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Research article

Acute resistance exercise load modulates brain haemodynamics, working memory, and inhibitory performance

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ABSTRACT

Background: Acute resistance exercise (RE) has been shown to improve executive function (EF), but its effects at different intensities on specific EF domains (e.g., inhibition, working memory) and underlying brain mechanisms (i.e., brain hemodynamics) remain unclear.
Methods: Forty-two young, active, and healthy adults (mean age = 26.9 ± 0.8 years; 24 men) were randomly allocated to one of three experimental groups: 1) RE at high load (HRE) (75 % of 1RM), 2) RE at moderate load (MRE) (50 % of estimated of 1RM) and 3) a resting control condition (CON). Participants completed Stroop and N-back tasks (i.e., measuring inhibition and working memory) to assess EF at three time points: pre-exercise, post-exercise (Post), and 45 min post-exercise (Post45). Functional near-infrared spectroscopy (fNIRS) was used to determine changes in brain hemodynamics during cognitive testing.
Results: HRE produced small to moderate improvements in Stroop incongruent trial performance (d=0.40) and moderate gains on the 2-back working memory task (d=0.80 post), with smaller improvements on the 1-back task. In comparison, MRE showed weaker effects on Stroop performance but moderate improvements on the 2-back task (d=0.65). HRE showed increases in right hemisphere oxygenated haemoglobin (O_2Hb) across tasks, particularly under higher cognitive load (d = 0.65 in congruent Stroop trials). MRE induced smaller but notable O_2Hb increases (d=0.35–0.54), whereas CON showed little or declining O_2Hb levels.
Conclusion: HRE was associated with greater improvements in EF, particularly inhibition and working memory, and was associated with stronger and more sustained functional brain hemodynamics changes compared to MRE.

1. Introduction

Resistance exercise (RE) has been shown to transiently improve executive function (EF), with subdomains such as inhibition, working memory, and cognitive flexibility [1,2]. Although RE is considered effective for improving EF, the effects of a single bout of RE, also referred to as acute RE, at different intensities (loads) and its underlying brain mechanisms need further exploration [3–6]. This is, in part, due to the small number of studies and inconsistent findings reported in the literature, as highlighted in a recent review [1].

Working memory is a core component of EF that enables the temporary storage and manipulation of information necessary for complex cognitive tasks such as reasoning, decision-making, and language comprehension [7]. In adults, working memory is important for maintaining productivity in professional settings (e.g., multitasking in high-pressure environments and academic performance), and plays a crucial role in lifelong learning, such as acquiring new skills or adapting to changing technologies [8]. Inhibitory control, the ability to suppress irrelevant or distracting information, works alongside working memory to maintain task focus and behavioural regulation (e.g., a teacher managing a noisy classroom). Deficits in either working memory or inhibition are associated with poorer work performance, reduced learning efficiency, and difficulties with emotion regulation [9,10]. Emerging evidence suggests that RE may enhance both working memory and inhibition by promoting neuroplasticity, increasing cerebral blood flow, and modulating neurochemical pathways involved in Efs [11,12]

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offering a promising, accessible strategy to support cognitive health across the adult lifespan.

RE is a planned and structured form of physical activity that uses external resistance to induce muscle contractions and improve muscular strength, endurance, and hypertrophy [13]. Unlike aerobic exercise, RE usually imposes intermittent bouts of neuromuscular and metabolic demand, including brief but intense periods of effort that stimulate cardiovascular responses and cerebral autoregulation[1,14]. These responses may enhance PFC oxygenation by increasing cerebral blood flow and improving the efficiency of oxygen delivery and utilisation [15]. Functional increases in brain oxygenation within the PFC are thought to reflect greater engagement of neural circuits responsible for EFs, including working memory and inhibition [16]. Moreover, brain oxygenation is linked to cognitive performance in that higher or more efficient responses during cognitive tasks often correlate with improved reaction times, especially in tasks requiring rapid updating, inhibition, or task switching [17]. However, the sustained effects of RE on brain oxygenation is limited, making follow-up measurements (e.g., 45 min post-exercise) relevant to determine the temporal nature of RE benefits on cortical function and behaviour [12,16,17].

RE may also enhance EF, with effects potentially varying based on the RE load and specific EF domains assessed [1,2]. Recent systematic reviews by Huang et al. [2] and Hsieh et al. [18] suggested that acute moderate-load RE (MRE) may be more effective across EF domains compared to high-load RE (HRE). However, the findings of other studies suggest that acute HRE can result in cognitive benefits that are not seen with MRE [4]. Given these inconsistent findings, largely derived from a relatively small number of studies, further research is needed to clarify the effects of different RE loads on specific EF domains [2,4]. Additionally, another systematic review by Herold et al. [1] emphasised that besides comparing different loads, the underlying neurophysiological mechanisms (i.e., functional and/or structural brain changes) need to be further explored to verify the previously reported findings.

Despite the growing body of work using widely established methods such as EEG (i.e., neuroelectric assessment) to examine the effects of acute RE on EF [19,20], very few studies have applied fNIRS to investigate these effects. fNIRS is a relatively novel optical neuroimaging technique that allows measuring changes in oxygenated (O_2Hb) and deoxygenated (HHb) haemoglobin in the cortical layers of the brain [21]. Based on the principles of optical spectroscopy and neurovascular coupling, fNIRS allows conclusions to be drawn on the activity patterns in specific brain regions at rest or in response to a particular task (e.g., cognitive task probing EF) [22]. Given the limited understanding of the neurophysiological mechanisms underlying the effects of acute physical exercise (i.e., RE with different loads), on cognitive functions such as EF, particularly in younger adults, the use of fNIRS is well-justified [3]. Its advantages, including portability and ease of use, make it a suitable tool for advancing insights into these underlying neurophysiological processes [14].

fNIRS strengths lies in the spatially localising activity across multiple prefrontal subregions, such as the left and right dorsolateral prefrontal cortex (DLPFC), thereby allowing exploration of potential lateralised hemodynamic responses. The DLPFC, a key region implicated when EFs are requested, is known to exhibit lateralised patterns of activation [23,24]. For example, the left DLPFC has been more strongly linked to verbal and goal-directed tasks, whereas the right DLPFC is frequently involved in inhibitory control and spatial working memory [23–25]. Therefore, using a multi-channel fNIRS to measure right and left DLPFC activity enables the identification of potential lateralised hemodynamic responses to acute resistance exercise, which has not yet been explored in the literature.

To date, the neurophysiological responses following acute RE at different loads on EF have only been investigated in one study exploring the effects of RE (80 % of 1 RM) on inhibitory and brain responses (i.e., brain hemodynamics on the prefrontal cortex [26]). This study reported decreased brain hemodynamics during the Stroop test but no significant differences in brain hemodynamics compared to combined resistance (30 % 1RM) and walking moderate intensity protocol [26]. However, the study by Chang et al. [26] had a small sample size, including only nine participants per group, and prefrontal cortex measures were obtained by Tissue Hemodynamics Index (TOI), using a two-channel device. This approach did not capture changes in other brain areas. As a consequence, the limitations of the study by Chang, do not extend understanding of the effect of RE on brain hemodynamics in a manner that is robust enough to base solid conclusions upon. More importantly, there are clear gaps in the literature concerning our understanding of the neurobiological mechanisms driving the effects of acute RE on cognition. Moreover, existing research has yet to consider follow-up measurements to capture the effects of training load, lateralisation and delayed responses in the brain[3]. These follow-up measurements are crucial for understanding the duration and persistence of exercise-induced changes in brain function.

To address these research gaps, the current study investigated the acute effects of MRE and HRE on inhibitory control and working memory, including their after effects at 45 min post-exercise, while also examining oxygenated (O_2Hb) haemoglobin responses as a potential underlying mechanism, thereby providing a novel contribution by assessing whether MRE and HRE elicit different activation profiles in each hemisphere of the PFC and how these patterns relate to EF performance.

2. Methods

2.1. Participants and sample size

Eighty healthy, physically active men and women aged 18–35 years from the West Midlands, UK, were recruited for the study through convenience sampling via online advertisements and word of mouth. Participants were excluded if they had musculoskeletal, cognitive, or other health-related impairments as assessed by the General Health Questionnaire (GHQ-12), Patient Health Questionnaire (PHQ-9), Generalised Anxiety Disorder Assessment (GAD-7), Insomnia Severity Index (ISI), Raven's Standard Progressive Matrices, or the Physical Activity Readiness Questionnaire (PAR-Q), or if they were taking medication for blood pressure or cardiac conditions. Participants were healthy young adults (aged 18–30 years), right-handed, and with normal or corrected-to-normal vision. Inclusion criteria required a minimum of six months of prior resistance training experience to ensure familiarity with exercise procedures. Exclusion criteria were a self-reported history of neurological, cardiovascular, or psychiatric disorders; current use of medication known to affect cognitive or cardiovascular function; smoking or substance abuse; and previous head injury. In total, 42 participants were recruited. Three individuals did not meet the inclusion criteria (two due to left-handedness and one due to insufficient resistance training experience). An additional two participants were excluded from analyses due to poor fNIRS signal quality and non-compliance with task instructions. The final sample therefore comprised 39 participants. The minimum number of participants required to detect significant differences (n = 39), was based on an a priori power calculation conducted using G-power software (Power =.85 and α =.05; ES(f) = .25) [27]. An effect size of ES(f) = .25 was chosen to reflect small-to-moderate effects reported in previous acute exercise and fNIRS studies examining executive function [28,29].

2.2. Study design and protocol

To explore the objectives of this study, a between-subjects design with pre-, post-, and Post45 was employed to help reduce variability in neurophysiological measures and learning effects [21]. Post-exercise measurements were conducted 5–10 min after completing the exercise protocol to allow time for fitting the fNIRS headcap and adjusting the optodes for optimal data collection. Participants were randomly

allocated to one of three groups prior to data collection by the lead researcher using an online randomisation tool (https://www.randomizer.org/): (a) MRE (3 sets of 12 reps at 50 % of estimated 1RM), (b) HRE (3 sets of 8 reps at 75 % of estimated 1RM) and (c) a rested control (CON) (watching non stimulant video for the same duration). RE intensities were classified based on low (30–49 % 1-RM), moderate (50–69 % 1-RM) and high-load (70–84 % 1-RM) [2]. Allocation concealment was ensured by revealing group assignment only on the day of testing. Neither participants nor the researchers involved in recruitment knew in advance which group participants would be assigned to, thereby reducing the risk of selection bias.

2.3. Procedures

Following ethics approval and written consent, participants were invited to participate in two testing sessions (at least 72 h apart). The first day included 1) estimation of the 1 repetition maximum (1RM) for 4 compound exercises: barbell box squat, flat barbell bench press, deadlift and bent over row 2) familiarisation with the cognitive tests 2–4 times to diminish learning effects due to practice and 3) measures of body height, weight, and percent body fat via bioelectrical impedance (Tanita Mc-780MA, Tanita, Tokyo, Japan).

Participants were instructed to avoid physical exercise and psychotropic substances (e.g., alcohol, cannabis) in the 24 h before testing, and to refrain from solid food or caffeine for 3 h prior. They were also asked to drink ~500 mL of water 2 h before testing to ensure proper hydration, following protocols used in similar studies [30].

2.3.1. One-repetition maximum estimation

An estimated 1RM was determined by using a 5-repetition maximum (5RM) test according to recommendations from the National Strength and Conditioning Association [13]. For each of the four compound exercises (barbell box squat, flat barbell bench press, deadlift and bent over row) participants performed, with self-selected light resistance, 3 × 10 repetitions of each exercise to familiarise themselves with the movement pattern, after resting for 2–3 min, a weight selected by the participants were used with the goal to achieve a maximum of 5 repetitions. If the participant were not able to lift the weight 5 times or could lift more than 5 times, the participants were provided with a 3- to 5-minute rest before beginning a second set with increased or decreased weight (2.5–10 % for upper body and 5–20 % for lower body) [30].

2.3.2. Resistance exercise protocol

On testing day, participants started the session with a 5 min warm-up of stationary cycling (self-paced). Following this, participants completed 3 × 10 repetitions of each exercise with a warmup self-selected load (but no more than 10 % of 1RM), with 1–2 min rest between sets and exercises [30]. Once the warm-up was completed, participants performed one of the experimental protocols by either completing 3 sets at 50 % (i.e., 12 reps MRE) or 75 % (i.e., 8 reps HRE) of their estimated 1RM. 75 % of 1RM was calculated for each individual the number was reps was as standard (example: 1RM = 80 kg: 75 %: 60 kg x 8 reps = 480 kg and 50 %: 40 kg x 12 reps ≈ 480 kg), we aimed to equalise workload across groups by adjusting the weight and repetitions so that total work performed was comparable. Exercises were performed with controlled repetition velocity (tempo: 2–0–2–1 s; concentric–pause–eccentric–pause) and full range of motion under the lead researcher's supervision. 1–2 min rest between sets and exercises. All participants followed the same exercise order: (1) barbell box squat, (2) flat barbell bench press, (3) deadlift, and (4) bent over row (Fig. 1). All participants wore an HR monitor (Polar H10, Polar Electro Oy, Kempele, Finland) to control the cardiovascular strain and capillary blood samples were collected from the fingertip using standard aseptic procedures and analysed for lactate concentration using a benchtop analyser (Biosen C-Line, EKF Diagnostics, Barleben, Germany) at pre-, post-, and post45 minute time points.

2.3.3. Seated rest group

Participants sat quietly while watching a minimally to non-stimulating video (i.e., a video about nature and landscapes) for a duration equivalent to that of the RE condition employed in the experimental groups, consistent with previous studies using RE protocols [30]. All measurements were conducted at the same time points as in the experimental groups.

2.4. Cognitive assessment

Stroop and N-Back tests were performed using E-prime 3.0 software (Psychology Software Tools, Inc., Sharpsburg, PA, USA) on an HP ProBook using a 15.4" screen connected to a three-key fixed answering box to avoid any unnecessary movement.

2.4.1. Inhibitory responses

For the Stroop test, participants were asked to identify the colour of each word written (i.e., purple, yellow, and orange) and answer as quickly and accurately as possible. The test presented 4 blocks of congruent (e.g., purple written in purple, involving well-learned reading processes) and 4 blocks of incongruent (e.g., purple written in orange, involving cognitive control mechanisms) stimuli alternately. For each condition, there was one practice block with 20 trials (that could be repeated until a 75 % accuracy was reached) [31–33]. The parameters were defined as inter-stimulus interval [170–370 ms] presentation time [200 ms], jitter: [270 ms], response time [2000 ms] and a total block duration averaged 55 s. With an inter-block interval [15,000–17,000 ms] to avoid anticipation. To avoid participants' guessing, if the reaction times were lower than 200 ms, the answer to that stimulus was excluded from the analyses [34], and only correct trials were considered. The total average time per response (reaction time in ms), and the accuracy of responses (%) were used to gauge inhibitory control performance.

2.4.2. Working memory

Participants completed a computer-based version of the n-back task, previously used in other studies [35]. The task involved the presentation of a sequence of letters, and participants were asked to detect whether or not the current letter matched the letter presented 1 or 2 trials earlier in

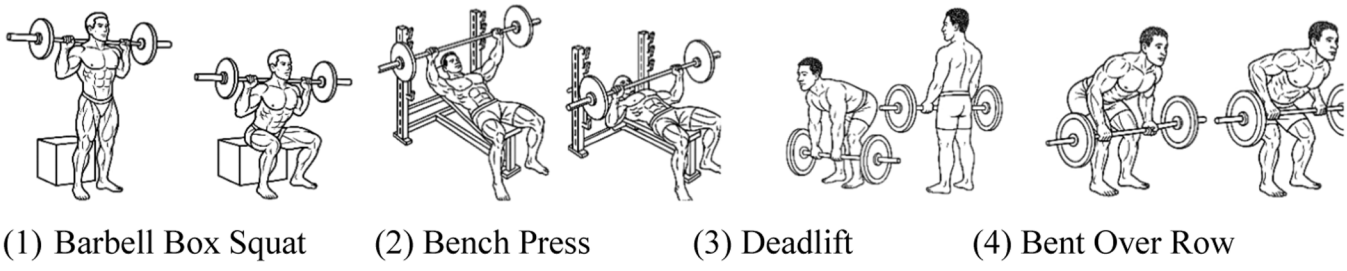

Fig. 1. Resistance exercises and form, including upper and lower body.

the series. For each trial, participants responded by pressing a button on the response box corresponding to yes or no. The task comprised two difficulty level blocks (1-back and 2-back). For each difficulty, there was one practice block with 20 trials before the test (that could be repeated until a level of 75 % accuracy was reached). The parameters were defined as inter-stimulus interval [1000 ms] presentation time [500 ms], response time [1500 ms], and a total block duration averaged 60 s. With a inter-block interval [15,000–17,000 ms] to avoid anticipation.

In each block, targets (letter matching the letter presented earlier) would occur with a probability of 20 %. Task performance was assessed by averaging the mean reaction time for correct responses separately in the one-back and two-back trials. Additionally, the adjusted hit rate was calculated by dividing the hit rate (Number of Correct Responses for Targets / Total Number of Targets) by the error rate (Number of Errors for Non-targets / Total Number of Non–targets) [35,36]. False alarm rate was calculated as the proportion of incorrect "target" responses made on non-target trials, defined as the number of false alarms (incorrect responses to non-targets) divided by the total number of non-target trials. This metric provides an index of impulsive responding, with lower values reflecting better inhibitory control [37] .

2.5. Neurophysiological assessment

fNIRS (Brite 24, Artinis Medical Systems, Netherlands) was used while performing the cognitive tests pre, post, and 45 min post to measure differences between groups on oxygenated (O_2Hb) and deoxygenated (HHb) haemoglobin using 2 wavelengths (760 nm and 850 nm at 50hz). As done in previous studies, fNIRS optodes were separated by 3 cm with semi-rigid spacers from each other [14] and a location decider toolbox (fOLD) [38] was used to define brain regions of interest (ROI), by using Brodmann DLPFC at 30 % specified for the DLPFC bilaterality. This approach has been previously used for Artinis devices [39,40]. Therefore, ROI were defined by the left DLPC (S3R3, S2R3, S3R1, S2R1, S1R1) and the right DLPC (S10R7, S10R8, S8R8, S9R8, S8R7), as seen in Fig. 2.

A block design was used for both cognitive tests, and triggers were automatically sent from Eprime 3.0 to Oxysoft via the LSL (Lab Streaming Layer) as suggested by Artinis (i.e., manufacturer). A fixation time of 20 s before and between blocks was used to normalise the hemodynamic response. During the assessments, participants were instructed to be seated, with their hands on the answering box and refrain from any unnecessary body movement or talking to reduce

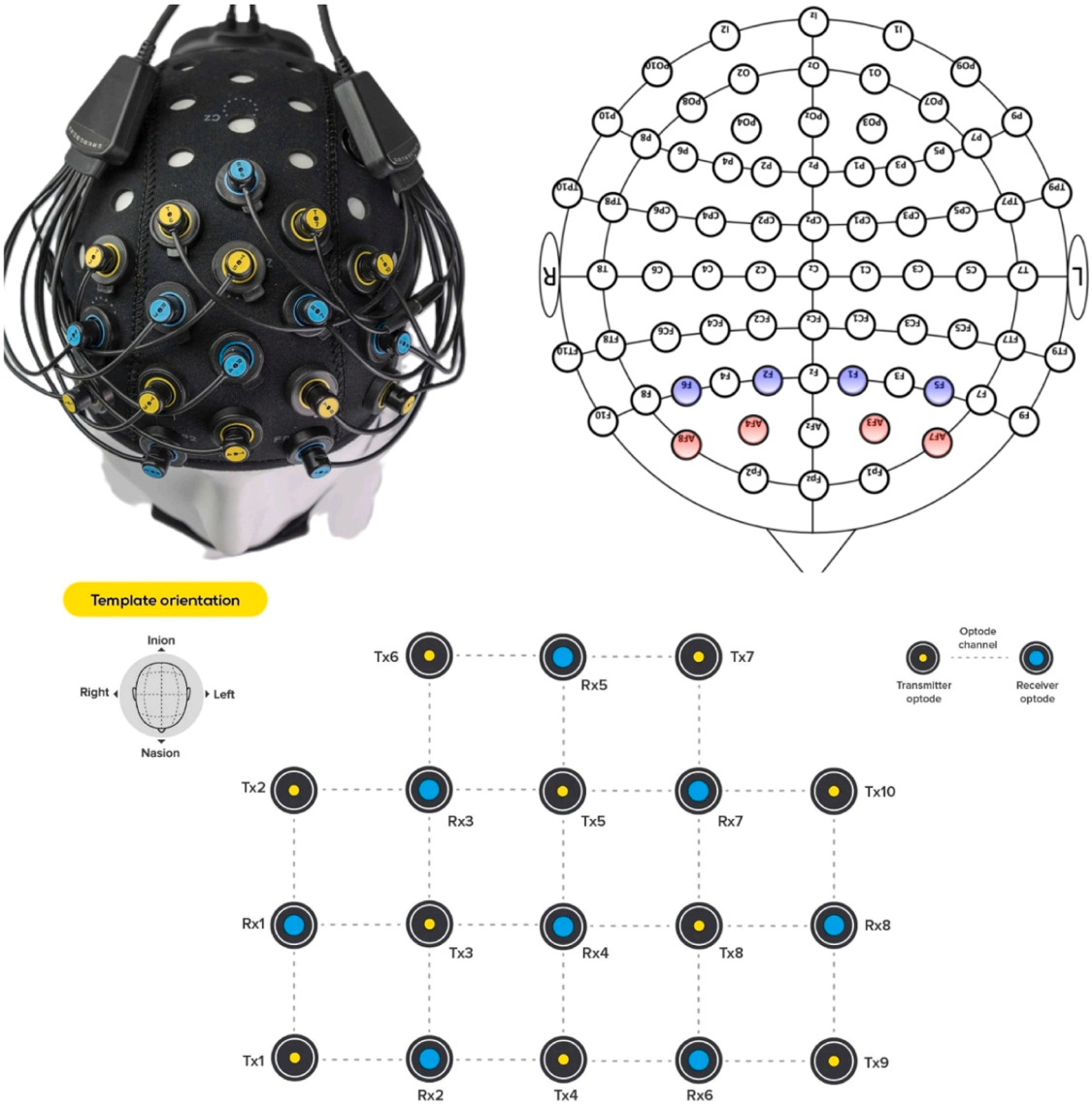

Fig. 2. Visualisation of the headcap and template used for the fNIRS system (Artinis Brite 24), followed by the fNIRS optodes configuration, and their locations in the Electroencephalography (EEG) 10–20 system, which correspond to Brodmann DLPFC at 30 % specified for the right and left DLPFC.

artifacts and ensure a reliable fNIRS measurement. If participants had vision impairments, they were instructed to wear glasses (over the fNIRS headcap) or contact lenses according to their medical recommendations. All tests were conducted in an isolated university lab with no disturbances or noises, and the device utilised had a headcap that ensures opacity and it is not affected by changes in the environmental light.

2.6. Other measures

2.6.1. Cardiorespiratory fitness

was assessed via a ramp VO_2max test on a cycle ergometer, starting at 25 W with 25 W·min^{-1} increments until volitional exhaustion. Maximal effort was confirmed if at least two of the following criteria were met: heart rate $\geq$ 90 % of age-predicted max, RER $\geq$ 1.10, RPE $\geq$ 18, VO_2 plateau (<150 mL·min^{-1} increase), and/or post-exercise blood lactate $\geq$ 8 mmol·L^{-1} .

2.6.2. Affective valence and perceived arousal

were measured using the Feeling Scale (FS) [41] and the Felt Arousal Scale (FAS) [42], respectively. These measures were administered pre, during, and post RE to examine variations in participants' affective responses and arousal level.

2.7. Data analyses

2.7.1. Behavioural data analysis

Analyses were performed in Jamovi (version 2.6.44) using ESCI (Effect Sizes and Confidence Intervals for R and Jamovi) and JMV packages. These tools provided raw and adjusted descriptive confidence intervals (CIs) around paired mean differences. For each outcome, within-group changes (Post – Pre and Post45 – Pre) were analysed separately for the HRE, MRE, and CON groups. Changes were reported with 95 % CIs and Cohen's dz effect sizes. Between-group comparisons were explored by examining differences in effect sizes (Cohen's d) between each intervention group and the CON. Results were interpreted based on the direction, magnitude, and precision of the estimated effects, without reliance on p-values. While p-values are commonly reported, they offer a dichotomous interpretation of results (i.e., significant vs. non-significant) and are highly sensitive to sample size, potentially obscuring meaningful information about the magnitude, direction, and precision of observed effects [43,44]. To address these limitations, all statistical results in the present study are reported using effect sizes accompanied by 95 % CIs. This approach facilitates interpretation of both the practical significance and statistical uncertainty of findings [43,45]. As sample size increases, CIs naturally narrow around the point estimate, providing a clearer indication of the precision of the effect information that p-values alone cannot convey, regardless of how small they may be [44]. The combined use of effect sizes and CIs offers a more robust, transparent, and informative framework for interpreting intervention effects in cognitive neuroscience research [43].

Effect sizes interpretations followed Cohen's conventional benchmarks: 0.20 (small), 0.50 (medium), and 0.80 (large), with values below 0.20 considered trivial and those $\geq$ 1.20 classified as very large. Prior to correlation analysis, the distribution of change scores (Δ = Post – Pre; Post45 – Pre) was examined. While some variables approximated normality, others showed deviations and heteroscedasticity. Therefore, Spearman's rho, a non-parametric rank-order correlation, was used as it provides a robust estimate of monotonic associations between brain activation and behavioural performance when normality cannot be assumed for all variables. Confidence intervals (95 %) for each correlation coefficient were calculated using bootstrapping (1000 resamples). This method aligns with recommendations for evaluating functional brain–behaviour relationships where inter-individual variability is expected [46,47].

2.7.2. Neurophysiological data processing

Data cleaning was processed by using the Homer3 toolbox in Matlab (2022a) by using the recommendations by Brigadoi et al. [48], Teo et al. [39], Pinti et al. [49], Herold et al. [14] Scholkmann et al. [50] and Yeung et al. [51]. In particular, based on previous literature, we employed a wavelet filter to account for motion artifacts [48], and reduce the confounding influence of systemic physiological artifacts in the absence of short-separation channels a principal component analysis approach to r (i.e., to account for superficial blood flow) [50], and an appropriate low-pass filter (i.e., to removed Mayer-waves) [49]. We tried to reach a good compromise between the over exclusion of good data and the under exclusion of noisier data sets by adjusting the parameters to better fit the data collected. Therefore, we used the following preprocessing stream in Homer3.

Step	Function	Parameters
1	hmrR_preprocessingIntensity_NAN	No parameters (handles NaNs in intensity data)
2	hmrR_PruneChannels	dRange = [5.0e−04, 1.0e00] SNRthresh = 6.7 SDRange = [0, 45]
3	hmrR_Intensity2OD	No parameters (converts raw intensity to optical density)
4	hmrRMotionArtifactByChannel	tMotion = 0.5 tMask = 1 STDEVthresh = 50 AMPthresh = 5

We performed a visual inspection of the brain waves for each participant and each measurement and removed all the unidentified artefacts. Following this, another processing stream was applied to ensure reliable data.

Step	**Function**	**Parameters**
1	hmrR_PreprocessIntensity_NAN	No parameters – Handles NaNs in intensity data
2	hmrR_PruneChannels	dRange = [5.0e−04, 1.0e+ 00] SNRthresh = 6.7 SDRange = [0.0, 45.0]
3	hmrR_Intensity2OD	No parameters – Converts intensity to optical density
4	hmrR_MotionArtifactByChannel	tMotion = 0.5 tMask = 1.0 STDEVthresh = 50.0 AMPthresh = 5
5	hmrR_MotionCorrectSpline	p = 0.99 turnon = 1
6	hmrR_MotionCorrectWavelet	iqr = 1
7	hmR_PCAFilter: PCA_Filter_Delta_OD	nSV = 0.8
8	hmrR_MotionArtifactByChannel	tMotion = 0.5 tMask = 1.0 STDEVthresh = 50.0 AMPthresh = 5
9	hmrR_StimRejection	tRange = [−3.0, 40.0]
10	hmrR_BandpassFilt	hpf = 0.010 lpf = 0.090 Bandpass Filter on Optical Density
11	hmrR_OD2Conc	ppf = [6.0, 6.0] Converts optical density to concentration
12	hmrR_BlockAve	tRange = [−3.0, 40.0] Block averaging on concentration data

Following the final data processing, we performed another visual inspection to ensure there were no remaining visual artifacts for each measurement and excluded all the noisier channels. Thereafter, all data were converted to HRF to be then exported to Excel where bad channels were manually excluded. To calculate the mean activation, over the task period (0 s to 20 s), we coded and ran Excel macros to average the channels that were included in our ROIs.

Our ROI included an average over five channels, including the right and left DLPC to highlight lateralised hemodynamic differences [36,52]. As an exclusion criteria, we adopted the same exclusion criterion as Carius et al. [53], where if more than 30 % of the channels within an ROI were excluded, all brain data for that participant were also excluded. In our case, since each ROI contained five channels, the exclusion of more than one channel per ROI led to the removal of that participant's brain data. This criterion resulted in the exclusion of 5 participants (11 % of the recruited sample), leaving a final sample of 39 participants for analysis.

3. Results

The three groups were comparable in age, sex distribution, training experience, and baseline intelligence. Intelligence was assessed using the short version of the Raven's Progressive Matrices (score range 0–9), with mean scores showing no meaningful differences between groups (HRE: 8.23 ± 1.09; MRE: 8.21 ± 1.12; CON: 8.08 ± 1.31). Pairwise comparisons confirmed trivial effect sizes (HRE vs. MRE: d = 0.01, 95 % CI [–0.74, 0.77]; HRE vs. CON: d = 0.01, 95 % CI [–0.66, 0.91]; MRE vs. CON: d = 0.08, 95 % CI [–0.66, 0.88]), indicating that baseline intelligence was equivalent across groups. Post-exercise blood lactate values validated the exercise intensity manipulation. HRE resistance exercise elicited the greatest increase (M = 7.33 mmol·L^{-1}), which was substantially higher than both MRE (M = 5.23 mmol·L^{-1}; Hedges' g = 0.85, 95 % CI [0.07, 1.64]) and CON (M = 1.13 mmol·L^{-1}; g = 2.75, 95 % CI [1.65, 3.85]). MRE was also clearly elevated relative to control (g = 3.27, 95 % CI [2.06, 4.49]). At 45 min post-exercise, lactate levels had declined toward baseline in both exercise groups (HRE: M = 2.11; Moderate: M = 1.76), though they remained modestly higher than control (HRE vs. CON: g = 1.27, 95 % CI [0.43, 2.12]; Moderate vs. CON: g = 0.80, 95 % CI [0.00, 1.59]).

3.1. Stroop test

3.1.1. Test performance (behaviour)

In the congruent trials, MRE led to consistent improvements in reaction time, with a decrease from Pre (M = 557.75 ms, 95 % CI [517.86, 597.64]) to Post (M = 531.25 ms, 95 % CI [491.89, 570.61]; d = 0.44), and further improvement at Post45 (M = 514.75 ms, 95 % CI [475.13, 554.37]; d = 0.67), compared to both HRE and CON groups at this time point. For incongruent trials, HRE resulted in small improvements from Pre (M = 595.32 ms, 95 % CI [535.16, 655.48]) to Post (M = 562.51 ms, 95 % CI [510.76, 614.27]; d = 0.40) and Post45 (d = 0.30), compared to CON, which worsened immediately after exercise cessation (d = 0.36).

3.1.2. Brain hemodynamics

In congruent trials, HRE increased O_2Hb in both hemispheres, with moderate effects in the right hemisphere (Post: M = 1.94 μmol/L, 95 % CI [0.118, 3.77]; Post45: M = 1.25 μmol/L, 95 % CI [–0.128, 2.63]) compared to the left (Post: M = 0.796 μmol/L, 95 % CI [–0.838, 2.43]; Post45: M = 0.474 μmol/L, 95 % CI [–0.327, 1.28]). MRE also increased activation in the left hemisphere (Post: M = 0.720 μmol/L, 95 % CI [0.0887, 1.35]), while the CON group exhibited low or declining in O_2Hb concentration. Compared to CON, Δeffect sizes were higher for the MRE group in the left hemisphere at Post45 (Δd = 0.85) and highest in the right hemisphere at Post45 (MRE Δd = 1.02; HRE Δd = 0.46). In incongruent trials, HRE group increased right hemisphere O_2Hb from Pre (M = 0.788 μmol/L, 95 % CI [0.282, 1.29]) to Post (M = 2.75 μmol/L, 95 % CI [–2.49, 8.00]), although the wide confidence interval (95 % CI [–2.49, 8.00]) indicates variability in individual responses, followed by a return toward baseline at Post45 (M = 0.534 μmol/L, 95 % CI [0.0268, 1.04]). MRE produced small-to-moderate increases (see Fig. 3), while the CON group showed consistent reductions over time (see Fig. 3).

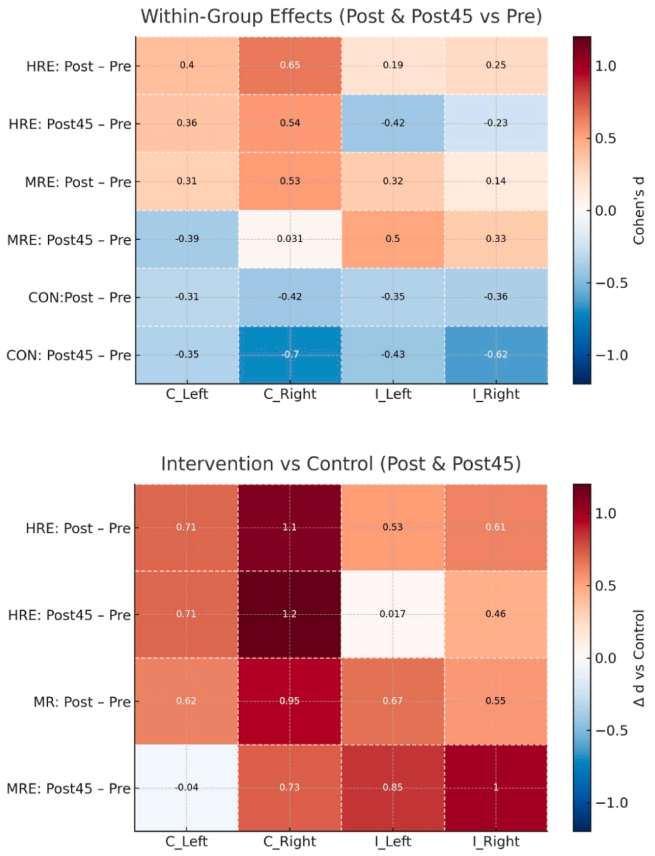

Fig. 3. Visualisation of the effect sizes by using a heatmap (blue by lower effect sizes and red higher effect sizes). The positive or negative values show the direction of the effect. "C" represents congruent stimuli and "I" incongruent stimuli.

3.2. N-back test

3.2.1. Test performance (behaviour)

In the 1-back task, HRE led to a moderate reduction in reaction time from Pre (M = 457.15 ms, 95 % CI [424.30, 490.00]) to Post (M = 416.81 ms, 95 % CI [389.80, 443.81]) and a further reduction at Post45 (M = 404.84 ms, 95 % CI [378.49, 431.19]; d = 0.69). MRE produced similar improvements (Pre: 471.83 ms, 95 % CI [440.77, 503.88]; Post45: 417.11 ms, 95 % CI [391.71, 442.50]; d = 0.60). The CON group showed smaller improvements by Post45 (d = 0.39). In the more demanding 2-back task, HRE resulted in large reductions in RT from Pre (M = 539.05 ms, 95 % CI [492.77, 585.34]) to Post (M = 472.71 ms, 95 % CI [430.00, 515.43]) and Post45 (M = 448.68 ms, 95 % CI [407.35, 490.00]; d = 0.80 and 0.93, respectively). These reductions exceeded those seen in the MRE (d = 0.60) and CON (d = 0.30–0.45). Hit rate followed a similar trend. In the 1-back task, hit rates were maintained or slightly increased across RE groups, but declined in the CON from 0.71 (95 % CI [0.66, 0.76]) to 0.67 (95 % CI [0.60, 0.75]). In the 2-back task, HRE increased hit rate from 0.65 (95 % CI [0.49, 0.82]) to 0.81 (95 % CI [0.69, 0.93]) and 0.79 at Post45 (95 % CI [0.68, 0.90]), indicating moderate to large gains. MRE also improved hit rates (e.g., Post = 0.78, 95 % CI [0.67, 0.89]), whereas the CON showed little or no improvement. False alarm rate (FAR) followed a similar trend. In the 1-back task, FARs remained low across groups, with slight reductions observed in both HRE (Pre = 0.04, 95 % CI [0.00, 0.09] to Post = 0.03, 95 % CI [0.01, 0.05]) and MRE (Pre = 0.08, 95 % CI [0.02, 0.14] to Post = 0.06, 95 % CI [0.01, 0.11]), while the CON group showed only minimal change (Pre = 0.07, 95 % CI [0.03, 0.10] to Post = 0.06, 95 % CI [0.01, 0.11]). In the more demanding 2-back task, FARs were

consistently higher, but HRE decreased from 0.14 (95 % CI [0.07, 0.21]) at Pre to 0.11 (95 % CI [0.05, 0.17]) at Post and 0.09 (95 % CI [0.03, 0.15]) at Post45, with a similar reduction in MRE (Pre = 0.16, 95 % CI [0.08, 0.24] to Post45 = 0.12, 95 % CI [0.05, 0.19]). By contrast, the CON group showed little change over time (Pre = 0.17, 95 % CI [0.08, 0.26] to Post45 = 0.16, 95 % CI [0.07, 0.25]).

3.2.2. Brain hemodynamics

In the 1-back task, HRE increased O_2Hb in the right hemisphere from Pre (M = –0.0428 μmol/L, 95 % CI [–0.589, 0.503]) to Post (M = 1.31 μmol/L, 95 % CI [0.200, 2.41]; d = 0.50), with a smaller increase at Post45 (d = 0.29). In contrast, the MRE and the CON showed negligible or negative changes (d = 0.18–0.03). Between-group differences showed an increase for HRE (Δd = 0.64 vs CON). Left hemisphere activation remained relatively stable across all groups (HRE d = 0.04; MRE d = 0.03; CON d = 0.12). In the 2-back task, right hemisphere O_2Hb concentration also increased in the HRE group from Pre (M = –0.685 μmol/L, 95 % CI [–2.57, 1.19]) to Post (M = 1.10 μmol/L, 95 % CI [0.288, 1.92]; d = 0.41), with a small effect at Post45 (d = 0.04). MRE showed small decreases (d = 0.19–0.29), while the CON showed modest increases (d = 0.26–0.11), resulting in a Δeffect size of ~0.15–0.30 for the HRE group. In the left hemisphere, both intervention groups produced small and inconsistent effects (HRE d = 0.10–0.32; MRE d = 0.15–0.16), while CON activation modestly increased (Post45 d = 0.25, see Fig. 4) (Fig. 5).

3.2.3. Correlation behaviour vs brain

Spearman's rank-order correlations were used to examine associations between behavioural and hemodynamic (O_2Hb) changes across Pre, Post, and Post45. For the Stroop task, no significant correlations were found between ΔBehaviour and ΔO_2Hb in either hemisphere during congruent trials (left: ρ =.208; right: ρ =.176). However, O_2Hb changes were strongly correlated between hemispheres (ρ =.674, p < .001). In incongruent trials, brain–behaviour associations were negligible (left: ρ =.059; right: ρ =.022), though inter-hemispheric O_2Hb remained moderately correlated (ρ =.484, p = .005). For the 1-back task, ΔBehaviour and ΔO_2Hb were not significantly correlated in either hemisphere (Post – Pre: left ρ =.01, right ρ =.15; Post45 – Pre: left ρ =.05, right ρ =.16). However, inter-hemispheric O_2Hb changes were strongly associated (ρ =.63, p = .001). In the 2-back task, brain–behaviour correlations remained weak (Post – Pre: left ρ =.07, right ρ =.06; Post45 – Pre: left ρ =.04, right ρ =.04), while inter-hemispheric O_2Hb coupling was moderate (ρ =.45, p = .022). In summary, for both the 1-back and 2-back tasks, no strong brain-behaviour correlations were found between ΔBehaviour and ΔO_2Hb, with most correlations being weak or negligible. However, inter-hemispheric O_2Hb changes consistently showed moderate-to-strong correlations, particularly in the 1-back task, suggesting a degree of cortical coordination between the left and right hemispheres during task performance.

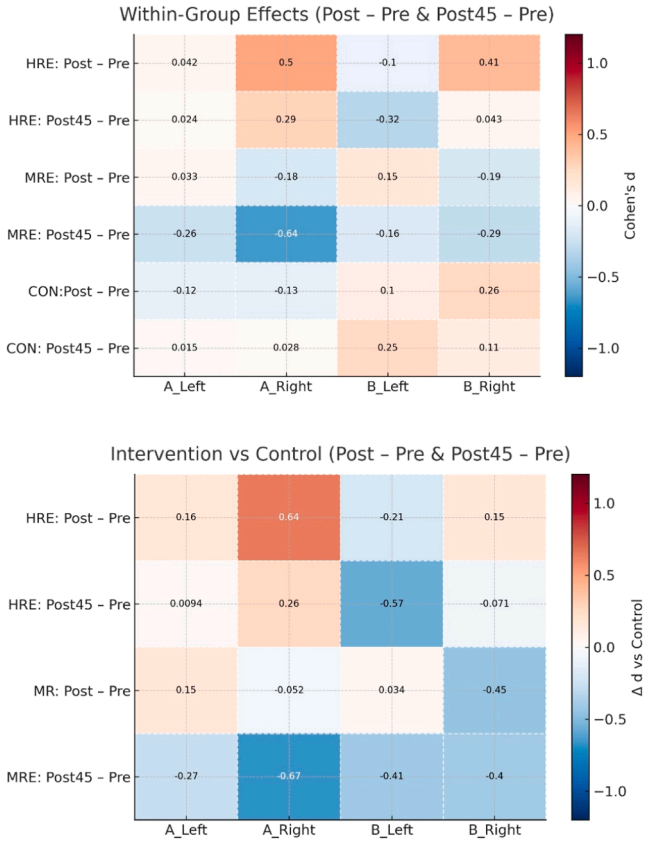

Fig. 4. Visualisation of the effect sizes by using a heatmap (blue by lower effect sizes and red higher effect sizes). The positive or negative values show the direction of the effect. "A" represents 1_back stimuli and "B" 2_back stimuli.

3.2.4. EF and blood lactate

Spearman rank-order correlations were conducted to examine associations between blood lactate levels and changes in cognitive performance from Δ = Post – Pre and Δ = Post45 – Pre. A significant negative correlation was found between post-exercise lactate and 1-back task performance change (ρ = 0.348, p = .033), indicating that higher post-exercise lactate was associated with greater improvements in 1-back performance. No other significant associations were observed, and all correlations with lactate measured 45 min post-exercise were near zero, suggesting no meaningful relationships at that time point.

3.2.5. EF and arousal

Spearman rank-order correlations were conducted to examine associations between arousal levels (as measured by the FAS) and changes in cognitive performance from Δ = Post – Pre and Δ = Post45 – Pre. A significant negative correlation was observed between FAS_post and 1-back task performance change (ρ = −0.388, p = .016), indicating that higher arousal immediately post-exercise was associated with greater improvements in working memory. No other significant associations were found between FAS_post and changes in Stroop or 2-back performance. At 45 min post-exercise, a significant negative correlation was observed between FAS_post45 and 2-back task performance change (ρ = –0.336, p = .039), suggesting that elevated arousal levels at that time point were associated with enhanced 2-back performance. All other correlations at this time point were non-significant, indicating limited associations between delayed arousal and cognitive outcomes in the Stroop and 1-back tasks.

4. Discussion

The present study advances understanding in a number of ways, by comparing the effects of different RE loads on working memory and inhibitory control, employing a multi-timepoint design to capture both immediate and delayed effects and the use of fNIRS provides valuable insight into task-related prefrontal activation, offering a mechanistic understanding of cognitive changes. The inclusion of both behavioural and neurophysiological measures enhances the robustness of the findings and underscores the potential of resistance exercise as a targeted intervention for cognitive enhancement

4.1. Behavioural findings

The results of the present study suggest that HRE improves EF performance, particularly under high cognitive load (i.e., Stroop incongruent condition and the 2-back task), with the most pronounced and lasting behavioural effects observed in the HRE group. While MRE enhanced performance on simpler tasks, such as the congruent Stroop

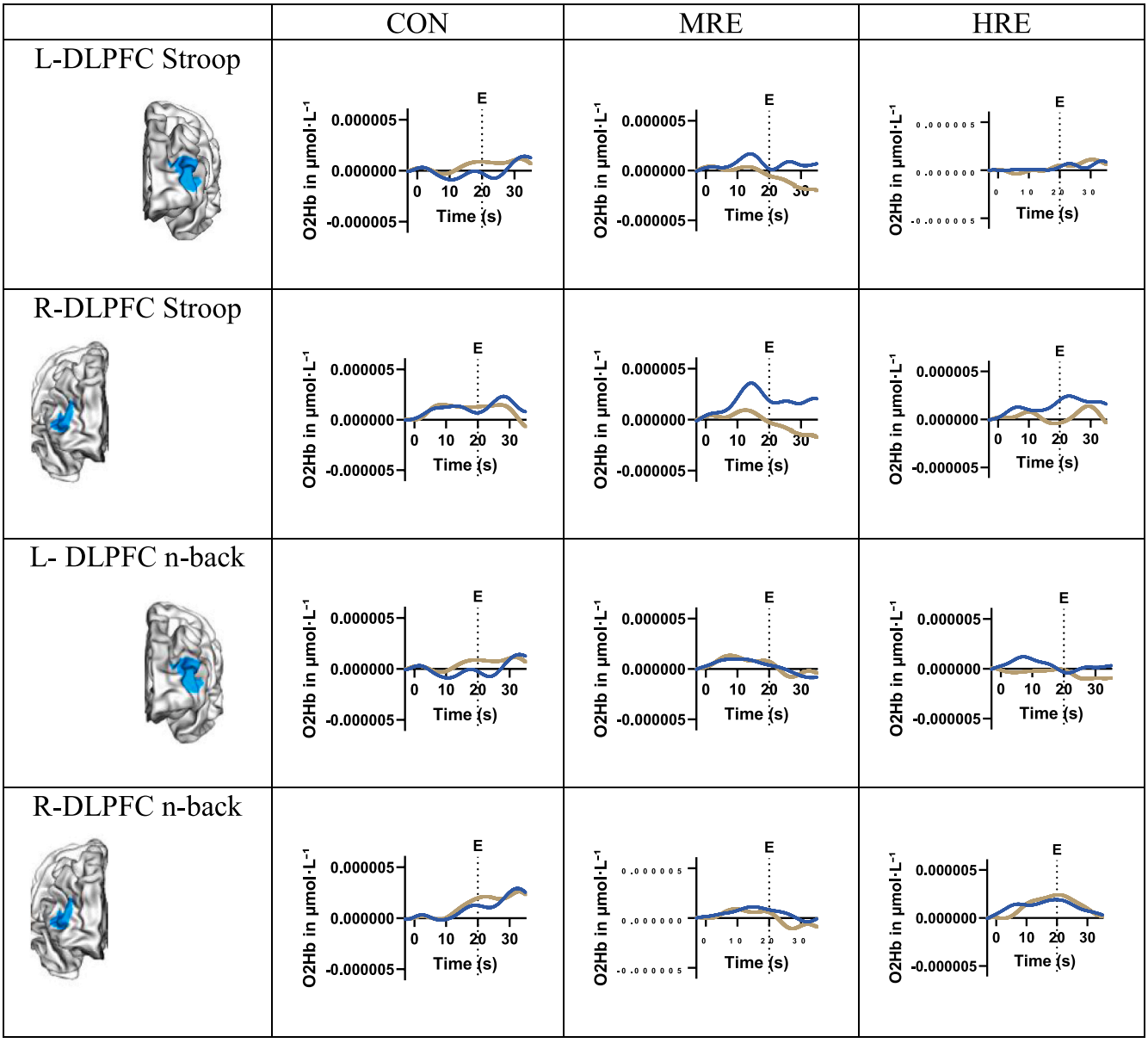

Fig. 5. O_2Hb responses to simple cognitive stimuli (e.g., congruent condition in the Stroop test or 1-back task in the N-back test). O_2Hb responses to complex cognitive stimuli (e.g., incongruent condition in the Stroop test or 2-back task in the N-back test). E represents the end of the task.

condition, and showed some benefits for working memory, these effects were less consistent. These findings align with previous research that that RE improves EF [2,4,18], and a previous systematic review on the acute effects of RE has suggested significant positive effects observed on EF following light (57 % of the cases), moderate (72 %) and high (42 %) load RE [2], with consistent improvements for all loads across inhibition (54–78 %) and working memory without consistent results due to the small number of studies included in the review. Another review by Wilke [4] suggested that there are positive effects of light and HRE, that are not observed in MRE, suggesting a U-shaped relationship (superiority of low and high load). However, both reviews suggest that the relationship between RE and EF needs further investigation with a call for future studies including more than one intensity and more than one subdomain of EF to be directly comparable. Therefore, on the one hand, our study directly highlights the differences between MRE and HRE on different domains of EF, suggesting that HRE might lead to a better EF response when exposed to more challenging trials of inhibitory and working memory tasks, and leading to longer lasting effects for working memory. This is a key novel finding of the present study, MRE seemed to be more effective when the EF tasks were simpler, with effects lasting post 45 min, but not as consistent as HRE.

4.2. *Brain haemodynamics*

The findings of the current study suggest that HRE consistently increased oxygenated haemoglobin (O_2Hb) in the right hemisphere across both cognitive tasks and trial types, with the strongest effects observed immediately post-exercise. MRE produced smaller and less consistent increases, often more evident in the left hemisphere, while the CON group showed minimal or declining activation. Left hemisphere changes were generally smaller across all groups, and right hemisphere responses were more sensitive to HRE, particularly under higher cognitive demand. The stronger right-lateralised activation aligns with established neural models of executive processing, such as the hemispheric asymmetry (HAROLD) model [23] and the Dual Mechanisms of Control framework [54], and suggests that HRE may lead to an

optimally higher and more lateralized engagement of the DLPFC during demanding cognitive operations. This right-dominant pattern is theoretically plausible for tasks emphasising inhibitory control and high-load working memory. Right prefrontal circuits (especially right DLPFC/IFG) are frequently recruited when response inhibition, conflict monitoring, and spatial/visuomotor maintenance demands increase, and acute high-load resistance exercise may transiently up-regulate these control networks under greater task difficulty [55,56]. In our context (incongruent Stroop; 2-back), the combination of elevated cognitive demand and post-exercise arousal could bias engagement towards right-lateralised control processes, yielding the observed O_2Hb asymmetry. We emphasise that this interpretation is theory-consistent rather than definitive, and we retain it as a cautious account of the lateralisation we observed, using the same sources already cited in this section to support right-hemisphere contributions to inhibitory control and working memory.

These results contrast with previous findings by Chang et al. [26], who reported decreased DLPFC oxygenation following acute HRE, particularly during incongruent Stroop trials. Although this is the only study exploring the brain haemodynamic responses to RE using fNIRS, the behavioural (Stroop test) effects were also null or not different from CON and the same tendency was found for the hemodynamic responses. In our study, and in comparison, to Chang et al. [26], the HRE was designed in a similar load (75 vs 80 % of 1RM) and used a similar inhibitory test (Stroop), making it directly comparable. However, our results suggest increased inhibitory responses and increased O_2Hb which contradicts Chang et al. [26] findings but confirm previous studies exploring the relationship between RE and EF, which suggest consistent improvements in EF [2,4,18]. These discrepancies may reflect differences in sample composition (Chang et al. [26] studied females only, whereas our sample was mixed-sex), the use of TOI rather than oxyHb to index brain activity, and the timing of cognitive testing (15 min post-exercise in Chang vs. 5–10 and 45 min in the present study). In addition, contextual factors such as cultural familiarity with resistance exercise may have influenced responses. Taken together, these differences suggest that the two studies should be viewed as complementary rather than directly contradictory. Additionally, our data support canonical neurovascular activation patterns following HRE, particularly during cognitively demanding tasks. This strengthens the case for HRE as an effective modulator of prefrontal activity and EF. Specifically, HRE consistently elicited stronger and more neurophysiological distinct responses, characterised by increased O_2Hb and decreased HbR, suggesting robust engagement of the DLPFC. In contrast, MRE and CON conditions exhibited weaker or inconsistent brain haemodynamic patterns, which may reflect reduced cognitive challenge or lower engagement of top-down regulatory processes. These findings align with previous fNIRS research indicating that greater task demands [55,56] and higher-intensity physical activity [57] tend to elicit more pronounced prefrontal hemodynamic responses. Finally, fNIRS indexes haemodynamic coupling rather than direct neuronal firing despite our preprocessing and systemic-noise mitigation, residual extracerebral influences cannot be entirely excluded, so the right-lateralised effect should be interpreted cautiously.

4.3. Correlations

Correlational analyses suggested a significant positive association observed between post-exercise blood lactate levels and improvements in 1-back task performance, suggesting that individuals with higher lactate responses experienced greater enhancements in working memory. This aligns with emerging evidence implicating lactate as a neuromodulatory agent capable of influencing EF via pathways modulating cognitive performance by (i) acting as potential fuel for cognitive processes [58–60], may explaing the observed by neurobiobehavioral associations as seen in our in other studies [61–63], and (ii) stimulating brain-derived neurotrophic factor (BDNF) release [64], which has been associated with post-exercise improvements in executive functioning [65]. However, our study did not measure BDNF, and further studies should include BDNF measures. Future work should further investigate these mechanistic pathways by integrating biomarkers (e.g., BDNF, cortisol) and neuroimaging to disentangle the relative contributions of metabolic and arousal-based modulation of post-exercise cognition.

Subjective arousal, measured via the Felt Arousal Scale, was also associated with EF changes, with higher arousal immediately post-exercise linked to better 1-back performance and delayed arousal associated with improved 2-back performance. These results support the role of arousal in modulating working memory, consistent with previous studies showing that the cognitive benefits of high-intensity exercise depend on arousal, task difficulty, and recovery timing [66,67].

These findings highlight the importance of considering individual physiological responses (e.g., lactate accumulation) and psychological states (e.g., perceived arousal) when interpreting the effects of RE on EF. They also reinforce the idea that RE, especially at higher intensities, may engage both metabolic and affective pathways that transiently enhance cognitive functioning, particularly under high working memory load. Future work should further investigate these mechanistic pathways by integrating biomarkers (e.g., BDNF, cortisol) and neuroimaging to disentangle the relative contributions of metabolic and arousal-based modulation of post-exercise cognition.

4.4. Strengths and limitations

This study possesses several methodological and conceptual strengths that enhance the robustness and relevance of its findings. The randomised, controlled design, inclusion of multiple EF tasks (Stroop and N-back), and multi-timepoint assessments (Pre, Post, Post45), for which there is a paucity of studies in the literature, especially concerning [2,3]. The integration of fNIRS provided a mechanistic understanding of how RE influences brain oxygenation. Furthermore, the use of both behavioural and neurophysiological outcomes allowed for a comprehensive evaluation of the effects of RE load. Despite these strengths, several limitations should be noted. First, the between-subjects design may have introduced variability across groups despite randomisation and matching on baseline characteristics. A within-subject or crossover design would have further minimised individual differences and should be considered in future work. Second, no correction for multiple comparisons was applied. Our analyses were estimation-focused and spanned distinct outcome categories (behavioural vs haemodynamic measures), and applying strict multiplicity control in this exploratory context would have substantially increased type II error and obscured potentially meaningful effect patterns. Instead, we prioritised transparent reporting of effect sizes and confidence intervals to convey both magnitude and uncertainty [3,68]. Third, the wide confidence intervals observed for some outcomes likely reflect true inter-individual variability in responses to acute resistance exercise, a feature increasingly recognised in this field. Understanding the sources of such variability is essential for designing effective interventions. Future studies employing within-subject or crossover designs, alongside larger samples, may help reduce error variance and disentangle individual response patterns. Fourth, although rigorous and standardised preprocessing pipelines were applied, fNIRS is inherently limited by restricted depth penetration and sensitivity to factors such as hair type and skin tone, which may compromise signal quality in some participants [69]. While PCA filtering and motion correction procedures were employed to reduce extracerebral and systemic influences, residual artefacts cannot be entirely ruled out. Finally, the sample consisted of healthy young adults with training experience, which may limit the generalisability of findings to clinical, paediatric, or older populations.

Future research should explore the effects of acute RE in different populations, such as clinical ones as well as in children and older adults, to examine the generalisability and potential benefits across the

lifespan. Longitudinal studies and within-subject designs may also help clarify individual responses and long-term impacts of RE on EF and neurophysiological correlates.

4.5. Conclusion

This study provides novel evidence that a single bout of RE, particularly HRE, may influence EF and increase task-related DLPFC activity, especially under greater cognitive demand. By combining behavioural and neurophysiological measures across multiple time points, our findings suggest that HRE could elicit more consistent cognitive effects compared to MRE or CON in young healthy adults. The observed right-lateralised increases in oxygenated haemoglobin indicate potential engagement of EFs networks in the brain. These findings highlight the possible role of RE, beyond its physical health benefits, in supporting EF acutely. However, these results should not be generalised to other populations or interpreted as evidence for long-term cognitive improvement; further research is needed to examine clinical relevance and chronic adaptations.

CRediT authorship contribution statement

Matteo Crotti: Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Fabian Herold:** Writing – review & editing, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Mathew Hill:** Writing – review & editing, Resources, Methodology, Conceptualization. **Vera Nina Looser:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization. **Michael Duncan:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Sebastian Ludyga:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Conceptualization. **Ricardo Martins:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manuel Hanke:** Writing – review & editing, Visualization, Supervision, Software, Resources, Methodology, Investigation, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices

Table A
Effect sizes for HbR and multiple comparisons between and within groups. The positive or negative values show the direction of the effect

Task Condition	Group	Effect (d) (Post-Pre)	Compared to CON (Post-Pre)	Effect (d) (Post45-Pre)	Compared to CON (Post45-Pre)
Stroop Congruent - HbR Left	CON	d = −0.38	Reference	d = 0.72	Reference
Stroop Congruent - HbR Left	HRE	d = −1.61	−1.23	d = −1.37	−1.09
Stroop Congruent - HbR Left	MRE	d = 0.62	1.0	d = −0.55	−1.27
Stroop Congruent - HbR Right	CON	d = 1.49	Reference	d = 0.16	Reference
Stroop Congruent - HbR Right	HRE	d = −0.58	−2.07	d = −0.65	−0.81
Stroop Congruent - HbR Right	MRE	d = 0.25	−1.24	d = 1.21	1.05
Stroop Incongruent - HbR Left	CON	d = −0.39	Reference	d = 1.59	Reference
Stroop Incongruent - HbR Left	HRE	d = −0.19	0.2	d = −0.37	−1.96
Stroop Incongruent - HbR Left	MRE	d = 0.22	0.61	d = 0.66	−0.93
Stroop Incongruent - HbR Right	CON	d = 1.72	Reference	d = −0.43	Reference
Stroop Incongruent - HbR Right	HRE	d = 0.16	−1.56	d = −0.59	−0.16
Stroop Incongruent - HbR Right	MRE	d = 0.41	−1.31	d = 0.45	0.88
1-Back - HbR Left	CON	d = 0.84	Reference	d = 0.02	Reference
1-Back - HbR Left	HRE	d = −2.04	−1.88	d = −1.24	−1.26
1-Back - HbR Left	MRE	d = 0.74	−0.1	d = 0.50	0.48
1-Back - HbR Right	CON	d = 1.54	Reference	d = −0.03	Reference
1-Back - HbR Right	HRE	d = −0.61	−1.15	d = 0.30	0.33
1-Back - HbR Right	MRE	d = 0.46	−1.08	d = 0.88	0.91
2-Back - HbR Left	CON	d = 0.27	Reference	d = −0.19	Reference
2-Back - HbR Left	HRE	d = −1.02	−1.29	d = 0.30	0.49
2-Back - HbR Left	MRE	d = −0.22	−0.49	d = −0.48	−0.29
2-Back - HbR Right	CON	d = −0.11	Reference	d = −0.39	Reference
2-Back - HbR Right	HRE	d = −0.65	−0.54	d = −0.02	0.37
2-Back - HbR Right	MRE	d = −0.20	−0.09	d = −0.30	0.09

Table B
Descriptive values for FS and FAS, HR and RPE for different time points

Measure	Time Point	HRE	MRE	CON
Feeling scale (FS)	FS_pre	1.85 ± 1.68	2.31 ± 2.06	2.00 ± 1.41
	FS_1	2.69 ± 1.25	2.08 ± 1.44	2.08 ± 1.51
	FS_2	2.77 ± 1.48	2.31 ± 1.93	2.08 ± 1.51
	FS_3	2.77 ± 1.42	1.54 ± 2.11	2.08 ± 1.51
	FS_post	3.00 ± 1.83	2.00 ± 2.08	2.17 ± 1.53
	FS_post45	2.85 ± 1.41	2.92 ± 1.19	2.17 ± 1.27
Heart Rate (HR)	RestingHR	69 ± 9	75 ± 11	71 ± 13
	HR_Post1	155 ± 12	150 ± 10	72 ± 16
	HR_Post2	130 ± 19	120 ± 15	73 ± 15
	HR_post3	163 ± 12	158 ± 10	73 ± 15
	HR_post	151 ± 13	151 ± 15	71 ± 12
	HR_post45	72 ± 11	75 ± 8	70 ± 12
OMNI RPE	OMNI_pre	0.31 ± 0.48	0.62 ± 0.96	0.33 ± 0.65
	OMNI_1	5.62 ± 1.71	4.69 ± 1.65	0.33 ± 0.65
	OMNI_2	5.31 ± 1.97	4.08 ± 1.66	0.33 ± 0.65
	OMNI_3	6.69 ± 1.70	5.69 ± 1.93	0.33 ± 0.65
	OMNI_post	5.85 ± 2.08	5.38 ± 2.10	0.42 ± 0.79
	OMNI_post45	0.62 ± 0.96	1.38 ± 0.87	0.50 ± 0.80
Felt Arousal Scale (FAS)	FAS_pre	1.46 ± 0.52	2.46 ± 1.05	1.92 ± 0.67
	FAS_1	3.38 ± 1.04	3.92 ± 0.64	1.92 ± 0.90
	FAS_2	3.46 ± 0.97	3.54 ± 1.13	1.83 ± 0.94
	FAS_3	4.15 ± 1.14	4.31 ± 0.75	1.83 ± 0.94
	FAS_post	4.08 ± 1.12	4.00 ± 0.82	1.75 ± 0.97
	FAS_post45	1.92 ± 0.86	2.38 ± 1.12	1.83 ± 0.72

Data availability

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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