.

decision making (Botvinick & Braver, 2015) and performance monitoring (Botvinick et al., 2001) during physical exercise. These adaptations may be similar to those experienced by elite athletes. Athletes constantly participate in high volumes of aerobic training, which have been shown to increase the volume of cortical tissue (Colcombe et al., 2006). It is therefore possible that high levels of endurance training cause morphological and functional adaptations of the PFC that increase resistance to mental fatigue and improve cognitive control observed, similar to what has been noted in elite athletes (Martin et al., 2016). The sustained prefrontal oxygenation in the BET group compared to the control group in our study may also help athletes tolerate higher levels of physical exertion.

It has been suggested that the perception of effort is the limiting factor for endurance performance (Marcora et al., 2010). Marcora demonstrated that RPE during a cycle test to exhaustion was lower in a BET group at the onset of the fixed workload task compared to a control group. As the rate of increase in RPE was the same in both groups, the control group reached their maximum level of perceived exertion and disengaged from physical exercise earlier. It is notable that we did not observe any difference in RPE between the two groups. However, the performance tasks in our present study required participants to generate as much force as possible for five minutes, resulting in the same RPE for more force in the BET group. This finding is consistent with our previous concurrent BET study (Dallaway et al., 2021). Another factor which can inluence the performance of endurance exercise is motivation. However, success motivation was the same in both groups across both testing conditions, and, therefore, the enhanced performance in the BET group is unlikely to be due to motivational differences.

Interpretation of our findings should be tempered by potential methodological limitations. First, both the cognitive and physical tasks were novel to all participants. A period of task familiarisation was provided to the participants, but it was completed on the same day for time considerations. Ideally, a separate familiarisation session would have occurred. The reliability of performance in the physical hand grip task is also unknown, which could be established with additional familiarisation. The control group did not have any matched activities prior to the physical task during training. However, they were asked to maintain their regular routine prior to training and there were no differences in baseline MF ratings between groups. A third, non-training, group could also have been added to establish improvements in the physical only component of the training. It is possible that the sustained oxygenation observed in the PFC in the BET group was a result of increased blood flow to the forearm as they generated more force in the physical tasks. Further research should investigate whether the efficacy of *prior BET* can benefit whole-body endurance exercises, which has implications for potential sport and military populations. The evidence suggests that cortical regions, such as the PFC and ACC, become active during mentally effortful tasks, such as the Stroop task. However, controlling emotions (Wagstaff, 2014), maintaining focus during physical tasks, and revising for exams can have a similar effect. By examining effort more globally, as opposed to simply thinking of mental fatigue arising from just cognitive tasks, we may uncover further linkages between effortful tasks and their regulation. Finally, whilst NIRS provides insight into regional brain oxygenation during physical exercise, extending this using other brain imaging methods, such as functional magnetic resonance imaging (fMRI), to characterise activity in other brain regions could paint a fuller picture of the physiological mechanisms underpinning BET.

To conclude, we have provided the first evidence that five weeks of *prior BET* improves endurance performance beyond physical training alone. This finding replicates those of previous studies showing that concurrent BET improved endurance performance (Dallaway et al., 2021; Marcora et al., 2014). Moreover, and in line with past research (Dallaway et al., 2021), the BET-related improvement in performance was associated with sustained prefrontal oxygenation, providing further evidence to suggest that BET might cause beneficial adaptations in the PFC, a region of the brain involved in the regulation of effort-based decision making and goal-directed actions. Such cortical regulation may increase the thresholds for physical exertion and mental fatigue, thereby leading to improved physical performance. This speculation awaits further research using other functional imaging methods with greater spatial resolution (i.e. fMRI). Finally, our preliminary evidence shows that *prior BET* protocols, which can be readily integrated into ongoing training sessions (e.g. during warm-up activities), may represent a more attractive and practical way of using BET in different sports and activities.

Disclosure statement

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