

# Effect of acute high-intensity intermittent exercise on choice reaction time and its related prefrontal cortex hemodynamic change

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## Abstract:

**Introduction.** An acute bout of exercise is associated with an increased cognitive performance and oxygenation levels in the cortical areas of human brain. **Aim of Study.** In the current study we evaluated the effect of acute bout of high-intensity intermittent exercise (HIIE) on choice reaction time (CRT) and the associated changes in the prefrontal cortex (PFC) hemodynamic function in young adults. **Material and Methods.** Twenty-five participants (12 males and 13 females) were included in a randomized crossover trial with control and HIIE sessions in a counterbalanced order. (VTS) was used to assess CRT during various sessions. Functional near-infrared spectroscopy system was used to evaluate cortical hemodynamic changes during the cognitive task. **Results.** Results showed a significant decrease in CRT ( $p < 0.001$ ) and motor time ( $p < 0.001$ ) following the HIIE intervention. HIIE showed a significant ( $p < 0.05$ ) effect on hemodynamics of bilateral dorsolateral PFC and bilateral frontopolar areas of PFC. **Conclusions.** CRT performance is improved in response to a single session of HIIE. These improvements are associated with the changes in hemodynamics of PFC. This information helps to understand relationship between HIIE, cognitive domains and its associated PFC activation.

**KEYWORDS:** functional near-infrared spectroscopy, reaction time, prefrontal cortex, dorsolateral prefrontal cortex, frontopolar area.

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## Introduction

Recent literature has advanced the knowledge about the acute effect of exercise on cognitive functioning. Previous research has shown that an acute bout of exercise is associated with increased concentrations of oxygen in specific cortical areas of the human brain and that it enhances cognitive performance [1-3], including improvements of measures such as choice reaction time [4]. Existing studies have rarely examined how high-intensity intermittent exercise (HIIE) influences both behavioral responses—such as choice reaction time (CRT)—and concurrent cortical hemodynamic changes measured through Functional Near-Infrared Spectroscopy (fNIRS). To address this gap, the present study investigates the combined effects of acute HIIE on CRT and the associated prefrontal cortex (PFC) hemodynamic responses in young adults.

Simple reaction time refers to the duration between the appearance of a single repeated cue and the initiation of a specific response to that cue, whereas CRT refers to the duration between the appearance of one of several cues and the initiation of a corresponding response to each specific cue [5]. Typically, CRT is measured using the Lafayette Reaction Time Apparatus for visual choice reaction time [6], an auditory choice reaction task [7], or a computer-based visual reaction time task

[8]. Stimuli in these tasks may be auditory [9] during, and after 40 min of ergometer cycling. In a separate session, the same sequence of testing was completed while seated on an ergometer without pedalling. Results indicate that exercise (1), visual [8] or spatial cues [10]. One such test is the Reaction Test of Vienna Test System (VTS), which measures CRT and has been shown to be a reliable [11] and valid tool for assessing audio-visual choice reaction performance [12].

Reaction time is influenced by physical exercises [13], with exercise intensity linearly affecting CRT [14]. Performance of CRT improves with exercise performed at high intensities, particularly at around lactate threshold [15]. However, little is known about the acute effects of HIIE on CRT. High-intensity intermittent exercise is an exercise regime performed at 80-90% of maximal heart rate ( $HR_{max}$ ), interspersed with intervals of rest or relative rest at lower intensities [16]. HIIE is a popular choice of daily activity among young people, as it has been shown to effectively increase metabolic activity and is therefore correlated with better weight management [17].

HIIE is an efficient exercise method for individuals with limited time, as it requires a relatively short duration (20-30 minutes) per session, yet has been consistently documented to produce positive health benefits [16, 18, 19]. These health benefits not only include improvements in cardiovascular, respiratory and musculoskeletal health but also positive effects on cognition.

Previous studies have demonstrated the release of several neurotransmitters, such as noradrenaline, serotonin and acetylcholine, from various brain nuclei that project to and interact with the PFC [20].

This region of the brain plays an important role in the functioning of CRT [10]. Changes in PFC functioning during a CRT task can be measured using a non-invasive optical imaging technique known as fNIRS [21, 22]. It is a modern technique that assesses cortical activation patterns by measuring changes in the concentration of oxygenated (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) [23, 24] through the absorption of near-infrared spectrum light by the hemoglobin molecules. This technique is based on the Modified Beer-Lambert Law and is used to assess cortical activation with high temporal resolution [24] compared with other neuroimaging techniques such as fMRI or PET scan. Although acute changes in the hemodynamic functioning of PFC during different cognitive tasks [25, 26] have been described in response to various exercise interventions, little attention has been directed toward the neural processes underlying choice reaction

functioning. Changes in cortical hemodynamics during CRT performance have been assessed in older adults in one study [7]. However, the effect of exercise on hemodynamic functions of PFC has not been well understood. We hypothesized that HIIE would improve CRT performance and it would influence the hemodynamic functions of PFC areas.

### Aim of Study

Hence, this study aimed to evaluate the effect of an acute bout of HIIE on CRT performance and the associated changes in PFC hemodynamic functions in young adults.

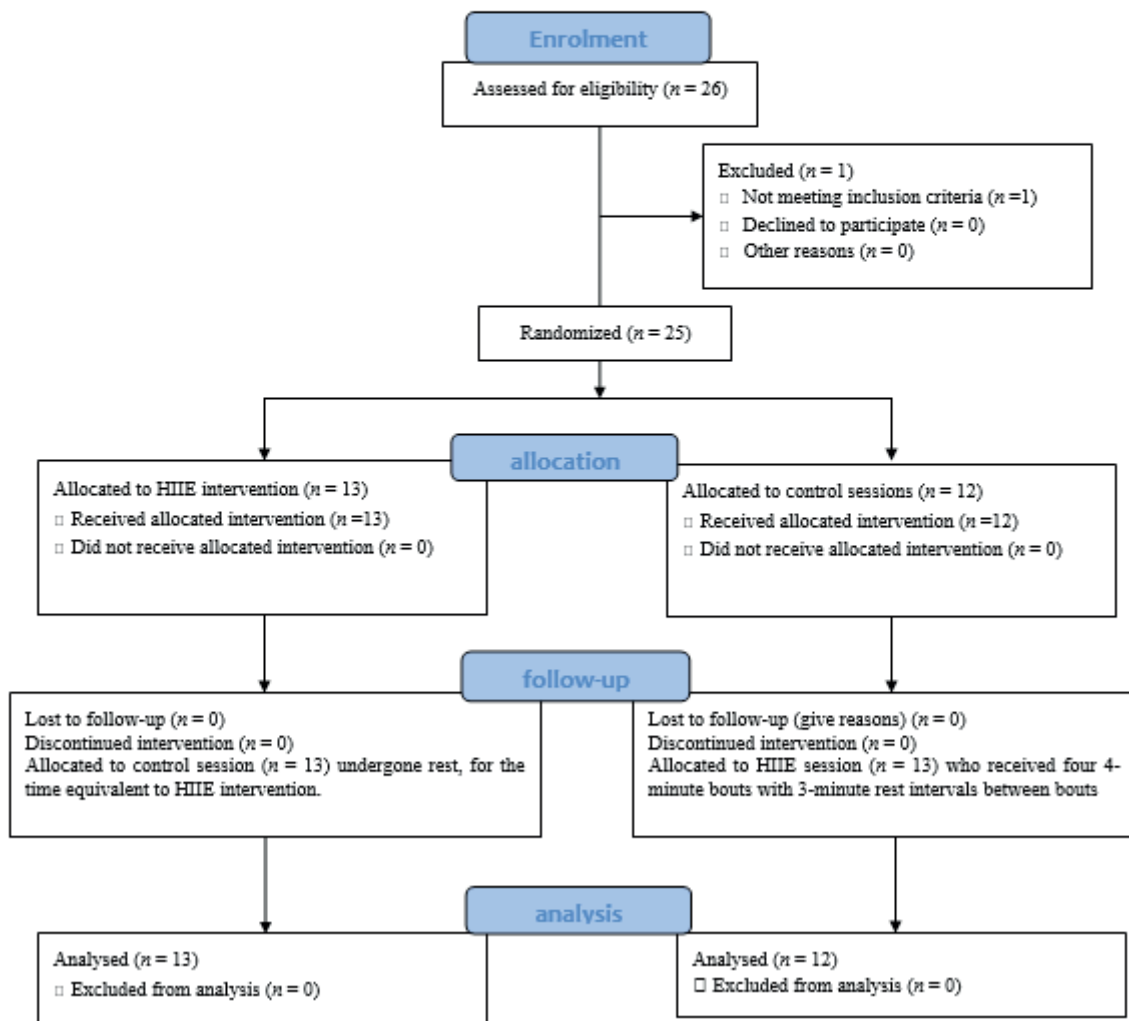
### Material and Methods

Participants volunteered from different departments of the university. The CONSORT 2010 statement (Figure 1) was used to report enrollment, allocation and follow-up of participants in the experimental trials [27]. Using G\*Power (version 3.1.9.4, Germany), a sample size of 22 was determined assuming an effect size of 0.60, a significance level of 5%, and a statistical power of 80%. Twenty-five participants (12 males and 13 females), aged 18 to 30 years, took part in this study. Simple random sampling using the fish-bowl method (participants drew slips to determine session order) was used to randomize study participants. Using a crossover trial design, participants were randomly assigned to complete the control and HIIE sessions in a counterbalanced order. Allocation concealment was maintained by having an independent researcher prepare folded slips for the fish-bowl draw, ensuring that the investigators conducting the sessions could not predict the assignment. CRT performance, oxy- and deoxy-Hb concentrations were considered primary outcomes measures, whereas motor time was treated as a secondary outcome measure.

It was a randomized crossover trial with 25 participants (12 males, 13 females). Participants were healthy, right-handed adults aged 18–30 years with normal or corrected-to-normal vision and hearing, free from any known neurological, psychiatric, cardiovascular, or metabolic disorders, and able to safely perform high-intensity intermittent exercise based on the PAR-Q screening. Individuals were required to be medication-free from substances that could influence cardiovascular responses, cortical hemodynamics, reaction time, or cognitive performance (e.g., beta-blockers, stimulants, sedatives). Participants were excluded if they had any orthopedic or musculoskeletal injury that limited safe cycling; used psychoactive substances or excessive caffeine close to testing; consumed alcohol within the



## CONSORT 2010 flow diagram



**Figure 1.** CONSORT 2010 flow diagram

previous 24 hours; had inadequate sleep; or exhibited poor fNIRS signal quality due to excessive hair density or unresolved motion artifacts. Additional exclusion criteria included inability to comply with pre-session restrictions, failure to complete both HIIE and control sessions, and any factor preventing proper optode placement. All participants were required to understand task instructions and provide written informed consent prior to participation.

Data analysts who processed the CRT and fNIRS datasets were masked to session identity to minimize analytical bias. CRT testing began immediately after a 5-7-min cool-down. This period was identical for all the participants. During the control session, participants remained seated quietly for a duration matched to the full length of the HIIE visit (~25-30 minutes, including the time corresponding to warm-up, work bouts, recovery intervals, and cool-down). They were

instructed to sit comfortably on a chair in an upright posture, keep their feet flat on the floor, and refrain from physical movements, stretching, or fidgeting. The testing environment, including room temperature, lighting, and noise level, was kept identical to that of the HIIE session. For HIIE session, they performed exercise on bicycle ergometer for a comparable duration.

To verify protocol fidelity, objective and subjective exercise-intensity markers were recorded during the HIIE session. Heart rate (HR) was monitored continuously throughout all high-intensity and recovery intervals, and the mean and peak HR values achieved during each bout were documented. Subjective exertion was measured using the Borg 6-20 Rating of Perceived Exertion (RPE) scale and recorded during each high-intensity interval.

The post-exercise testing window was standardized across all participants. CRT testing began immediately after completion of the cooldown period, which lasted 5-7 minutes, resulting in a consistent post-exercise delay of approximately 5-7 minutes for all visits.

There was a gap of at least 2 weeks between control and HIIE sessions in order to minimize learning the cognitive task. The long-form of International Physical Activity Questionnaire (IPAQ) was used to evaluate participants' physical activity (PA) level (low, moderate, or high). Participants' sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI). We ensure that our manuscript complies with the STROBE guidelines.

Participants within the specified age range and with normal or corrected-to-normal vision were involved in the study. Participants were excluded if they reported any neurological or psychological disorder, or if they had a history of prolonged use of medications for systemic conditions such as diabetes, thyroid disorder, heart disease, or hypertension. A proforma capturing age, gender, height, weight and relevant past medical history was completed by the participants. The testing procedures were explained to all participants and written informed consent was obtained from each individual before the assessments began. Necessary Ethical approval [28] for the study was obtained from the Institutional Ethics Committee of the university.

#### *Exercise protocol*

The exercise intervention consisted of four 4-minute bouts ( $4 \times 4$ ) performed at 90-95% of  $HR_{max}$ , each separated by 3 minutes of active recovery at 70%  $HR_{max}$  [29], using a Lode Corival BV (Netherlands) bicycle ergometer. HR was continuously monitored using

a Polar HR monitor (Polar Vantage V Pro Multisport Watch).  $HR_{max}$  (beats/min) was calculated using the formula [29]:  $HR_{max} = 206.9 - 0.67 \times \text{age (y)}$

Cycling according to the above-mentioned protocol was preceded by a 3-minute warm-up and was followed by a 2-minute cool-down, performed at a cycling frequency of participant's choice and at an intensity corresponding to 8-12 on the 20-point Borg RPE scale [30] through functional near infrared spectroscopy (fNIRS). During each high-intensity bout, cycling power was maintained between 100 and 150 Watts, with an intensity of 15-18 on the Borg RPE scale. During the recovery periods, cycling was performed without resistance at an intensity of 8-12 on the Borg RPE scale. Cycling intensity was recorded one minute after of the beginning of each high-intensity bout and immediately after its completion [31]. A 5-7-minute cool-down phase at light intensity followed the interval block. Thus, the complete HIIE session - including the warm-up, interval sequence, and cool down - lasted approximately 30-32 minutes. The control session was matched in total duration, during which participants sat quietly for an equivalent period without engaging in any exercise.

#### *Reaction Test*

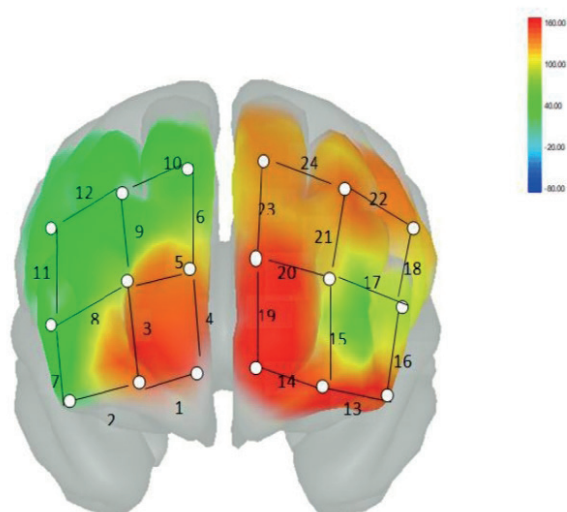
The S3 test form of the Reaction Test from the Vienna Testing System (SCHUHFRIED, Austria) was used to assess attention using a CRT test. It was an auditory-visual CRT task in which participants were instructed to react as quickly as possible when a yellow visual stimulus and a 2000-Hz beep occurred simultaneously. In this test, participants kept their finger on the gold button for the entire duration, lifting it only to press the black button when they perceived the target stimuli. One practice session was provided before the start of the actual test. A total of 48 stimuli were presented at random intervals, with 2-4 seconds between the stimuli to reduce the predictability of their occurrence. Scoring was recorded in milliseconds for variables: mean reaction time, mean motor time and the dispersion of both variables. It does not provide trial-level information on accuracy, omissions, or commission errors. Therefore, accuracy-related analyses could not be conducted. This is a standardized, computerized neuropsychological test that assesses both the cognitive decision component (reaction time) and the motor execution component (motor time) in response to multi-stimulus inputs. The VTS-RT employs a choice-response format in which participants must rapidly discriminate and select the correct response among multiple alternatives. The system outputs RT and motor time in milliseconds and

does not provide accuracy or error-type metrics. The same CRT module was used for all participants across both HIIE and control sessions.

#### *Evaluation of PFC hemodynamic changes*

A continuous-wave fNIRS system (Brite, Artinis Medical Systems, Netherlands) was used to assess oxy- and deoxy-hemoglobin concentrations in the PFC during the cognitive task. Eighteen optodes were arranged over the PFC using a soft neoprene cap, forming 24 channels (Figure 2) such that each side of the PFC was covered by 12 channels, in accordance with the international 10–20 system to ensure standardized placement. The arrangement covered key regions of interest, including the dorsolateral PFC (DLPFC), ventrolateral PFC (VLPFC), and the frontopolar area (FPA) as shown in Figure 3.

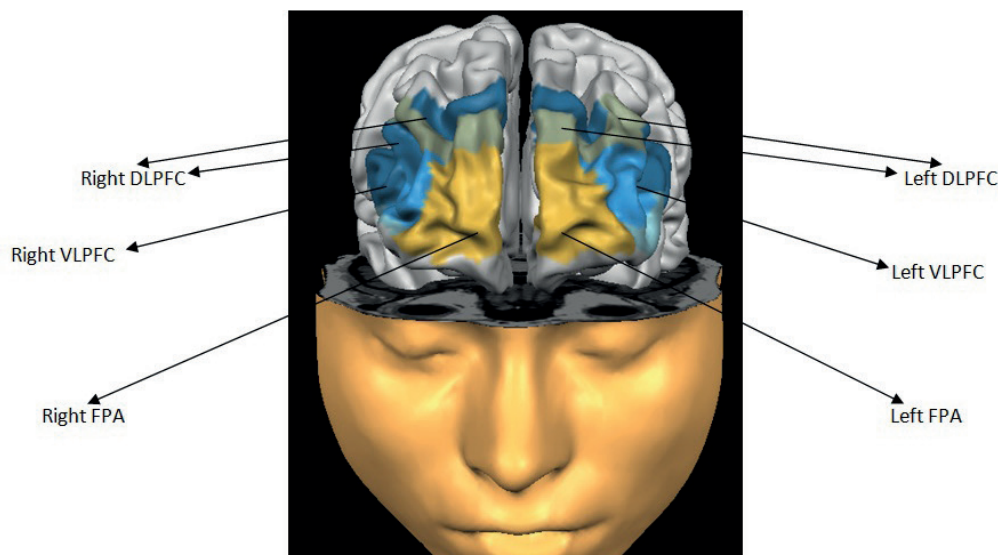
Care was taken to minimize signal interference by ensuring proper contact between the optodes and the scalp. The system recorded changes in cerebral oxygenation based on near-infrared light absorption, allowing estimation of task-related variations in oxy-Hb and deoxy-Hb levels. Hemodynamic responses were measured during two phases: a baseline period, during which participants sat quietly, and the CRT task period. This setup enabled the examination of cortical activation patterns associated with cognitive processing during the reaction-time task.



The figure above shows the location of the 24 channels over the bilateral PFC. The light-emitting and light-receiving optodes were positioned according to topographic probe layout map based on the standard EEG 10-20 coordinate system.

**Figure 2.** Representation of the fNIRS 24-channel setup over the PFC using a 3D cortical mesh view

fNIRS data were pre-processed using standard procedures described in recent methodological reviews [21, 23, 24]. The raw light-intensity signals were first converted to optical density. To reduce noise, low-amplitude or poor-quality channels were identified and



The figure above demonstrates the six ROIs over the bilateral PFC using a 3D cortex representation. The image was obtained from BrainVoyager Brain Tutor. DLPFC refers to the dorsolateral prefrontal cortex, VLPFC to the ventrolateral prefrontal cortex, and FPA to the frontopolar area, with Rt and Lt indicating the right and left hemispheres, respectively. Hemoglobin measures include oxy-Hb, representing oxygenated hemoglobin concentration, and deoxy-Hb, representing deoxygenated hemoglobin concentration, both expressed in micromolar units ( $\mu\text{mol}$ ).

**Figure 3.** Regions of interest over the prefrontal cortex

removed using prune-channel filter, applying standard deviation range of 0-45 [32]. Systematic artifacts were then attenuated using a principal component-based correction approach [33]. Channels with low amplitude were excluded from group-level processing, as such channels fail to accurately represent underlying neural activity and can compromise the measurement of cerebral hemodynamics [34]. Motion-related disturbances were managed in two steps. Spline interpolation was applied to segments containing abrupt movement. Wavelet-based filtering was then used to suppress sharp spikes typically produced by minor head movements [35]. To improve physiological interpretability, the signals were band-pass filtered to remove slow drifts and high-frequency noise. After filtering, the modified Beer-Lambert law was applied to compute changes in oxy-Hb and deoxy-Hb concentrations [32, 36]. Finally, block-averaging was performed to obtain a representative hemodynamic response during the CRT task for each region of interest. These averaged responses were compared between the HIIE and control conditions across all six predefined regions of interest (ROIs). Recent evidence highlights that post-exercise timing can influence cognitive and neural responses [1, 3, 37, 38], and our standardized testing window ensured consistent evaluation of hemodynamics immediately after exercise.

The optodes were positioned according to the topographic probe-layout map and the international EEG 10-20 coordinate system [39-41], and channel grids were arranged to cover the regions of ROIs in each hemisphere. The Montreal Neurological Institute (MNI) coordinate system was used to define the ROI spaces, following careful measurement of scalp landmarks and fNIRS optode positions using the 3D scalp-projection method [42] (Participants were individually fitted with a soft neoprene retaining cap that housed all source and detector fibers. This arrangement gave a total of 24 measurement channels (12 per hemisphere) with an emitter-detector separation of ~3 cm. Channels are marked by connecting lines and numbered for identification in Figure 2 [43]. The lab temperature was maintained between 15°C and 25°C during data acquisition.

We focused on examining changes in both oxy-Hb and deoxy-Hb concentrations during the cognitive task because oxy-Hb reflects oxygen delivery to the cortical tissue, whereas deoxy-Hb indicates oxygen consumption by the underlying neural tissue [21, 33]. Deoxy-Hb concentration is considered a more accurate predictor

of overall neural processing than oxy-Hb because oxy-Hb is more susceptible to extra-cerebral influences such as heartbeat or scalp blood-flow changes [35]. Increased activation was defined as an increase in oxy-Hb accompanied by a decrease in deoxy-Hb within the region of interest. Increased deactivation was defined as a decrease in oxy-Hb together with an increase in deoxy-Hb. An increase in blood volume was indicated by concurrent increases in both oxy-Hb and deoxy-Hb concentrations, whereas a decrease in blood volume was indicated by simultaneous decreases in both oxy- and deoxy-Hb concentrations.

#### *Statistical analysis*

Normality of the data was assessed using the Shapiro-Wilk test. Choice reaction-time score were compared between the HIIE and control sessions using a  $2 \times 2$  ANOVA (time: pre vs. post x session: HIIE/control). A paired t-test was used to determine the difference in post-sessions compared to pre-sessions during both the HIIE and control conditions. To examine potential crossover and carryover effects, participants were categorized according to session order (HIIE-first vs. control-first). For each participant, treatment effects were calculated as the difference between the HIIE and control sessions at post-test (e.g.,  $\Delta CRT = CRT\_Post\_HIIE - CRT\_Post\_Control$ ;  $\Delta motor\ time = MT\_Post\_HIIE - MT\_Post\_Control$ ). These treatment effects were then compared between sequence groups using independent-samples t-tests. Baseline (pre) values were also compared between sequences to assess possible period effects.

As described earlier, the unprocessed fNIRS signals were pre-processed and converted into oxy-Hb and deoxy-Hb concentration changes, which were then mapped across six ROIs within the PFC. A  $2 \times 2$  repeated-measured ANOVA with time (pre vs. post) and session (HIIE vs. control) as within-subject factors was applied to compare oxy-Hb and deoxy-Hb concentrations across the six ROIs between the two sessions. Bonferroni post hoc test was applied for multiple comparisons. Effect sizes were reported as partial  $\eta^2$ , and the means for the reaction-test variables were presented with their corresponding standard deviation and standard error.

For fNIRS outcomes, multiple comparisons across the six ROIs were controlled using the Benjamini-Hochberg false discovery rate (FDR) procedure, applied separately for oxy-Hb and deoxy-Hb families (6 tests each). We report both uncorrected p values and FDR-adjusted q values, with  $q < 0.05$  considered statistically significant.

## Results

Table 1 presents the demographic characteristics of the participants, including age, BMI, resting HR, PA level and Pittsburgh Sleep Quality Index (PSQI) scores.

**Table 1.** Descriptive characteristics of the participants

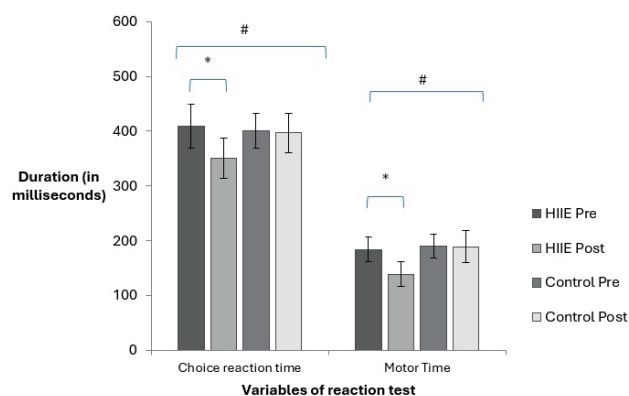
Variable	Mean ± standard deviation
Total number	25
Number of male/ female participants	12/13
Age (years)	22.50 ± 3.45
BMI (kg/m <sup>2</sup> )	22.25 ± 2.403
Resting HR (beats/min)	81.50 ± 13.3
HR during HIIE (beats/min)	151.17 ± 12.16
PA level (MET × min/week) (moderately active)	1743.76 ± 1276.90
PSQI score	3.09 ± 1.28 (good)
Mean Borg's rating of perceived exertion	16.2 ± 3.64 (during HIIE)

Note: BMI – body mass index; HR- heart rate, HIIE – high-intensity intermittent exercise, PA level – physical activity level measured by IPAQ, MET – metabolic equivalent, PSQI – Pittsburgh sleep quality index.

### Variation in reaction-time scores

A two-way ANOVA comparing CRT across the participants revealed a significant main effect of time (pre vs. post) [ $F(1,96) = 18.56, p < 0.001$ , partial  $\eta^2 = 0.162$ ], main effect of session (HIIE vs. control) [ $F(1,96) = 6.73, p = 0.01$ , partial  $\eta^2 = 0.066$ ]. In addition, a significant time × session interaction was observed, [ $F(1,96) = 14.07, p < 0.001$  partial  $\eta^2 = 0.128$ ], indicating that the HIIE intervention produced a greater improvement in CRT performance compared with the control condition. Post hoc analyses showed that CRT was significantly faster in the post-HIIE session compared with the pre-HIIE (Figure 4).

Motor time showed a similar pattern of results. A two-way ANOVA revealed a significant main effect of time (pre vs. post) [ $F(1,96) = 23.10, p < 0.001$ , partial  $\eta^2 = 0.195$ ] and a significant main effect of session (HIIE vs. control) [ $F(1,96) = 33.82, p < 0.001$ , partial  $\eta^2 = 0.261$ ]. A significant time × session interaction was also observed [ $F(1,96) = 20.231, p < 0.001$ , partial  $\eta^2 = 0.174$ ], indicating that the HIIE intervention produced a greater improvement in motor-time performance compared with the control condition. Post hoc analyses showed that motor time was significantly faster in the post-HIIE session compared with the pre-HIIE session (Figure 4).



The figure above illustrates the changes in mean choice reaction time and motor time (in milliseconds) across the pre-post and control-HIIE sessions. Error bars represent standard deviation. \* indicates a significant difference between pre- and post-session values at  $p < 0.05$  significance level. # indicates a significant difference between the high-intensity intermittent exercise session and the control session at  $p < 0.05$  significance level.

**Figure 4.** Variations in reaction time scores

Crossover order did not significantly influence the treatment effects on behavioral outcomes. The HIIE–control difference in CRT ( $\Delta$ CRT) was similar in participants who completed HIIE first (mean  $-44.0$  ms) and those who completed the control session first (mean  $-48.4$  ms;  $t \approx 0.12, p = 0.91$ ). Likewise, the HIIE–control difference in motor time ( $\Delta$ motor time) did not differ between HIIE-first (mean  $-67.4$  ms) and control-first (mean  $-45.2$  ms) sequences ( $t \approx -0.61, p = 0.56$ ). Baseline pre-test values for CRT and motor time in both sessions did not differ between sequence groups (all  $p > 0.20$ ). These findings indicate no detectable order or carryover effects; therefore, data were pooled across session order for the main analyses.

Directional consistency analyses showed that 23 of 25 participants (92%) exhibited faster CRT ( $\Delta$ CRT  $< 0$ ) and 24 of 25 participants (96%) exhibited faster motor time ( $\Delta$ MT  $< 0$ ) after HIIE compared with the pre-session, indicating that the observed benefits were robust and not driven by a small subset of responders. In contrast, in the control session only 18 of 25 participants (72%) showed faster CRT and 16 of 25 (64%) showed faster motor time, and the mean pre–post changes were small. This pattern indicates that improvements were more consistent and larger in magnitude following HIIE than during the non-exercise control condition.

### Variations in prefrontal cortex hemodynamic functions

After Benjamini–Hochberg FDR correction across the six oxy-Hb ROIs, significant session effects remained

in right DLPFC, right VLPFC, right FPA, and left FPA (all  $q < 0.001$ ), whereas left DLPFC and left VLPFC did not survive correction ( $q \geq 0.62$ ). For deoxy-Hb, all regions except left FPA remained significant after FDR ( $q \leq 0.023$ ). Within-session pre–post comparisons showed significant oxy-Hb changes in all ROIs except right VLPFC after FDR correction ( $q \leq 0.012$ ). For deoxy-Hb, significant pre–post effects remained in right FPA, left VLPFC, and left FPA ( $q \leq 1.8 \times 10^{-2}$ ), whereas other regions did not survive FDR adjustment.

There was no significant area of increased activation (increased oxy- and deoxy-Hb) out of the six ROIs. However, paired t-test revealed a significant deactivation (decreased oxy-Hb and increased deoxy-Hb) of right DLPFC ( $t_{\text{oxy}} = 14.59$ ,  $p_{\text{oxy}} < 0.001$ ,  $t_{\text{deoxy}} = -4.23$ ,  $p_{\text{deoxy}} < 0.001$ ) area of PFC in post-session compared to pre-session. There were two areas, left DLPFC ( $t_{\text{oxy}} = -6.42$ ,  $p_{\text{oxy}} < 0.001$ ,  $t_{\text{deoxy}} = -4.23$ ,  $p_{\text{deoxy}} < 0.001$ ) and left VLPFC ( $t_{\text{oxy}} = -3.44$ ,  $p_{\text{oxy}} = 0.001$ ,  $t_{\text{deoxy}} = -12.86$ ,  $p_{\text{deoxy}} < 0.001$ ), in which an increased blood volume (increased oxy-Hb and increased deoxy-Hb) was found. A significant increase in activation (increased oxy-Hb and decreased deoxy-Hb) was observed in right DLPFC ( $t_{\text{oxy}} = -6.96$ ,  $p_{\text{oxy}} < 0.001$ ,  $t_{\text{deoxy}} = 2.27$ ,  $p_{\text{deoxy}} = 0.027$ ) and left VLPFC ( $t_{\text{oxy}} = -6.99$ ,  $p_{\text{oxy}} < 0.001$ ,  $t_{\text{deoxy}} = 7.79$ ,  $p_{\text{deoxy}} < 0.001$ ) after the HIIE session. A significant deactivation was seen in right FPA ( $t_{\text{oxy}} = 7.12$ ,  $p_{\text{oxy}} < 0.001$ ,  $t_{\text{deoxy}} = -7.69$ ,  $p_{\text{deoxy}} < 0.001$ ), whereas there was a significantly increased volume of blood in right VLPFC ( $t_{\text{oxy}} = -3.53$ ,  $p_{\text{oxy}} = 0.01$ ,  $t_{\text{deoxy}} = -9.95$ ,  $p_{\text{deoxy}} < 0.001$ ) and left DLPFC ( $t_{\text{oxy}} = 3.23$ ,  $p_{\text{oxy}} = 0.02$ ,  $t_{\text{deoxy}} = 2.48$ ,  $p_{\text{deoxy}} = 0.016$ ) in response to HIIE. However, left FPA showed no significant difference in activation in response to the HIIE intervention.

A two-way ANOVA demonstrated a significant main effect of time (pre vs. post) on oxy-Hb concentration in the right DLPFC [ $F(1,96) = 24.37$ ,  $p < 0.001$ , partial  $\eta^2 = 0.203$ ], right FPA [ $F(1,96) = 50.42$ ,  $p < 0.001$ , partial  $\eta^2 = 0.344$ ], left DLPFC [ $F(1,96) = 18.35$ ,  $p < 0.001$ , partial  $\eta^2 = 0.160$ ], left VLPFC [ $F(1,96) = 18.35$ ,  $p < 0.001$ , partial  $\eta^2 = 0.160$ ] and left FPA [ $F(1,96) = 40.77$ ,  $p < 0.001$ , partial  $\eta^2 = 0.29$ ]. There was a significant main effect of time (pre vs. post) on deoxy-Hb concentration in the right VLPFC [ $F(1,96) = 29.91$ ,  $p < 0.001$ , partial  $\eta^2 = 0.238$ ] and left FPA [ $F(1,96) = 32.03$ ,  $p < 0.001$ , partial  $\eta^2 = 0.250$ ]. There was no other significant main effect of time on other variables. Altogether, the left FPA showed a significant main effect of time (pre vs. post), indicating an increase in blood volume – reflected by concurrent increases in

oxy-Hb and deoxy-Hb – in this PFC region during the post-session compared with the pre-session.

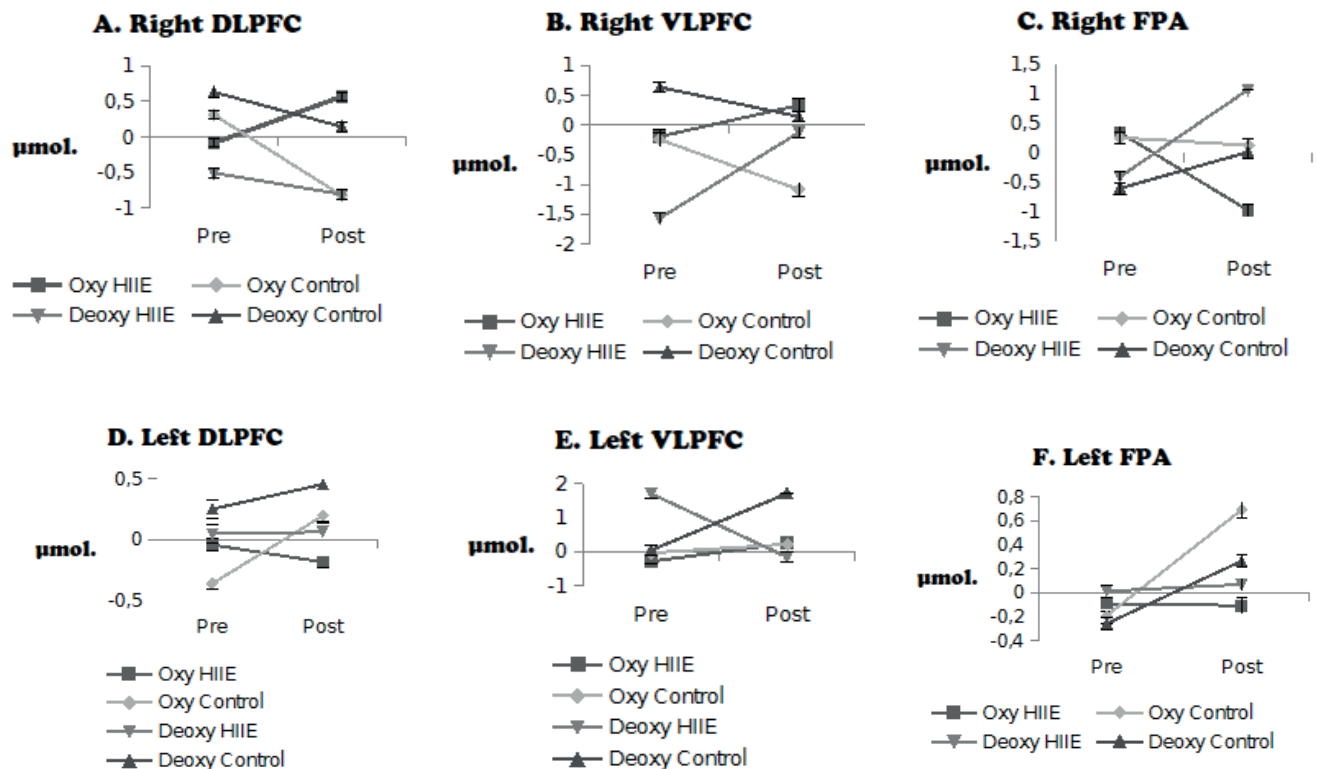
A significant main effect of session (HIIE vs. control) was observed in the oxy-Hb concentration across specific regions, including the right DLPFC [ $F(1,96) = 29.15$ ,  $p < 0.001$ , partial  $\eta^2 = 0.228$ ], right VLPFC [ $F(1,96) = 38.60$ ,  $p < 0.001$ , partial  $\eta^2 = 0.287$ ], right FPA [ $F(1,96) = 24.82$ ,  $p < 0.001$ , partial  $\eta^2 = 0.205$ ], left VLPFC [ $F(1,96) = 4.003$ ,  $p = 0.048$ , partial  $\eta^2 = 0.040$ ] and left FPA [ $F(1,96) = 26.52$ ,  $p < 0.001$ , partial  $\eta^2 = 0.216$ ]. A significant main effect of session was observed on deoxy-Hb concentration in the right DLPFC [ $F(1,96) = 27.06$ ,  $p < 0.001$ , partial  $\eta^2 = 0.218$ ]. Thus, overall, there was significantly greater activation in the right DLPFC during the HIIE session compared with the control session, reflected by higher oxy-Hb and lower deoxy-Hb concentrations.

A significant time  $\times$  session interaction effect was observed on oxy-Hb concentration in the right DLPFC [ $F(1,96) = 27.35$ ,  $p < 0.001$ , partial  $\eta^2 = 0.219$ ], right VLPFC [ $F(1,96) = 33.49$ ,  $p < 0.001$ , partial  $\eta^2 = 0.259$ ], right FPA [ $F(1,96) = 34.02$ ,  $p < 0.001$ , partial  $\eta^2 = 0.262$ ], left DLPFC [ $F(1,96) = 51.76$ ,  $p < 0.001$ , partial  $\eta^2 = 0.350$ ], left VLPFC [ $F(1,96) = 7.04$ ,  $p = 0.009$ , partial  $\eta^2 = 0.068$ ] and left FPA [ $F(1,96) = 43.91$ ,  $p < 0.001$ , partial  $\eta^2 = 0.314$ ]. A time  $\times$  session interaction effect was observed on deoxy-Hb concentration in the right DLPFC [ $F(1,96) = 13.92$ ,  $p < 0.001$ , partial  $\eta^2 = 0.127$ ], right FPA [ $F(1,96) = 18.32$ ,  $p < 0.001$ , partial  $\eta^2 = 0.160$ ], left DLPFC [ $F(1,96) = 14.02$ ,  $p < 0.001$ , partial  $\eta^2 = 0.127$ ] and left FPA [ $F(1,96) = 20.98$ ,  $p < 0.001$ , partial  $\eta^2 = 0.179$ ]. Overall, the results demonstrate that HIIE has a significant effect on the specific regions, including the right DLPFC, right FPA, left DLPFC and left FPA. Detailed changes in oxy- and deoxy-Hb concentrations are presented in Figure 5.

The pattern of significant vs. non-significant results remained identical before and after FDR correction.

## Discussion

We examined the effect of an acute 25-minute bout of HIIE, compared to resting conditions, on CRT, measured using the reaction test from the VTS. We also assessed changes in PFC hemodynamic functions associated with the reaction test in young adults. We found a significant effect of the HIIE intervention on reaction-time variables, indicating improved CRT following the exercise intervention. A significant effect was also observed in the activation of several PFC regions, indicating that HIIE may contribute to PFC-mediated improvements in CRT.



The figure above demonstrates changes in the mean concentration of uncorrected oxygenated and deoxygenated hemoglobin ( $\mu\text{mol}$ ) during the pre-, post-, high-intensity intermittent exercise session and control sessions across the following regions of interests: (A) right DLPFC (dorsolateral prefrontal cortex), (B) right VLPFC (ventrolateral prefrontal cortex), (C) right FPA (frontopolar area), (D) left DLPFC, (E) left VLPFC and (F) left FPA. Error bars represent standard error values.

**Figure 5.** Variation in oxygenated and deoxygenated hemoglobin concentration before and after the control and HIIE sessions

#### *Effect on choice reaction time*

Two variables were assessed using the reaction test from the VTS: CRT and motor time. CRT is the time between the onset of a relevant stimulus and the moment the finger leaves the rest button, whereas motor time is the interval between the finger leaving the rest button and making contact with the reaction button.

Beyond the group-level improvements in CRT and motor time, the consistent direction of individual responses further strengthens the robustness of our findings. In the present study, the large majority of participants showed performance improvements in the same direction after HIIE, with 92% exhibiting faster CRT and 96% exhibiting faster motor time relative to their own pre-exercise values. This pattern indicates that the observed benefits were not driven by a small subset of highly responsive individuals but instead reflected a broad, population-level effect of HIIE on cognitive-motor performance. In contrast, the control condition showed comparatively lower consistency (72% for CRT and 64% for motor time), suggesting that simple

test repetition or practice effects cannot fully account for the magnitude or uniformity of the HIIE-related improvements. Such strong directional agreement across participants highlights that acute HIIE elicits a reliable and biologically consistent enhancement in reaction-time performance and supports the generalizability of these effects to young healthy adults.

Both of these are measured in milliseconds. The first variable is related to the ability to quickly react to a relevant stimulus, whereas the second variable is related to the ability to implement the intended action quickly in a given situation. Altogether, this represents the time required for the brain to select an appropriate response strategy and initiate corresponding action to produce an accurate reaction. Previous research has been focusing on the techniques and methods to further decrease this time, as doing so can enhance performance in various aspects of daily life, including sports or demanding tasks such as driving. Past literature [13] has described an inverted-U relationship of exercise intensity and CRT, with high-intensity

exercise leading to decreased performance. Fifteen to twenty minutes of continuous high-intensity steady-state exercise improved performance of CRT in young adults [9]. In agreement with these findings, breaking high-intensity bouts into small periods of low-intensity active recovery periods also improved CRT performance in our study. This indicates that CRT is influenced by total exertion caused by exercise and not merely by the intensity of exercise.

We observed a decrease in motor time in response to HIIE in our study. Exercise sessions lasting more than 15-20 minutes elevate muscle and core temperature [44], which increases the conduction velocity of muscle fibers and peripheral nerves. This, in turn, enhances motor control, which was reflected in the improved motor-time performance observed in this study. We observed co-occurring changes in the hemodynamic responses within the specific ROIs described below, which help explain the physiological mechanisms underlying the HIIE-related effects observed in this study.

#### *Effect on PFC hemodynamic changes*

We found clear difference in the regions of activation during the HIIE and control sessions. Specific regions, for example the right DLPFC and left VLPFC, were activated in response to the HIIE session, but not during the control session. In contrast, other regions, such as the right FPA, were deactivated in response to HIIE, but did not show comparable deactivation during the control session. This finding may suggest that better task performance was associated with a reallocation of neural resources, as changes in activation patterns in fNIRS studies [45, 46] have been linked to improved cognitive performance.

HIIE produced a robust activation in the right DLPFC ( $\sim +0.4\text{-}0.5$   $\mu\text{mol oxy}$ ;  $-0.15\text{-}0.20$   $\mu\text{mol deoxy}$ ) and moderate activation in the right VLPFC ( $\sim +0.25\text{-}0.30$   $\mu\text{mol oxy}$ ;  $-0.10$   $\mu\text{mol deoxy}$ ), while the right FPA showed deactivation ( $\sim -0.20\text{-}0.30$   $\mu\text{mol oxy}$ ;  $+0.15\text{-}0.20$   $\mu\text{mol deoxy}$ ) and the left FPA exhibited increased blood volume ( $\sim +0.20\text{-}0.25$   $\mu\text{mol oxy}$ ;  $+0.10\text{-}0.15$   $\mu\text{mol deoxy}$ ).

On the basis of the observed activation measures, a significant effect of HIIE was observed on specific regions, including the right DLPFC, right FPA, left DLPFC and left FPA. The dorsolateral regions of the PFC (DLPFC) are involved in top-down attention control (defined as the internal guidance of attention based on prior knowledge, intentional plans, and current goals) and are activated during higher-order aspects of motor control, such as movement selection and planning [47].

The frontopolar regions (FPA) are responsible for goal-directed behavior in humans [48]. One explanation for our findings could be that these behavioral models share similarities with the reaction-time task we used in our study. Thus, it can be postulated that activation of these related areas translated into improved performance on the behavioral task in response to HIIE in our study.

Another possible explanation is the release of several neurotransmitters, such as noradrenalin, dopamine, acetylcholine and serotonin, from the brain [20]. Acute exercise influences the release of noradrenalin and dopamine across several brain regions [49]. Noradrenaline is involved in activating the DLPFC, anterior cingulate cortex and hippocampus – regions associated with cognitive processing and responsible for a more efficient allotment of neural resources [50]. The dopaminergic system, which originates in the midbrain, has neural projections to several brain regions – including the PFC, amygdala and hippocampus – and contributes to the activation of these regions, which support functions related to motor control and decision making. Activation of these areas could potentially regulate the reaction task response. Thus, it can be postulated that acute HIIE has a similar activating role in enhancing PFC engagement during the choice reaction-time task.

After Benjamini–Hochberg FDR correction (Table S1, Supplementary Materials) across the six oxy-Hb ROIs, significant Session effects remained in the right DLPFC, right VLPFC, right FPA, and left FPA (all  $q < 0.001$ ), whereas the left DLPFC and left VLPFC did not survive correction ( $q \geq 0.62$ ). For deoxy-Hb, all regions except the left FPA remained significant after FDR ( $q \leq 0.023$ ). Within-session Pre–Post comparisons after Benjamini–Hochberg FDR correction (Table S2, Supplementary Materials) showed significant oxy-Hb changes in all ROIs except the right VLPFC ( $q \leq 0.012$ ). For deoxy-Hb, significant Pre–Post effects remained in the right FPA, left VLPFC, and left FPA ( $q \leq 1.8 \times 10^{-2}$ ), whereas the other regions did not survive FDR adjustment.

The interpretation of fNIRS findings warrants caution, particularly in the context of acute post-exercise physiology. Increases in oxy-Hb accompanied by concurrent decreases in deoxy-Hb are typically interpreted as reflecting enhanced neural activation driven by elevated cerebral metabolic demand. However, increases in both oxy-Hb and deoxy-Hb can instead reflect changes in cerebral or extracerebral blood volume rather than neural activation per se. While the regional patterns and consistency across participants support genuine task-related modulation of prefrontal activity, the present

results should be interpreted as reflecting a combination of neural and systemic hemodynamic contributions, rather than unequivocal evidence of isolated cortical activation.

### *Limitations*

There were certain limitations related to our study. Several alternative explanations and potential moderators should be considered when interpreting these findings. First, although improvements in CRT and motor time followed HIIE, these changes could partially reflect heightened arousal rather than exercise-specific cognitive enhancement; however, the minimal changes in the control condition argue against a simple arousal-only account.

Second, a possible factor that may have influenced the observed improvements in reaction time is the learning effect associated with repeated exposure to the psychological tests. Reaction-time assessments, particularly those involving computerized choice-reaction tasks, are known to show performance improvements simply due to increased familiarity with the test procedure, stimulus–response patterns, and motor requirements rather than genuine physiological or cognitive changes. Participants often demonstrate faster responses during subsequent trials as they become more accustomed to the testing interface, anticipate the task structure, or develop more efficient cognitive-motor strategies. In the context of the present study, although a randomized crossover design and counterbalanced session order were employed, the possibility of a practice-related improvement cannot be fully excluded. Repeated administration of the VTS's CRT task may have contributed partially to the reduction in CRT and motor time observed across sessions. This learning effect may confound the interpretation of whether the improvements are solely attributable to the acute high-intensity intermittent exercise intervention. Future studies may minimize this potential bias by incorporating additional familiarization sessions, increasing the interval between repeated measurements, or using alternate test forms to reduce task predictability. Including statistical adjustments for practice effects may further enhance the validity of the cognitive outcomes. Third, ventilatory and cardiovascular responses immediately after intense exercise can alter systemic physiology, potentially influencing fNIRS signals through changes in skin blood flow or scalp perfusion. We mitigated these influences through motion correction, PCA-based global component removal, and band-pass filtering, yet extracerebral contamination

cannot be fully excluded, especially given the absence of short-separation channels.

Further, while we evaluated the effects of a 25-minute high-intensity intermittent exercise session, this included the effect of a brief 5-minute warm-up and cool-down. High-intensity exercise sessions are generally accompanied by warm-up and cool-down sessions that serve as safety measures to prevent sudden changes in physiological parameters. Accordingly, the inclusion of this period was necessary for our participants. Although repeated exposure to reaction-time tasks can induce a learning or practice effect, the randomized crossover design used in the present study helped minimize this potential source of bias. Because each participant performed both the control and HIIE sessions in a counterbalanced order, any familiarity gained during earlier testing was distributed equally across both conditions. This ensured that improvements related to task repetition, rather than the intervention itself, would affect both sessions similarly. Additionally, maintaining a sufficient washout period between sessions further reduced the likelihood that immediate practice-related enhancements would carry over in a systematic manner. While the design cannot completely eliminate learning effects, it strengthens internal validity by ensuring that each participant serves as their own control, thereby isolating the effect of the HIIE intervention from performance gains due to repeated testing. Nonetheless, some residual practice effect may still remain, and future work could consider adding a separate familiarization session to further reduce this influence.

Another limitation is that the version of the VTS used in this study does not export accuracy or error-type data. As a result, we could not evaluate the speed–accuracy trade-off. Although RT improvements after HIIE were evident, the absence of accuracy metrics limits our ability to determine whether participants changed speed without altering response correctness. Future studies should utilize CRT paradigms that provide trial-level accuracy data to allow complete behavioral analysis.

### **Conclusions**

This study demonstrates that an acute 25-minute session of high-intensity intermittent exercise leads to improved CRT in young adults, accompanied by increased hemodynamic activation in the PFC, specifically in the bilateral dorsolateral and frontopolar regions. These findings directly support our aim by showing that HIIE elicits both measurable cognitive benefits alongside corresponding changes in PFC activation during a reaction-time task.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Supplementary Materials**

Supplementary data to this article can be found online at: <https://tss.awf.poznan.pl/SuppFile/214936/1/>

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