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A mechanistic understanding of cognitive performance deficits concurrent with vigorous intensity exercise

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ABSTRACT

This study aimed to evaluate whether cerebral oxygenation of the prefrontal cortex and associative-dissociative focus while completing the task mediate changes in cognition during exercise. Seventy-five young college-aged adults participated in this within-subjects randomized cross-over two-arm experimental design. During each session, participants completed a Stroop task four separate times: at baseline, two times during the exercise session, and at post-test. The experimental arm session involved participants cycling first at a moderate intensity, followed by cycling at a vigorous intensity. The active control arm session involved participants cycling at a very light intensity to ensure any effects were attributable to the level of exertion rather than the control of motor coordination. Cerebral oxygenation of the prefrontal cortex was assessed using fNIRS, while associate-dissociate attention was assessed using a self-report scale to provide insight into two hypothesized mechanisms which may contribute to alterations in cognition during exercise. Replicating well-established findings, results showed that during vigorous-intensity exercise, accuracy rates decreased for the most cognitively demanding conditions of the Stroop task, while reaction times were generally shorter compared to baseline. Neither shifting of attention in response to the dual-task nor prefrontal cortex oxygenation were observed to mediate cognitive deficits associated with vigorous exercise.

1. Introduction

Cognitive function can both improve and decline during a single bout of exercise — a short-duration session of physical activity that focuses on immediate, temporary physiological responses, such as sprinting and interval training (Budde et al., 2012, 2016) — with the effects varying based on exercise intensity and the specific cognitive domain. For example, acute moderate-intensity aerobic exercise (60–85 % of VO_{2max} or 50–75 % HRR; Garber et al., 2011) has been linked to enhanced attention and processing speed (Martins et al., 2013), while acute vigorous-intensity aerobic exercise (≥85 % of VO_{2max} or ≥75 % HRR; Garber et al., 2011) may result in decreased performance in tasks requiring executive control (Komiyama et al., 2020). This task-dependent effect is particularly notable during vigorous exercise, where reaction times on simple cognitive tasks (e.g., visual search tasks, choice reaction time tasks) are likely to improve (Audiffren et al., 2008; Davranche et al., 2005; 2006), but the quality of responses — especially those involving the management of conflicting information — tends to decline (Ando et al., 2011; Komiyama et al., 2020; McMorris et al., 2009; Stone et al., 2020). Such changes in cognition, which are dependent on exercise intensity (Gronwald et al., 2018; 2019) and cognitive task type (Loprinzi, Day, et al., 2019), are supported by experimental studies

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(Chang et al., 2017; Labelle et al., 2013; Mekari et al., 2015; Knatauskaitė et al. 2022), as well as narrative (Audiffren, 2009; 2016; Tomporowski & Qazi, 2020) and meta-analytic (Jung et al., 2022; Loprinzi, Blough et al., 2019) reviews. These studies indicate that cognition supported by the prefrontal cortex may be particularly affected in dual-task situations where acute higher intensity exercise coincides with complex cognitive tasks. Yet, the mechanisms for these findings remains infrequently studied and poorly understood.

Amongst the most prominent theories in this area of research, the transient hypofrontality theory suggests that deficits in cognition during vigorous-intensity exercise occur as a result of redistributions of metabolic and neural resources toward the sensory and motor cortices (Dietrich 2003; 2006). During such exercise, our priority shifts towards supporting motor function and maintaining homeostasis, leading to a temporary downregulation of the prefrontal cortex to conserve energy in brain metabolism (Audiffren, 2016; Dietrich & Audiffren, 2011). Consequently, as metabolic resources are pulled away from the prefrontal cortex to support operations within the sensory and motor cortices, the neurobiological functioning of the tissue in the prefrontal cortex is compromised. Therefore, tasks which are reliant upon structures in the prefrontal cortex — such as cognitive control tasks — would be expected to demonstrate reductions in performance; whereas tasks which rely less on prefrontal cortex would be expected to demonstrate sustained performance despite the engagement in vigorous exercise.

Such an attribution is generally supported by the literature, which has observed that performance on tasks which require relatively little engagement of the prefrontal cortex are less affected (or even improved) by vigorous-intensity exercise; while tasks that are heavily reliant upon the prefrontal cortex appear to be compromised by vigorous-intensity exercise (Dietrich & Sparling, 2004). Investigations which have used functional near-infrared spectroscopy (fNIRS) to gain insight into oxygenated and deoxygenated hemoglobin concentrations within the prefrontal cortex have observed decreases in cerebral oxygenation associated with more intense exercise in a manner consistent with the transient hypofrontality theory (Tempest & Reiss, 2019). Specifically, extant research suggests that such changes in cerebral oxygenation occur when exercising at, or slightly above, the ventilatory threshold — the point at which expired ventilation occurs at a faster rate than inspired oxygenation (Bhambhani et al., 2007; Rooks et al., 2010; Shibuya et al., 2004). Although compelling evidence exists indicating that such changes co-occur with deterioration of cognitive performance on more difficult/cognitively engaging tasks (Komiyama et al., 2020; Mekari et al., 2015), a key question remains as to if these changes in cerebral oxygenation of the prefrontal cortex serve to mediate the changes in cognition that occur during more vigorous intensities of exercise.

Transient cognitive deficits that occur during exercise may also be influenced by changes in focus resulting from varying exercise intensities (Wollseiffen et al., 2016). Specifically, it may be that during vigorous exercise, mental focus may shift away from attending to task-relevant information in favor of attending to the exercise itself and the associated physiological sensations induced by exercise. Such a hypothesis is conceptually similar to the transient hypofrontality theory but attributes changes that occur during exercise to the mental characteristics rather than the more brain-based physiological attributions which might be assessed through the use of cerebral oxygenation of the prefrontal cortex. Within the broader field of exercise psychology, such shifting of mental focus is typically characterized as associate-dissociate attention (Hutchinson & Tenenbaum, 2007). Dissociative attentional focus describes a mental state where an individual seemingly disengages from the immediate physical sensations and processes of exercise; enabling thoughts associated with personal matters or task unrelated to the activity (Jones & Ekkekakis, 2019). In the context of completing a cognitive task while exercising, given the resource limited nature of neural systems this dissociative attentional focus would enable allocation of extensive resources to support high levels of performance on the cognitive task as relatively fewer resources would be allocated towards monitoring of the exercise stimulus. Alternatively, associative attentional focus describes a mental state whereby the individual disengages from the external environment in order to attend to the bodily sensations and internal processes associated with the exercise (Jones & Ekkekakis, 2019). Such a focus is typically oriented towards monitoring breathing patterns, muscle activation, and physical sensations (e.g., fatigue, soreness, or perceived exertion levels). Thus, associative attentional focus may represent a state whereby performance on a cognitive task is sacrificed to allow focus on the more immediately relevant physiological stimulus associated with exercise. As easier cognitive tasks would present with minimal cognitive burden, performance on these tasks may still be maintained despite shifts towards associative states; however, focusing on internal states may deprive neural systems of necessary resources to support higher level cognitive operations such as those necessary for assessments of cognitive control. Thus, more difficult cognitively engaging tasks would be expected to show diminished performance in association with this associative state.

Conceptually, the premise that associate-dissociate attention may serve as a mechanism related to changes in cognition during exercise aligns well with the extant literature, which has observed enhancements/sustainment of cognition during more moderate intensities of exercise, but deteriorations during more vigorous intensities. Indeed, prior research exploring the relationship between exercise intensity and attentional focus has suggested that shifts in associate-dissociate attention occur in response to exercise intensity with greater intensity resulting in shifts towards more internally focused associative states (Jones & Ekkekakis, 2019; Welch et al., 2007). In particular, the critical point at which this shift occurs appears to be when exercising at, or slightly above, the ventilatory threshold (Welch et al., 2007). Following the cessation of exercise however, associate-dissociate attention would shift back towards more dissociate states as the imperative stimulus associated with exercise diminishes. Despite this plausibility, there is little evidence on the extent to which such shifts in associate-dissociate attention may underlie the negative effects of more vigorous exercise intensities on cognition.

Accordingly, given the potential influences of cerebral oxygenation of the prefrontal cortex and associate-dissociate attention as mechanisms underlying the effects of vigorous-intensity exercise on cognition, the present investigation sought to specifically test these factors using a rigorous within-subjects randomized cross-over two-arm experimental design. Using such an approach, changes in cognition could be assessed alongside changes in cerebral oxygenation of the prefrontal cortex and associate-dissociate attention in response to multiple intensities of exercise relative to an active control condition to enable specifically testing the mediating influence of these factors on cognition. It was hypothesized that vigorous aerobic exercise would result in reduced oxygenation of the prefrontal cortex as well as a shift towards associate attentional states, and that these factors would both contribute to explaining deteriorations in cognitive performance. While more moderate intensities of aerobic exercise would result in minimal changes in oxygenation of the prefrontal cortex and maintenance of more dissociate attentional states, enabling the enhancement/sustainment of cognitive performance during exercise.

2. Method

2.1. Participants

Analyses were conducted on a sample of 75 college-aged young adults from the University of Mississippi. All participants completed a health history and demographics questionnaire, reported being free of daily tobacco use, alcohol within 24 h, marijuana or other illegal drugs within the past 30 days, and history of head trauma within the past 24 months. No participants indicated the presence of any learning disabilities/disorders and ADHD, color blindness, left-hand dominance, or physical restriction that might limit their ability to engage in physical activity as determined using the PAR-Q (Physical Activity Readiness Questionnaire). To reduce potential confounds, all participants were native English speakers and had skin pigmentation of less than a score of 4 on the Fitzpatrick skin type scale — as darker skin tones have been observed to reduce signal quality of NIRS devices (Wassenaar & Van den Brand, 2005). Further, participants were instructed to avoid exercising within 9 h of testing and to consume a cup of water within one hour prior to arriving to the laboratory (Riebl & Davy, 2013). The experimental procedures used in this study adhered to the approved protocols of the University of Mississippi Institutional review Board, ensuring compliance with relevant guidelines and regulations pertaining to the involvement of human subjects. Demographic data are provided in Table 1.

2.2. Procedure

Using a within-subjects randomized cross-over two-arm experimental design (Herold et al., 2021), participants visited the laboratory on three separate days (Day 1: maximal exercise test, study equipment familiarization; Day 2 and 3: experimental protocol involving active control and experimental control study arms). The initial testing session was conducted to obtain each participant's maximal aerobic capacity to set the workload intensity during the experimental protocol sessions. Following assessment of maximal aerobic capacity, participants were familiarized with the experimental procedures and equipment. Participants were given the opportunity to practice the cognitive task until accuracy exceeded 80 % correct.

Following the initial testing session, participants were randomized into one of two counterbalanced session orders (Day 2: active control arm, Day 3: experimental arm; or, Day 2: experimental arm, Day 3: active control arm) to ensure that any observed effects were unrelated to the specific order in which participants received the experimental conditions and on separate days to reduce the potential of carryover effects. These sessions were scheduled at the same time of day (±2 h) and occurred at least 48–72 h apart. During each session, participants completed a Stroop task four separate times: at baseline, two times during the exercise session, and at post-test. Central to the focus of the present investigation, hypothesized mechanisms which may contribute to alterations in cognition during exercise (cerebral oxygenation of the prefrontal cortex and associate-dissociate attention) were assessed prior to each administration of the Stroop task. All aspects of the Day 2 and Day 3 sessions were identical except for the exercise session components; with oxygen consumption, heart rate, rating of perceived exertion (RPE), and affective valence (via Feeling Scale ranging from −5 to +5) measured throughout the exercise periods. See Fig. 1 for a schematic of the study procedures.

Experimental Arm: The experimental condition of interest to the present investigation had participants begin pedaling a stationary bike at a fixed workload that corresponded to their ventilatory threshold for a period of 12 min. While the participant was exercising, the Stroop task was administered at minute 5 to provide a cognitive assessment at a moderate exercise intensity with the task taking approximately 3 min to complete. Participants were then given a fixed recovery period of 1 min without exercise. Following the brief 1 min recovery period, participants pedaled a stationary bike at a workload corresponding to 100 % of peak workload. The Stroop task was administered during this vigorous intensity period (corresponding to minute 14). If the participant was not able to maintain the cadence (50 rpm) at 100 % of peak workload, the level of resistance was lowered (0.5–1.0 Kp) to allow them to finish the Stroop task while concurrently exercising.

Active Control Arm: To ensure that any potential differences in cognitive performance, prefrontal cortex oxygenation, or associate-dissociate attention could be attributed to the level of exertion rather than the control of motor coordination, an active control arm was used. During the exercise session, participants pedaled a stationary bike at a 25-watt intensity (i.e., 0.5 Kp at 50 rpm) for a total duration of ~17 min. While the participant was exercising, the Stroop task was administered at minute 5 (very light intensity) and again at minute 14 (very light intensity), taking approximately 3 min to complete each time.

Table 1
Demographic and behavioral characteristics of the sample (N=75).

Variable	Point Estimate	SD
Age, mean years	20.3	1.6
Sex, % Women	50.7	
Measured body mass index, mean kg/m^2	24.3	4.1
Physical activity, mean min/week of MVPA	261.1	192.9

MVPA, Moderate-to-vigorous physical activity, as assessed via the Physical Activity Vital.
Signs questionnaire.

2.3. Measures

Cognition: To assess the extent to which changes in cognition occurred during exercise, participants completed a computerized version of the modified Stroop task (Mekari et al., 2015). This task presents strings of characters either in a green, red, blue, or yellow colored font. During the Color trials — which were presented 14.3 % of the time (12 of 84 trials) — the characters were three X's in a row and participants were instructed to respond to the color of the font. During the Color Word trials — which were presented 42.9 % of the time (36 of 84 trials) — the characters were the words green, red, blue, or yellow in capital letters and participants were instructed to respond to the color of the font while inhibiting the tendency to respond to the word (i.e., respond blue if the word "RED" was shown in blue ink). All trials in the Color Word condition were incongruent; the color of the font and the word itself always differed, ensuring that no congruent trials (where the color and the word were the same) were included. Finally, the Switch trials — which were presented 42.9 % of the time (36 of 84 trials) — followed the same format of the Color Word trials but were presented with a black box surrounding the word. This black box served as a perceptual cue for participants to respond to the color word while inhibiting the response to the color of the font (i.e., respond red if the word "RED" was shown in blue ink).

A single block of 84 trials was presented in a random order each time the Stroop task was run during the experimental protocol using E-prime (v. 3.0). Stimuli were presented focally on a 24-inch monitor placed on a portable desk directly in front of the stationary bike approximately 65 cm away from the participant's head with a visual angle of 6.171°. Participants responded during the task using two buttons attached to the bike handlebars to enable concurrent completion of the cognitive task while cycling. Each color was linked to a specific response button located on the handlebars of the cycle ergometer (e.g., left button was for green and red responses; right button was for blue and yellow responses); and the color-button response mappings were counterbalanced across participants. During the test, no feedback was provided unless reaction times exceeded 1.4 s in which case a "response too slow" message was presented. Both mean reaction time (ms) and response accuracy (% correct) were computed for all three item types (Color, Color Word, and Switch). Only correct trials were used for calculation of reaction time. Reaction times less than 200 ms were excluded as outliers as were reaction times that fell outside 2.5 times the median absolute deviation (Leys et al., 2013).

Cerebral Oxygenation of the Prefrontal Cortex: To assess the extent to which changes in cognition during exercise may result from changes in prefrontal oxygenation, cerebral oxygenation was assessed using fNIRS throughout the completion of the Stroop task. Participants were outfitted with an eight-lead optode headset (2 × 4 channel, 20 × 7 cm headband, optodes 35 mm apart; OctaMon, Artinis, Netherlands) located on the forehead, just above the supraorbital ridge. To reduce the

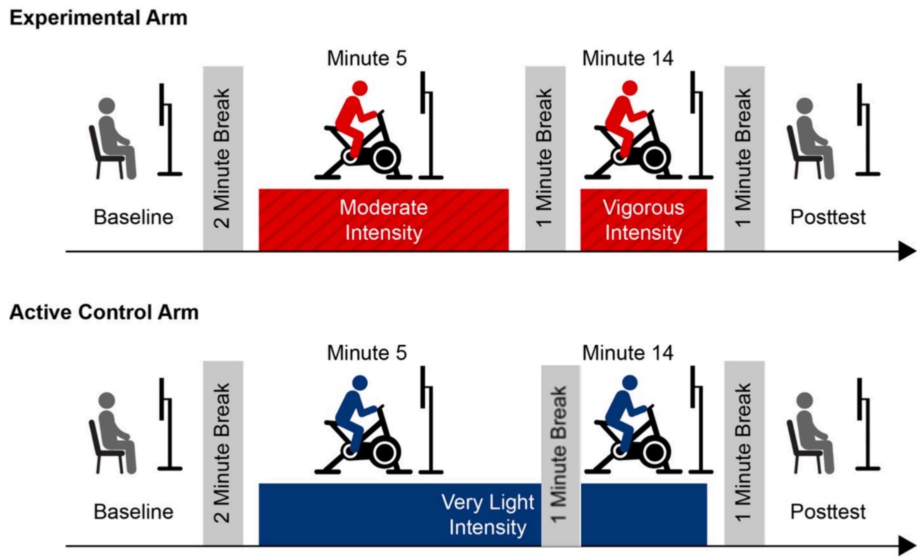

Fig. 1. Illustration of the within-subjects two arm experimental protocol.

potential for ambient light contamination, the fNIRS device was wrapped in black Vetrap bandaging tape. Right and left tissue saturation indices were used as a measure of prefrontal oxygenation. Tissue saturation index was calculated from measured oxygenated (HbO_2) and deoxygenated hemoglobin (HHb) summed across all four lateralized optode leads with right and left tissue saturation index computed separately as (HbO_2 / [HbO_2 + HHb]) × 100. Changes in tissue saturation index were computed relative to a 2-minute period when participants viewed a flashing black dot in the center of the screen at the beginning of the experimental protocol.

Given that prefrontal cortex assessments for this experiment occurred during intense cycling, various fNIRS filter processing techniques were implemented to minimize the impact of noise induced by motion artifacts and physiological changes (Jones & Ekkekakis, 2019). As a first step, raw-intensity signals collected with fNIRS were converted into optical density data, and then the optical density data were converted into relative concentrations of HbO_2 and HHb based on the modified Beer-Lambert law. The HbO_2 and HHb data were then exported to Matlab (R2021, The MathWorks, Natick, MA, USA) for further processing. Second, a bilateral filter, which employs a Gaussian weight function by multiplying the spatial proximity Gaussian kernel and the numerical similarity Gaussian kernel functions (Liu & Schumacher, 2020), was applied to remove spikes (i.e., near-instantaneous signal inflections much larger in amplitude than the typical amplitude of the hemodynamic signal) and correct discontinuities (i.e., baseline shifts). Third, a third-order Butterworth bandpass filter was applied from 0.008 to 0.5 Hz to remove the low- and high-frequency oscillations due to heart pulsations and respiration during exercise. Fourth, a denoising algorithm (Feuerstein et al., 2009) was applied to remove noise from the signal (if the noise has greater amplitude than the underlying hemodynamic signal).

Associate-Dissociate Attention: To assess the extent to which changes in cognition during exercise may result from shifts towards associative attention, participants completed an attentional focus assessment using the Attention Scale (proposed by Baden et al., 2004). This measure has participants rate the extent to which their thoughts were primarily associative or dissociative on a 10-point bipolar scale. The single-item attentional focus scale ranges from 1, indicating total internally associative focus (i.e., sweatiness, heavy breathing, and pain), to 10, indicating total externally dissociative focus (i.e., not thinking about exercise itself and its associated physiological sensations, such as daydreams and external thoughts). Providing evidence of convergent validity, this scale has been shown to correlate with ratings of exertion and does so reliability across multiple experiments (Baden et al., 2004).

Maximal Aerobic Capacity: To set each participant's workload intensity during the exercise sessions, a maximal cycle-based VO_{2max} assessment was performed. Participants cycled on a Monark cycle ergometer while oxygen consumption was assessed via indirect calorimetry using a metabolic cart (ParvoMedics TrueOne 2400, ParvoMedics Inc., Sandy, UT). The protocol for the maximal exercise test had participants begin a 3-minute warm up period with an initial workload set at 25 W (i.e., 0.5 Kp). Following this period, the exercise intensity was increased by 25 W every 4 min until exhaustion while maintaining a pedaling rate of 50 rpm (audio feedback, via a metronome, was provided). Exhaustion was defined as volitional cessation of exercise or failure to maintain a pedaling cadence of 50 rpm despite verbal encouragement. Heart rate and RPE, respectively, were documented immediately after completion of each stage (i.e., before moving to the next stage) using a portable HR monitor (Polar, *H*10, Lake Success, NY, USA) and Borg's 6–20 scale (Borg, 1982). Attainment of maximal effort was evidenced by (1) a plateau in VO_2 when moving from the last workload to the final workload (increase < 150 mL/min with increase in cycle watt), (2) a respiratory exchange ratio > 1.10, (3) a HRmax within 10 % of the age-predicted maximum (220 – age), and (4) a RPE>17 (very hard) on Borg's 6–20 scale.

This approach enabled calculation of each participant's ventilatory threshold and respiratory compensation point which were used to set the workload for the subsequent exercise visit. These values were calculated using WinBreak software (v. 3.7, Epistemic Mindworks, Ames, IA, USA) using the ventilatory equivalents for oxygen (V_E/VO_2) and carbon dioxide (V_E/VCO_2) to identify a breakpoint in the regression-based slopes of plotted ventilatory data (Ekkekakis et al., 2008). The ventilatory threshold was determined as the breakpoint at which V_E/VCO_2 showed a greater increase than V_E/VO_2 (Beaver et al., 1986). The respiratory compensation point was characterized by the breakpoint at which there was an increase in V_E/VO_2 without a concurrent increase in V_E/VCO_2 (Davis et al., 1979; Reinhard et al., 1979).

2.4. Statistical analysis

All data analyses were performed in R Version 4 (R Core Team, 2019) utilizing a familywise alpha level of 0.05. Analyses were conducted using a multi-step approach. First, analyses of behavioral performance (reaction time and response accuracy) were conducted using a 2 (Condition: experimental, active control) × 4 (Time: baseline, during exercise at minute 5 and minute 14, and post-test) × 3 (Type: color, color word, switch) univariate multi-level model including the random intercept for each participant to determine the effect of exercise on cognition. Analyses were conducted to determine the effect of exercise on cerebral oxygenation of the prefrontal cortex using a 2 (Condition: experimental, active control) × 4 (Time: baseline, during exercise at minute 5 and minute 14, and post-test) × 2 (Hemisphere: left, right) univariate multi-level model including the random intercept for each participant. Similarly, analyses were then conducted to determine the effect of exercise on associate-dissociate attention using a 2 (Condition: experimental, active control) × 4 (Time: baseline, during exercise at minute 5 and minute 14, and posttest) univariate multi-level model including the random intercept for each participant. Potential confounders were examined for inclusion in the multi-level modeling approach as additional random intercepts associated with demographic characteristics (i.e., gender, race, BMI, aerobic fitness, MVPA). However, as none of these were identified as statistically relevant (i.e., $p < 0.05$), they were excluded from the modeling approach. The multi-level model analyses were performed using the Rmimic (Pontifex, 2022) package, which provides a standardized implementation wrapper and automated post-hoc decompositions. The analyses utilized the lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), and emmeans (Lenth et al., 2017) packages in R (R Core Team, 2019). Kenward-Roger degrees of freedom approximations and Benjamini-Hochberg false discovery rate control (set at 0.05) were applied for post-hoc decompositions. Cohen's f^2 and d with 95 % confidence intervals were computed as standardized measures of effect size, using appropriate variance corrections for within-subject (d_{rm}) comparisons (Lakens, 2013). Given a sample size of 75 participants and beta of 0.20 (i.e., 80 % power), the present research design theoretically had sufficient sensitivity to detect conventional ANOVA within factors interactions exceeding $f = 0.136$ (with a correlation among repeated measures of 0.5) and conventional t-test differences exceeding $d = 0.32$ (with a two-sided alpha) as computed using G*Power 3.1.2 (Faul et al., 2007).

For each behavioral performance outcome (reaction time and response accuracy), cerebral oxygenation of the prefrontal cortex and associate-dissociate attention were separately assessed as potential mediators of the difference in change in performance from baseline for light relative to moderate-intensity exercise (minute 5), for light relative to vigorous-intensity exercise (minute 14), and for post light intensity exercise relative to post vigorous-intensity exercise. Mediation analyses were performed using the Rmimic (Pontifex, 2022) package, which provides a standardized implementation wrapper around the mediation (version 4.4.7; Tingley et al., 2014) package in R with unstandardized indirect effects computed using 1,000 nonparametric bootstrapped samples.

3. Results

3.1. Manipulation check

The heart rate responses, RPE, and affective valence during the experimental visits are summarized in Table 2.

3.2. Changes in cognition in response to exercise

Reaction Time: We found that reaction time was generally shorter during vigorous-intensity exercise compared to baseline (see Fig. 2a). Analyses revealed a main effect of Time, $F(3, 1702) = 85.6$, $p < 0.001$, $f^2 = 0.66$ [95 % CI: 0.30–1.28]. Post hoc comparisons indicated that reaction time was longer at Baseline (790.3 ± 204.4 ms) relative to Minute 5 (725.1 ± 159.0 ms), Minute 14 (695.8 ± 155.3 ms), and Posttest (681.8 ± 148.6 ms), t's(1702) ≥ 8.9, p's < 0.001, d_{rm}'s ≥ 0.47 [95 % CI: 0.37–0.9]. Reaction time was also observed to be longer at Minute 5 relative to Minute 14 and Posttest, t's(1702) ≥ 4.0, p's < 0.001, d_{rm}'s ≥ 0.18 [95 % CI: 0.09–0.47]. A main effect of Type, $F(2, 1702) = 297.4$, $p < 0.001$, $f^2 = 1.53$ [95 % CI: 0.89–2.80], was also observed with shorter reaction time for Color trials (633.4 ± 111.6 ms) relative to ColorWord (764.5 ± 176.2 ms) and Switch (771.8 ± 185.7 ms) trials, t's (1702) ≥ 20.5, p's < 0.001, d_{rm}'s ≥ 1.4 [95 % CI: 1.26–1.7]. No Condition × Time interaction was observed, $F(3, 1702) = 2.4$, $p = 0.064$, $f^2 = 0.02$ [95 % CI: 0.0–0.08].

Table 2
Heart rate responses, RPE, and affective valence (Feeling) across the experimental sessions (mean (SD)).

Variable	Before S1	Before Cycling	Before S2	Before Break	Before S3	Before S4
EX HR	81.5 (11.7)	88.3 (14.5)	142.9 (17.6)	171.4 (13.1)	157.3 (13.1)	173.5 (15.3)
EX RPE	6.0 (0.1)	6.1 (0.2)	10.8 (1.6)	17.5 (1.0)	16.8 (1.1)	17.8 (1.1)
EX Feeling	3.7 (1.7)	3.7 (1.6)	2.6 (1.6)	0.9 (1.6)	1.0 (1.6)	0.4 (1.9)
CON HR	82.8 (12.5)	86.9 (13.6)	104.1 (15.8)	105.5 (16.0)	94.0 (16.1)	92.9 (15.4)
CON RPE	6.0 (0.1)	6.0 (0.2)	7.4 (1.1)	8.4 (1.6)	7.7 (1.6)	7.9 (1.7)
CON Feeling	3.8 (1.6)	3.8 (1.6)	3.6 (1.4)	3.5 (1.4)	3.5 (1.5)	3.6 (1.5)

HR, Heart rate; RPE, Rating of perceived exertion. EX represents the Exercise condition and CON represents the Active Control condition.
Notes. S1, First Stroop administration administration at baseline; S2, Second Stroop administration at minutes 5–7 (moderate-intensity); S3, Third Stroop administration at minutes 14–16 (vigorous-intensity); S4, Fourth Stroop administration at post-test.

Response Accuracy: Consistent with prior literature, we found that cognitive performance was most impaired during vigorous-intensity exercise (see Fig. 2a). Analyses revealed a main effect of Type, $F(2, 1701) = 127.7$, $p < 0.001$, $f^2 = 1.28$ [95 % CI: 0.72–2.37], with higher performance for Color trials (95.4 ± 7.0 %) relative to ColorWord (90.2 ± 7.9 %) and Switch (90.2 ± 8.7 %) trials, t's(1701) ≥ 13.8, p's < 0.001, d_{rm}'s ≥ 1.36 [95 % CI: 1.16–1.58]. Main effects of Condition, $F(1, 1701) = 41.9$, $p < 0.001$, $f^2 = 0.21$ [95 % CI: 0.03–0.48], and Time, $F(3, 1701) = 19.9$, $p < 0.001$, $f^2 = 0.30$ [95 % CI: 0.08–0.64] were also observed, which were superseded by a Condition × Time interaction, $F(3, 1701) = 6.6$, $p < 0.001$, $f^2 = 0.10$ [95 % CI: 0.01–0.26].

Post-hoc decomposition of the Condition × Time interaction was first conducted by examining the effect of Condition at each Timepoint. At Baseline, no significant differences were observed between the Active Control (92.6 ± 7.9 %) and Experimental (92.2 ± 7.6 %) conditions; $t(1701) = 0.6$, $p = 0.54$, $d_{rm} = 0.08$ [95 % CI: −0.18 to 0.34]; while at all other time points performance was higher for the Active Control (Minute 5: 91.9 ± 7.4 %, Minute 14: 92.8 ± 7.5 %, Posttest: 94.5 ± 6.5 %) relative to the Experimental (Minute 5: 90.1 ± 8.9 %, Minute 14: 88.6 ± 10.5 %, Posttest: 92.8 ± 7.9) condition; t's(1701) ≥ 2.7, p's ≤ 0.008, d_{rm}'s ≥ 0.34 [95 % CI: 0.09–1.09].

Secondary post-hoc decomposition of the Condition × Time interaction was conducted by examining the effect of Time within each Condition. For the Active Control condition, a main effect of Time, $F(3, 821) = 7.2$, $p < 0.001$, $f^2 = 2.66$ [95 % CI: 1.67–4.79], was observed such that performance was higher at Posttest (94.5 ± 6.5 %) relative to the Baseline (92.6 ± 7.9 %), Minute 5 (91.9 ± 7.4 %), and Minute 14 (92.8 ± 7.5 %) timepoints, t's(821) ≥ 2.9, p's ≤ 0.004, d_{rm}'s ≥ 0.28 [95 % CI: 0.09–0.8]. For the Experimental condition, a main effect of Time, $F(3, 822) = 16.7$, $p < 0.001$, $f^2 = 2.84$ [95 % CI: 1.80–5.11], was also observed such that performance was lower at Minute 5 (90.1 ± 8.9 %) and Minute 14 (88.6 ± 10.5 %) relative to Baseline (92.2 ± 7.6 %) and Posttest (92.8 ± 7.9 %), t's(822) ≥ 3.2, p's ≤ 0.001, d_{rm}'s ≥ 0.25 [95 % CI: 0.10–0.76]. Performance was also lower at Minute 14 relative to Minute 5, $t(822) = 2.1$, $p = 0.033$, $d_{rm} = 0.17$ [95 % CI: 0.01–0.33].

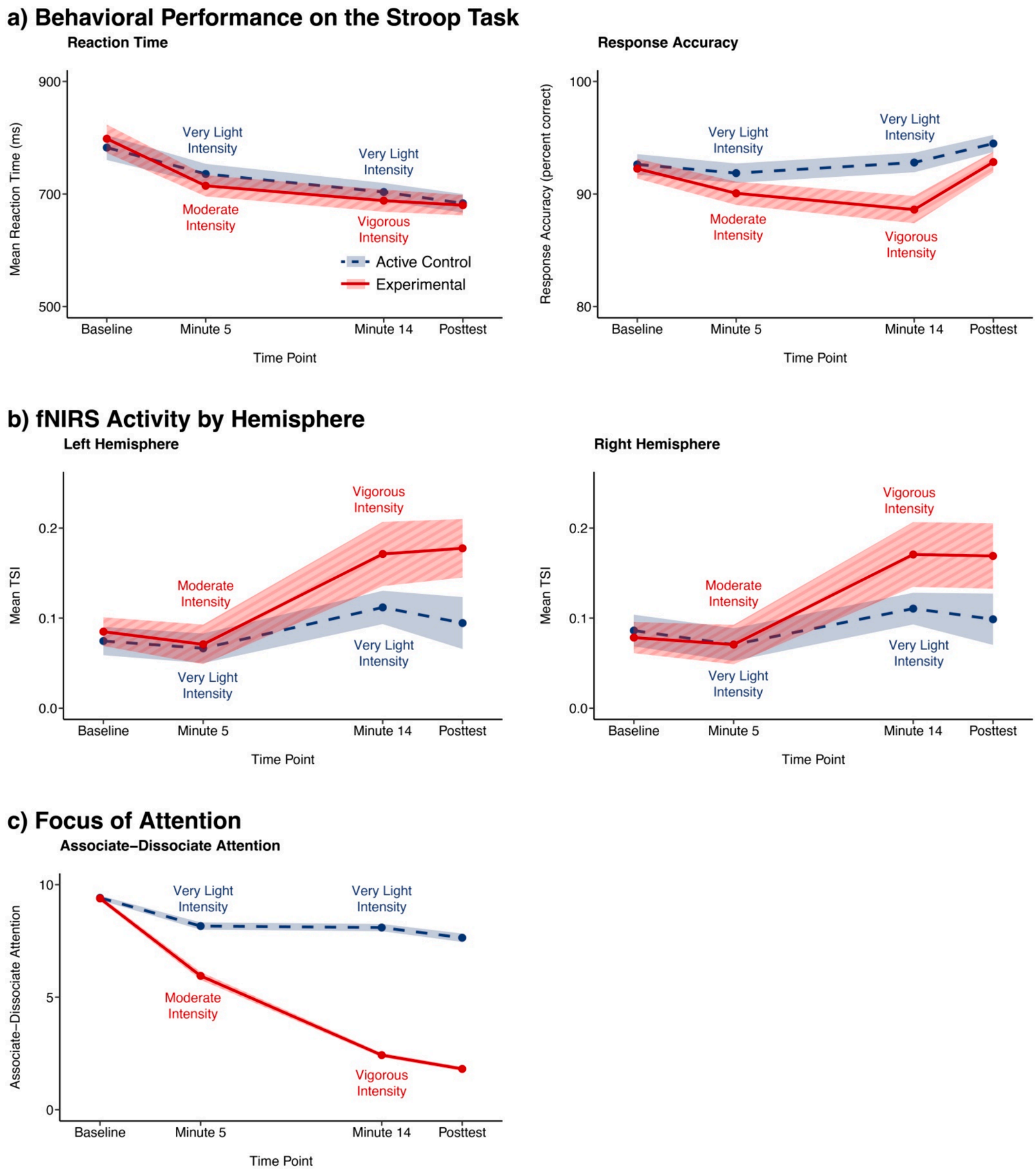

Fig. 2. Mean (SE) of behavioral performance on the Stroop task over time for each protocol (a). Mean (SE) TSI (tissue saturation index) of the prefrontal cortex, as measured by fNIRS, over time for each protocol (b). Mean (SE) attentional focus over time for each protocol (c). Note that on the y-axis of Fig. 2(c), lower values indicate a more associative attentional focus.

3.3. Changes in potential mechanisms in response to exercise

Cerebral Oxygenation of the Prefrontal Cortex: Inconsistent with our prediction, we observed an increase in cerebral oxygenation of the prefrontal cortex during vigorous-intensity exercise (see Fig. 2b). Analyses revealed main effects of Condition, $F(1, 1056) = 17.6$, $p < 0.001$, $f^2 = 0.33$ [95 % CI: 0.10–0.70], and Time, $F(3, 1056) = 28.6$, $p < 0.001$, $f^2 = 1.63$ [95 % CI: 0.96–2.98], which were superseded by a Condition × Time interaction, $F(3, 1056) = 5.2$, $p = 0.002$, $f^2 = 0.29$ [95 % CI: 0.08–0.62].

Post-hoc decomposition of the Condition × Time interaction was first conducted by examining the effect of Condition at each Timepoint. At Minute 14 (0.17 ± 0.2 %) and Posttest (0.17 ± 0.21 %), cerebral oxygenation of the prefrontal cortex was elevated in response to the Experimental, relative to the Active Control, condition (Minute 14: 0.11 ± 0.1 %, Posttest: 0.11 ± 0.16 %), t's(1062) ≥ 3.7, p's < 0.001, d_{rm}'s ≥ 0.66 [95 % CI: 0.32–1.07].

Secondary post-hoc decomposition of the Condition × Time interaction was conducted by examining the effect of Time within each Condition. For the Active Control condition, a main effect of Time, $F(3, 499) = 12.3$, $p < 0.001$, $f^2 = 2.80$ [95 % CI: 1.77–5.04], was observed such that cerebral oxygenation of the prefrontal cortex was elevated at Minute 14 (0.11 ± 0.1 %) and Posttest (0.11 ± 0.16 %) relative to Pretest (0.08 ± 0.08 %) and Minute 5 (0.07 ± 0.08 %), t's(498) ≥ 3.6, p's < 0.001, d_{rm}'s ≥ 0.40 [95 % CI: 0.18–0.82]. For the Experimental condition, a main effect of Time, $F(3, 492) = 31.3$, $p < 0.001$, $f^2 = 2.92$ [95 % CI: 1.85–5.25], was also observed such that cerebral oxygenation of the prefrontal cortex was elevated at Minute 14 (0.17 ± 0.21 %) and Posttest (0.17 ± 0.21 %) relative to Pretest (0.08 ± 0.1 %) and Minute 5 (0.07 ± 0.15 %), t's(490) ≥ 6.2, p's < 0.001, d_{rm}'s ≥ 0.67 [95 % CI: 0.46–1.21].

Associate-Dissociate Attention: As predicted, we observed a shift in attention towards an associate state during vigorous-intensity exercise (see Fig. 2c). Analyses revealed main effects of Condition, $F(1, 518) = 1614.8$, $p < 0.001$, $f^2 = 0.65$ [95 % CI: 0.30–1.26], and Time, $F(3, 518) = 609.6$, $p < 0.001$, $f^2 = 0.73$ [95 % CI: 0.35–1.41], which were superseded by a Condition × Time interaction, $F(3, 518) = 271.8$, $p < 0.001$, $f^2 = 0.33$ [95 % CI: 0.10–0.68]. Post-hoc decomposition of the Condition × Time interaction was first conducted by examining the effect of Condition at each Timepoint. At Minute 5, Minute 14, and Posttest associate-dissociate attention was lower for the Experimental condition (Minute 5: 5.9 ± 1.5, Minute 14: 2.4 ± 0.8, and Posttest: 1.8 ± 0.8) relative to the Active Control (Minute 5: 8.2 ± 1.4, Minute 14: 8.1 ± 1.4, and Posttest: 7.6 ± 1.6) condition, t's(518) ≥ 13.0, p's < 0.001, d_{rm}'s ≥ 1.65 [95 % CI: 1.38–6.13].

Secondary post-hoc decomposition of the Condition × Time interaction was conducted by examining the effect of Time within each Condition. For the Active Control condition, a main effect of Time, $F(3, 221) = 47.7$, $p < 0.001$, $f^2 = 2.95$ [95 % CI: 1.88–5.31], was observed such that associate-dissociate attention was reduced at Minute 5 (8.2 ± 1.4), Minute 14 (8.1 ± 1.4), and Posttest (7.6 ± 1.6) relative to Baseline (9.4 ± 0.9), t's(221) ≥ 8.0, p's < 0.001, d_{rm}'s ≥ 1.03 [95 % CI: 0.76–1.8]. Associate-dissociate attention was further reduced at Posttest relative to Minute 5 and Minute 14, t's(221) ≥ 2.9, p's ≤ 0.004, d_{rm}'s ≥ 0.26 [95 % CI: 0.08–0.54]. For the Experimental condition, a main effect of Time, $F(3, 222) = 959.7$, $p < 0.001$, $f^2 = 3.00$ [95 % CI: 1.91–5.39], was observed such that associate-dissociate attention was reduced at Minute 5 (5.9 ± 1.5), Minute 14 (2.4 ± 0.8), and Posttest (1.8 ± 0.8) relative to Baseline (9.4 ± 0.9), t's(222) ≥ 21.5, p's < 0.001, d_{rm}'s ≥ 3.08 [95 % CI: 2.68–8.87]. Associate-dissociate attention was further reduced from Minute 5 to Minute 14, $t(222) = 22.0$, $p < 0.001$, $d_{rm} = 3.50$ [95 % CI: 3.04–3.94], and at Posttest relative to Minute 5 and Minute 14, t's(221) ≥ 3.8, p's < 0.001, d_{rm}'s ≥ 0.41 [95 % CI: 0.2–4.38].

3.4. Mediation of cognitive changes

Reaction Time: Analyses indicated that cerebral oxygenation of the prefrontal cortex was not observed to mediate changes in reaction time from baseline between conditions across any of the time points of interest, (Proportion Mediated ≤ 5.8 % [95 % CI: −166.9 % to 110.9 %]; Average Causal Mediation Effect ≤ 6.81 [95 % CI: −7.38 to 18.45], p's ≥ 0.2). Similarly, associate-dissociate attention was not observed to mediate changes in reaction time from baseline between conditions across any of the time points of interest, (Proportion Mediated ≤ -19.9 % [95 % CI: −990.6 % to 872.0 %], Average Causal Mediation Effect ≤ 41.65 [95 % CI: −50.4 to 113.89], p's ≥ 0.2).

Response Accuracy: Analyses indicated that cerebral oxygenation of the prefrontal cortex was not observed to mediate changes in response accuracy from baseline between conditions across any of the time points of interest, (Proportion Mediated ≤ 16.6 % [95 % CI: −49.0 % to 201.8 %]; Average Causal Mediation Effect ≤ 0.12 [95 % CI: −0.85 to 0.43], p's ≥ 0.1). Similarly, associate-dissociate attention was not observed to mediate changes in response accuracy from baseline between conditions across any of the time points of interest, (Proportion Mediated ≤ 98.0 % [95 % CI: 753.4 % to 925.9 %], Average Causal Mediation Effect ≤ 0.47 [95 % CI: −7.29 to 2.05], p's ≥ 0.08).

4. Discussion

The purpose of the present investigation was to examine cerebral oxygenation of the prefrontal cortex and associate-dissociate attention as potential mechanisms underlying the effects of vigorous-intensity exercise on cognition. Consonant with prior meta-analytic (Jung et al., 2022) and experimental (Komiyama et al., 2020; Loprinzi et al., 2022; Mekari et al., 2015) research in this area, we observed impaired performance from the baseline cognitive assessment during moderate-intensity exercise — minute 5 of the experimental condition — that was further degraded in response to vigorous-intensity exercise — minute 14 of the experimental condition, as evidenced by generally poorer response accuracy across all trial types of the Stroop task. No differences in reaction time were observed between experimental conditions.

As the transient hypofrontality theory proposes, during vigorous exercise, the brain may shift resources away from higher-order cognitive functions towards the premotor cortex and supplementary motor areas to support the physical demands of exercise — potentially resulting in temporary deficits in cognitive performance (Dietrich 2003; 2006); it would follow that cerebral oxygenation of the prefrontal cortex may provide a physiologic indicator of this shift in neural resource availability. Accordingly, the novel contribution of the present investigation was in specifically testing cerebral oxygenation of the prefrontal cortex as a mediator of such changes in cognition. Within the present investigation, cerebral oxygenation of the prefrontal cortex was assessed using fNIRS during each of the Stroop task conditions and was observed to be elevated in response to vigorous-intensity exercise — minute 14 of the experimental condition — relative to both very light-intensity exercise (minute 14 of the active control condition) and moderate-intensity exercise (minute 5 of the experimental condition). This observed increase in cerebral oxygenation of the prefrontal cortex during vigorous-intensity exercise does not align with established theories of resource allocation within the brain, which do not support our hypothesis and the transient hypofrontality model that decreases in cerebral oxygenation of the prefrontal cortex are directly correlated with decreases in cognitive task performance (Herold et al., 2018; Takeda et al., 2017). This discrepancy indicates that while we observed heightened prefrontal oxygenation, this physiological change does not necessarily translate to the behavioral outcomes, thereby challenging certain aspects of the existing literature on the relationship between prefrontal oxygenation and cognition during exercise. Moreover, our investigation did not find cerebral oxygenation of the prefrontal cortex to be a mediating factor in the observed changes in behavioral performance on the Stroop task from baseline. As such, these findings suggest that while changes in prefrontal oxygenation do co-occur with changes in cognition, they do not appear to be a mechanism underlying alterations in behavioral performance.

Beyond brain-based physiological attributions which might be assessed through the use of cerebral oxygenation of the prefrontal cortex, it may also be that shifts in psychological characteristics provide an indicator consonant with the transient hypofrontality theory. Specifically, transient cognitive deficits that occur during exercise may be influenced by shifting attention away from task-relevant information in favor of attending to the exercise itself and the associated physiological sensations induced by exercise. Accordingly, within the present investigation, associate-dissociate attention was assessed prior to performance of the Stroop task at each timepoint. Although even very light-intensity exercise was associated with shifts in the focus of attention, there was a substantially larger effect associated with more intense exercise. Accordingly, the greatest internally associative focus was observed in response to the vigorous-intensity exercise. Mediation analysis again, however, observed that changes in associate-dissociate attention do not appear to be a mechanism underlying alterations in behavioral performance.

There are several potential reasons why associate-dissociate attention may not mediate cognitive performance deficits during vigorous exercise. First, exercise intensity may be a crucial factor. Vigorous exercise may require more attentional resources, regardless of whether individuals adopt an associative or dissociative attentional focus. In such cases, exercise itself may overwhelm the available attentional resources, leading to reduced cognition. Second, it is important to recognize that associative and dissociative attentional focuses may operate on different continua and be modulated separately, making it possible for individuals to exhibit relatively high or low levels in both dimensions. Although such a situation may not occur exactly at the same time, associative and dissociative thoughts could occur on a similar timescale within close proximity to each other during exercise (e.g., increased focus on pain while subsequently engaged in a dissociative thought to distract from the pain). More research is needed to obtain a deeper understanding of how attentional shifting during exercise, especially during vigorous-intensity exercise, may impact cognition, and whether it plays a role in mediating cognitive changes.

Interestingly, cognitive restoration occurred within just one minute following the cessation of the vigorous-intensity exercise bout, aligning with the findings of Loprinzi et al. (2023), while both cerebral oxygenation of the prefrontal cortex and associate-dissociate attention remained at similar levels post exercise as there were at following vigorous-intensity exercise. This rapid cognitive restoration post vigorous exercise suggests that the brain's higher-order cognitive functions are capable of rebounding quickly once the exercise has ended, even after being temporarily deprioritized in favor of physical demands. The sustained levels of cerebral oxygenation and attention after exercise may indicate psychophysiological states that could be beneficial for cognitive processes, despite the previous shift in resource allocation. This phenomenon might imply a certain resilience or flexibility in the brain's cognitive and oxygenation responses to intense exercise, which warrants further investigation to understand the underlying mechanisms and potential implications for cognitive recovery strategies post-exercise.

A limitation of this study is that our attentional measure was based on a self-reported scale. Instead of relying solely on self-report, future research may consider incorporating the evaluation of select event-related potentials (ERPs) that are known to be linked with attention. ERPs offer a powerful means to objectively measure neural markers of attentional allocation and processing, yet distinguishing between an internal and external focus of attention using ERPs might be still challenging. Thus, determining the exact focus of attention (internal vs. external) might require a combination of ERP data with other experimental paradigms or more specialized tasks designs. Doing so could provide a more objective and accurate assessment of whether attention mediates the exercise-cognition relationship. Furthermore, it is important to note that our findings may only be generalizable to the young adult population. Replicating this paradigm in other age groups, such as older adults, would be beneficial, as previous research demonstrated that dual-task interference is more pronounced in older adults compared to younger adults (Logie et al., 2007), which may increase the likelihood of observing mediating effects in this population. Despite these limitations, this study is the first attempt to evaluate two potential mediators — prefrontal oxygenation and attentional focus — of cognitive performance during exercise in a single within-subject study design.

In summary, our findings provide evidence that cognition supported by the prefrontal cortex is negatively affected during vigorous-intensity exercise. However, our study did not reveal any mediating effects of attention and cerebral oxygenation of the prefrontal cortex on cognitive performance during exercise. Subsequent research should explore other potential mediators, such as neurotransmitter levels, to identify the causal link between exercise and cognition (Jung et al., 2023). Furthermore, prior research demonstrated that different types of exercise, such as motor versus cardiovascular training, have varying impacts on children's working memory (Koutsandreou et al., 2016), suggesting the need for further differentiation in exercise types. Our findings highlight the importance of continued investigation in this area, as it may have implications for optimizing exercise interventions aimed at enhancing cognitive performance and preventing cognitive performance deficits in specific populations, such as firefighters, soldiers, and athletes who often require advanced cognitive skills during physically demanding activities (Budde et al., 2008). Additionally, our data suggest that even short breaks can be instrumental for cognitive recovery in these active professions. Another domain with broad implications is the cognitive effort required for the re-appraisal of negative affect in relation to exercise intensity. By delving deeper into how individuals cognitively navigate and reshape their perceptions of demanding exercise, we could refine exercise protocols to exploit this insight. Encouraging a more positive affect towards such exercises might enhance one's propensity to maintain regular exercise. These insights could pave the way for inventive strategies that make challenging exercises both more appealing and enjoyable, thereby boosting exercise adherence (Edwards et al., 2017; Jung et al., 2021).

CRediT authorship contribution statement

Myungjin Jung: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthew B. Pontifex:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Charles H. Hillman:** Writing – review & editing. **Minsoo Kang:** Writing – review & editing. **Michelle W. Voss:** Writing – review & editing. **Kirk I. Erickson:** Writing – review & editing. **Paul D. Loprinzi:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Data availability

Data will be made available on request.

References

Ando, S., Kokubu, M., Yamada, Y., & Kimura, M. (2011). Does cerebral oxygenation affect cognitive function during exercise? *European Journal of Applied Physiology, 111*(9), 1973–1982.

Audiffren, M. (2009). *Acute exercise and psychological functions: A cognitive-energetics approach.* In: Exercise and Cognitive Function. New York, Wiley, 2009, pp. 3-39.

Audiffren, M. (2016). The reticular-activating hypofrontality (RAH) model of acute exercise: Current data and future perspectives. In C. A. San Diego (Ed.), *Exercise-Cognition Interaction: Neuroscience Perspectives* (pp. 147–166). Elsevier Academic Press.

Audiffren, M., Tomporowski, P. D., & Zagrodnik, J. (2008). Acute aerobic exercise and information processing: Energizing motor processes during a choice reaction time task. *Acta Psychologica, 129*(3), 410–419.

Baden, D. A., Warwick-Evans, L., & Lakomy, J. (2004). Am I nearly there? The effect of anticipated running distance on perceived exertion and attentional focus. *Journal of Sport and Exercise Psychology, 26*(2), 215–231.

Bates, D., Kliegl, R., Vasishth, S., & Baayen, H. (2015). Parsimonious mixed models. *arXiv preprint arXiv:1506.04967*.

Bhambhani, Y., Malik, R., & Mookerjee, S. (2007). Cerebral oxygenation declines at exercise intensities above the respiratory compensation threshold. *Respiratory Physiology & Neurobiology, 156*(2), 196–202.

Borg, G. (1982). Ratings of perceived exertion and heart rates during short-term cycle exercise and their use in a new cycling strength test. *International Journal of Sports Medicine, 3*(03), 153–158.

Budde, H., Voelcker-Rehage, C., Pietrabyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters., 441*(2), 219–223.

Budde, H., Brunelli, A., Machado, S., Velasques, B., Ribeiro, P., Arias-Carrion, O., & Voelcker-Rehage, C. (2012). Intermittent maximal exercise improves attentional performance only in physically active students. *Archives of Medical Research, 43*, 125–131.

Budde, H., Schwarz, R., Velasques, B., Ribeiro, P., Holzweg, M., Machado, S., … Wegner, M. (2016). The need for differentiating between exercise, physical activity, and training. *Autoimmunity Reviews, 15*(1), 110–111.

Chang, H., Kim, K., Jung, Y. J., & Kato, M. (2017). Effects of acute high-intensity resistance exercise on cognitive function and oxygenation in prefrontal cortex. *Journal of Exercise Nutrition & Biochemistry, 21*(2), 1–8.

Davis, J. A., Frank, M. H., Whipp, B. J., & Wasserman, K. (1979). Anaerobic threshold alterations caused by endurance training in middle-aged men. *Journal of Applied Physiology, 46*(6), 1039–1046.

Davranche, K., Audiffren, M., & Denjean, A. (2006). A distributional analysis of the effect of physical exercise on a choice reaction time task. *Journal of Sports Sciences, 24*(3), 323–329.

Davranche, K., Burle, B., Audiffren, M., & Hasbroucq, T. (2005). Information processing during physical exercise: A chronometric and electromyographic study. *Experimental Brain Research, 165*, 532–540.

Dietrich, A. (2003). Functional neuroanatomy of altered states of consciousness: The transient hypofrontality hypothesis. *Consciousness and Cognition, 12*(2), 231–256.

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Research, 145*(1), 79–83.

Dietrich, A., & Audiffren, M. (2011). The reticular-activating hypofrontality (RAH) model of acute exercise. *Neuroscience & Biobehavioral Reviews, 35*(6), 1305–1325.

Edwards, M. K., Addoh, O., Herod, S. M., Rhodes, R. E., & Loprinzi, P. D. (2017). A conceptual neurocognitive affect-related model for the promotion of exercise among obese adults. *Current Obesity Reports, 6*(1), 86–92.

Ekkekakis, P., Lind, E., Hall, E. E., & Petruzzello, S. J. (2008). Do regression-based computer algorithms for determining the ventilatory threshold agree? *Journal of Sports Sciences, 26*(9), 967–976.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.

Feuerstein, D., Parker, K. H., & Boutelle, M. G. (2009). Practical methods for noise removal: Applications to spikes, nonstationary quasi-periodic noise, and baseline drift. *Analytical Chemistry, 81*(12), 4987–4994.

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I. M., … Swain, D. P. (2011). Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Medicine and Science Sports and Exercise, 43*(7), 1334–1359.

Gronwald, T., de Bem Alves, A. C., Murillo-Rodríguez, E., Latini, A., Schuette, J., & Budde, H. (2019). Standardization of exercise intensity and consideration of a dose–response is essential. Commentary on "Exercise-linked FNDC5/irisin rescues synaptic plasticity and memory defects in Alzheimer's models", by Lourenco et al., published 2019 in Nature Medicine. *Journal of Sport and Health Science, 8*(4), 353–354.

Gronwald, T., Velasques, B., Ribeiro, P., Machado, S., Murillo-Rodríguez, E., Ludyga, S., … Budde, H. (2018). Increasing exercise's effect on mental health: Exercise intensity does matter. *Proceedings of the National Academy of Sciences, 115*(51), E11890–E11891.

Herold, F., Wiegel, P., Scholkmann, F., & Müller, N. G. (2018). Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise–cognition science: A systematic, methodology-focused review. *Journal of Clinical Medicine, 7*(12), 466.

Herold, F., Torpel, A., Hamacher, D., Budde, H., Zou, L., Strobach, T., Muller, N., & Gronwald, T. (2021). Causes and consequences of interindividual response variability - A call to apply a more rigorous research design in acute exercise-cognition studies. *Frontiers in Physiology*. https://doi.org/10.3389/fphys.2021.682891

Hutchinson, J. C., & Tenenbaum, G. (2007). Attention focus during physical effort: The mediating role of task intensity. *Psychology of Sport and Exercise, 8*(2), 233–245.

Jones, L., & Ekkekakis, P. (2019). Affect and prefrontal hemodynamics during exercise under immersive audiovisual stimulation: Improving the experience of exercise for overweight adults. *Journal of Sport and Health Science, 8*(4), 325–338.

Jung, M., Kang, M., & Loprinzi, P. D. (2023). Hypothesized mechanisms of cognitive impairment during high-intensity acute exercise. In N. Rezaei (Ed.), *Brain, Decision Making and Mental Health* (Vol. 12, pp. 261–294). Stockholm, Sweden: Springer.

Jung, M., Kim, H. S., Loprinzi, P. D., & Kang, M. (2021). Serial-multiple mediation of enjoyment and intention on the relationship between creativity and physical activity. *AIMS Neuroscience, 8*(1), 161–180.

Jung, M., Ryu, S., Kang, M., Javadi, A. H., & Loprinzi, P. D. (2022). Evaluation of the transient hypofrontality theory in the context of exercise: A systematic review with meta-analysis. *Quarterly Journal of Experimental Psychology, 75*(7), 1193–1214.

Knatauskaitė, J., Akko, D., Pukenas, K., Trinkuniene, L., & Budde, H. (2022). Effect of acute game-based exercises on steroid hormones and cognitive performance in adolescents. *Acta Psychologica, 226*, Article 103584.

Komiyama, T., Tanoue, Y., Sudo, M., Costello, J., Uehara, Y., Higaki, Y., & Ando, S. (2020). Cognitive impairment during high-intensity exercise: Influence of cerebral blood flow. *Medicine and Science in Sports & Exercise, 52*(3), 561–568.

Koutsandreou, F., Wegner, M., Niemann, C., & Budde, H. (2016). Effects of motor versus cardiovascular exercise training on children's working memory. *Medicine & Science in Sports & Exercise, 48*(6), 1144–1152.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software, 82*(13), 1–26.

Labelle, V., Bosquet, L., Mekary, S., & Bherer, L. (2013). Decline in executive control during acute bouts of exercise as a function of exercise intensity and fitness level. *Brain and Cognition, 81*(1), 10–17.

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology, 4*, 863.

Lenth, R., Love, J., & Herve, M. (2017). emmeans: Estimated marginal means, aka least-squares means. https://github.com/rvlenth/emmeans.

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *Journal of Experimental Social Psychology, 49*(4), 764–766.

Liu, N., & Schumacher, T. (2020). Improved denoising of structural vibration data employing bilateral filtering. *Sensors, 20*(5), 1423.

Logie, R. H., Della Sala, S., MacPherson, S. E., & Cooper, J. (2007). Dual task demands on encoding and retrieval processes: Evidence from healthy adult ageing. *Cortex, 43*(1), 159–169.

Loprinzi, P. D., Blough, J., Crawford, L., Ryu, S., Zou, L., & Li, H. (2019). The temporal effects of acute exercise on episodic memory function: Systematic review with meta-analysis. *Brain Sciences, 9*(4), 87.

Loprinzi, P. D., Day, S., & Deming, R. (2019). Acute exercise intensity and memory function: Evaluation of the transient hypofrontality hypothesis. *Medicina, 55*(8), 445.

Loprinzi, P., Javadi, A. H., Jung, M., Watson, H., Sanderson, C., Kang, M., & Kelemen, W. L. (2022). Vigorous-intensity acute exercise during encoding can reduce levels of episodic and false memory. *Memory, 30*(8), 1031–1045.

Loprinzi, P. D., Roig, M., Tomporowski, P. D., Javadi, A. H., & Kelemen, W. L. (2023). Effects of acute exercise on memory: Considerations of exercise intensity, post-exercise recovery period and aerobic endurance. *Memory & Cognition, 51*(4), 1011–1026.

Martins, A. Q., Kavussanu, M., Willoughby, A., & Ring, C. (2013). Moderate intensity exercise facilitates working memory. *Psychology of Sport and Exercise, 14*(3), 323–328.

McMorris, T., Davranche, K., Jones, G., Hall, B., Corbett, J., & Minter, C. (2009). Acute incremental exercise, performance of a central executive task, and sympathoadrenal system and hypothalamic-pituitary-adrenal axis activity. *International Journal of Psychophysiology, 73*(3), 334–340.

Mekari, S., Fraser, S., Bosquet, L., Bonnéry, C., Labelle, V., Pouliot, P., … Bherer, L. (2015). The relationship between exercise intensity, cerebral oxygenation and cognitive performance in young adults. *European Journal of Applied Physiology, 115*, 2189–2197.

Pontifex, M. B. (2022). *Rmimic: An R package that mimic outputs of popular commercial statistics software packages with effect sizes and confidence intervals.* (1.0) [Computer software]. https://github.com/mattpontifex/Rmimic.

R Core Team. (2019). R: A language and environment for statistical computing (version 4) [Computer software]. https://www.R-project.org/.

Reinhard, U., Müller, P. H., & Schmülling, R. M. (1979). Determination of anaerobic threshold by the ventilation equivalent in normal individuals. *Respiration, 38*(1), 36–42.

Riebl, S. K., & Davy, B. M. (2013). The hydration equation: Update on water balance and cognitive performance. *ACSM's Health & Fitness Journal, 17*(6), 21–28.

Rooks, C. R., Thom, N. J., McCully, K. K., & Dishman, R. K. (2010). Effects of incremental exercise on cerebral oxygenation measured by near-infrared spectroscopy: A systematic review. *Progress in Neurobiology, 92*(2), 134–150.

Shibuya, K. I., Tanaka, J., Kuboyama, N., & Ogaki, T. (2004). Cerebral oxygenation during intermittent supramaximal exercise. *Respiratory Physiology & Neurobiology, 140*(2), 165–172.

Stone, B. L., Beneda-Bender, M., McCollum, D. L., Sun, J., Shelley, J. H., Ashley, J. D., … Kellawan, J. M. (2020). Understanding cognitive performance during exercise in Reserve Officers' Training Corps: Establishing the executive function-exercise intensity relationship. *Journal of Applied Physiology, 129*(4), 846–854.

Takeda, T., Kawakami, Y., Konno, M., Matsuda, Y., Nishino, M., Suzuki, Y., … Sakatani, K. (2017). PFC blood oxygenation changes in four different cognitive tasks. *Oxygen Transport to Tissue XXXIX*, 199–204.

Tempest, G. D., & Reiss, A. L. (2019). The utility of functional near-infrared spectroscopy for measuring cortical activity during cycling exercise. *Medicine and Science in Sports and Exercise, 51*(5), 979–987.

Tingley, D., Yamamoto, T., Hirose, K., Keele, L., & Imai, K. (2014). Mediation: R package for causal mediation analysis. *Journal of Statistical Software, 59*(5), 1–38.

Tomporowski, P. D., & Qazi, A. S. (2020). Cognitive-motor dual task interference effects on declarative memory: A theory-based review. *Frontiers in Psychology, 11*, 1015.

Wassenaar, E. B., & Van den Brand, J. G. H. (2005). Reliability of near-infrared spectroscopy in people with dark skin pigmentation. *Journal of Clinical Monitoring and Computing, 19*(3), 195–199.

Welch, A. S., Hulley, A., Ferguson, C., & Beauchamp, M. R. (2007). Affective responses of inactive women to a maximal incremental exercise test: A test of the dual-mode model. *Psychology of Sport and Exercise, 8*(4), 401–423.