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Effect of Acute Concurrent Exercise Training and the Mediating Role of Lactate on Executive Function: An ERP Study

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Data availability statement

Data will be made available on request to the corresponding author.

Ethics statement

The authors affirm that this work complies with the ethical standards approved by the Research Ethics Committee of National Taiwan Normal University (202101HM005) in accord with the 2013 Declaration of Helsinki. Informed consent was obtained from all participants included in the study. The study protocol, which was predicated on a true experimental design, was registered with ClinicalTrials.gov Registration (postregistration number: NCT05314634).

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Abstract

Both acute aerobic (AE) and resistance exercise (RE) have been acknowledged to be effective methods in enhancing executive function and brain-related P3 amplitudes. Nevertheless, the effect of acute concurrent exercise training (CET), combining both AE and RE, on executive function remains subject to speculation. Moreover, investigation of the mechanisms that underlie improvements in executive function would facilitate scientific understanding. Notably, lactate has emerged as a candidate among several potential mechanisms. Therefore, the main aim of the present study was to investigate the effect of acute CET on the cognitive flexibility dimension of executive function using behavioural and neuro-electric measures. A secondary aim was to determine the mediating effect of blood lactate in the acute exercise–executive function relationship. Seventy-eight young adults (38 women, 40 men; 22.8 ± 1.8 years) were randomly assigned to one of the following groups: CET, AE, or reading control (RC). Cognitive flexibility was evaluated using the Task-Switching Test and its derived electroencephalography (EEG) were assessed immediately prior to and following each treatment. Fingertip lactate assays were taken prior to, at the midpoint, and after each treatment. Both acute CET and AE shortened response time regardless of test conditions when compared to the RC group. Greater P3 amplitude was observed following CET in the heterogeneous condition and under AE in the switch condition. A significant mediation of blood lactate for response time emerged in both the CET and AE groups for the heterogeneous and switch conditions. The blood lactate mediation was not reflected in P3 amplitude. The present findings suggest that acute CET leads to positive behavioural and neuro-electric alterations of cognitive flexibility and its effect is similar to AE. Additionally, blood lactate serves as a mediator of the effects of acute exercise on executive function from a behavioural, but not neuro-electric standpoint.

Keywords: cognitive function; event-related potential; shifting; task switching

Introduction

Executive function is considered to be a meta-level and top-down cognitive process that facilitates the execution of goal-directed behaviours under novel or unanticipated situations (Diamond, 2020). It serves the essential role for shifting behaviours appropriately in accord with a changing environment (i.e., cognitive flexibility), giving attention to a specific task without overriding internal or external distraction (i.e., inhibition), and holding/manipulating information in the mind (i.e., working memory; Diamond, 2013). Executive function is also susceptible to normal and abnormal aging, with steep executive decline evident in older adults (Filippi et al., 2020) and executive dysfunction in neurodegenerative disease such as dementia and Alzheimer's (Guarino et al., 2018; Rouch et al., 2020; Tiel et al., 2019). Among younger adults, higher executive function is associated with lower risky behaviour (Reynolds et al., 2019), lower risk of cardiovascular disease (George et al., 2021), and better mental health (Schweizer et al., 2020). It is thus important that research efforts be directed towards interventions that hold potential for amelioration of the decline in executive function that is observed in human senescence.

Acute exercise, characterised by a single bout of exercise, has been considered an effective approach towards improving executive function (see e.g., (Chang et al., 2012). Moreover, such effects conferred have been added to the list of health benefits documented in the Physical Activity Guidelines for Americans (PAGA), which comes with a strong evidence grade (Erickson et al., 2019; Piercy et al., 2018; U.S. Department of Health and Human Services, 2018). In 2019, our group proposed a 3W1H framework (Chang et al., 2019) that encouraged investigation of the *What* (e.g., exercise modality, cognitive function elements), *When* (e.g., time-assessed cognitive function), *Whom* (e.g., differ population), and *How* (e.g., biological or neuro-electric examinations), to advance the understanding of acute exercise and cognitive function.

Concurrent exercise training (CET) has been promoted as an effective strategy with reference to the health benefits that it can confer. It is an exercise modality comprised of back-to-back endurance and resistance exercises used to improve multiple physical fitness parameters (i.e., cardiovascular capacity, muscular strength/endurance, and power; Doma et al., 2019; Hartono et al., 2022). The multifarious physical benefits accrue from the physiological adaptations elicited by a combination of cardiovascular and resistance-type exercise (Shamim et al., 2018). While CET was initially the preserve of athletes, its use has been extended to a variety of populations given the associated health benefits. CET can yield positive physiological outcomes that include reduced body fat and low-density lipoprotein cholesterol, as well as improved exercise capacity, muscle function, and oxidative stress (Khalafi et al., 2022; Timmons et al., 2018). Nonetheless, the effects of CET on cognitive function, particularly when applied acutely, rather than chronically, have attracted scant research interest to date.

A positive association between acute CET and executive function is conceivable given that CET encompasses aerobic and resistance exercise; both of which have been independently linked with cognitive function. Aerobic exercise (AE) has been the primary acute modality used to examine cognitive function and a moderate intensity administered for 20–30 min is well established in terms of potential benefits for executive function (Chang et al., 2012; Rademacher et al., 2021). Similar facilitation for cognitive performance was also observed in the modality of acute resistance exercise (Chang & Etnier, 2009a; Chang et al., 2014; Wu et al., 2019), with the dose–response relationship between intensity and executive function exhibiting a Wundt curve (Chang et al., 2011; Chang & Etnier, 2009b). More recent evidence has shown that the facilitative effect of AE and resistance exercise on executive function is of a similar magnitude, with a Hedges' *g* of 0.32 and 0.30, respectively (Oberste et al., 2021).

Both exercise modalities also influence executive function-elicited neuro-electric activations that are indexed by means of event-related potentials (ERPs; Kao, Cadenas-Sanchez, et al., 2020; Olson et al., 2016). This measure offers the advantage of high temporal resolution, to reflect real-time cognitive processing (Luck, 2014). Acute aerobic and resistance exercise not only improves performance on the Task-Switching Test – reflecting the cognitive flexibility aspect of executive function – but also enlarges the P3 amplitude of ERP. Such alterations show no statistically significant differences between the aforementioned exercise modalities (Wu et al., 2019). The greater P3 amplitude suggests that both aerobic and resistance exercise increase the amount of attentional allocation devoted to the task in progress (Polich, 2007; Wu et al., 2019). The acute alterations induced by both exercise modalities provide a premise with which to explore whether CET can affect executive function from a behavioural and neuro-electric perspective. There is presently a dearth of knowledge regarding the effects of acute CET on executive function and P3 amplitude.

In addition to ERPs, which can serve as real-time indicators of brain neuronal activation, examination of the mechanism that underlies enhancements in executive function would advance scientific understanding and it is notable that the function of lactate is speculated to be a key candidate (Hashimoto et al., 2021; Hashimoto et al., 2018). Lactate, a vital by-product of both aerobic and anaerobic metabolism, bridges glycolytic and oxidative metabolism (Riske et al., 2017), and provides signals in the regulation of neuronal excitability and brain plasticity (Magistretti & Allaman, 2018). It is also an essential physiological mechanism that underlies the effects of acute exercise on executive function (Hashimoto et al., 2021; Hashimoto et al., 2018).

Two approaches have been advanced regarding how lactate mediates acute exercise-enhanced executive function (Hashimoto et al., 2021; Magistretti & Allaman, 2018). The first

approach entails increasing the energy resource available to neurons to deal with the large energy demands when synaptic activity increases, as well as activating signalling transduction pathways to modulate cognitive-related molecular mechanisms. The second holds that exercise-induced lactate not only regulates the transmission of neurotrophic factors (El Hayek et al., 2019; Gold et al., 2003) but is also positively correlated with executive function (Hashimoto et al., 2018). Notably, although both CET and AE lead to higher blood lactate concentrations (Smilios et al., 2007), the concentration is highest in the former (Tsuchiya et al., 2015). This creates the possibility that the mediational role of lactate in the acute exercise–executive function relationship might differ in accord with the exercise modality that is employed. The potential mediating role of lactate has yet to be examined, which strengthens the rationale for the present study.

The main purpose was to examine the effect of acute CET on executive function with a focus on cognitive flexibility, using behavioural and neuro-electric measures. A secondary purpose was to examine the mediating role of lactate using PROCESS Macro mediation analysis. We hypothesised that CET would improve executive function to the same degree as AE, but that CET would exhibit a larger mediating effect of blood lactate when compared to AE.

Methods

Participants and Study Design

Sample size was determined by means of an a priori power analysis using G*Power 3.1 (two-way, within-within-subjects ANOVA, power = 0.80, alpha = 0.05, $f = 0.2$; Wu et al., 2019), which indicated that 54 participants would be required. Seventy-eight cognitively healthy young woman ($n = 38$; $M_{age} = 22.82$, SD = 1.72 years) and man ($n = 40$; $M_{age} = 22.83$, SD = 1.89 years) were recruited using flyers and advertisements in universities located in and around Taipei City, Taiwan. Participant inclusion criteria were as follows: (a) right-hand

dominant; (b) normal or corrected-to-normal vision; (c) no psychiatric or neurological disorders; (d) irregular exercise habits characterised by no more than 75 min/week of vigorous physical activity and/or 150 min/week of moderate physical activity over the preceding month; (American College of Sports Medicine, 2022); (e) non-obese (i.e., with a BMI < 25 kg/m^2); and (f) no cardiorespiratory diseases and/or neuromuscular disorders. Eligible participants were randomly allocated to two experimental groups (CET and AE) or a reading control (RC) group through the drawing of lots.

The study protocol, which was predicated on a true experimental design, was registered with ClinicalTrials.gov Registration (post-registration number: NCT05314634) and granted ethical approval by the Research Ethics Committee of National Taiwan Normal University (202101HM005), in accord with the 2013 Declaration of Helsinki. Participants provided written informed consent. Sample-related anthropometric and physiological data are presented in Table 1.

Assessment

Anthropometric and Physiological Characteristics of the Sample

Weight and height were measured by means of a stadiometer and digital scale (HW-3050, Super-View, Taipei, Taiwan), respectively. Short-term and working memory was assessed using the Digit Span Forward and Backward test (Ryan & Lopez, 2001). To ascertain that participants were not subject to any potential risk factors in being administered a fitness assessment and subsequently engaging in exercise, the Physical Activity Readiness Questionnaire (PAR-Q) was used (American College of Sports Medicine, 2022). Participants' total physical activity (i.e., MET/min/week) was estimated by means of the International Physical Activity Questionnaire (IPAQ; Hagströmer et al., 2006).

Cardiorespiratory fitness ($\dot{V}O_{2\ peak}$) was estimated using the YMCA Submaximal Cycle Ergometer Test (Corival cpet, Lode, Netherlands; American College of Sports

Medicine, 2022; Beekley et al., 2004). Ten repetition-maximums (10-RM) were measured following National Strength and Conditioning Association guidelines (National Strength and Conditioning Association, 2016) for standard exercises: chest press, rowing, lat (latissimus) pull down, shoulder press, biceps curl, leg extension, leg press, and leg curl. Multifunctional strength equipment (Cybex Strength, Cybex International Inc., Owatonna, MN) was used to administer the resistance exercises.

Cognitive Flexibility

Cognitive flexibility was assessed by means of a computerised version of the Task-Switching Test using Neuroscan Stim software (version 2.0; Compumedics Neuroscan, Charlotte, NC; Hung et al., 2018). The test includes six blocks of 64 trials, within which the trial stimuli are white digits (1–9, without #5) surrounded by a square (solid or dotted line) presented at the centre of a black background screen. For Block 1, the participant was instructed to identify whether the digits within the solid-line square were larger (6, 7, 8, and 9) or smaller (1, 2, 3, and 4) than the digit 5 (i.e., AAA…). For Block 2, the participant was required to identify whether the digits within the dotted-line square were odd (i.e., 1, 3, 7, and 9; i.e., BBBB…) or even (i.e., 2, 4, 6, and 8). In Blocks 3–6, the participant was required to identify the number according to the current rule presented to them (i.e., AABBAA…). Once the digit was presented within the dotted-line square (same as Block 1), the participant was required to identify whether the number was larger or smaller than the digit 5. These blocks were further categorised by four conditions: (1) homogeneous (i.e., AAAA or BBBB; Blocks 1 and 2); (2) heterogeneous (i.e., AABBAA…; Blocks 3–6); (3) non-switch (i.e., AA or BB in the heterogeneous condition), and (4) switch (i.e., AB or BA in the heterogeneous condition). The mean response time for the correct responses and accuracy scores from each condition were subject to statistical analysis.

Electroencephalogram (EEG) Processing and Analyses

Neuro-electric activity was recorded using a 32-channel electrode cap (Quik-Cap Neo Net; Compumedics Neuroscan, Charlotte, NC) with CURRY 8 Data Acquisition and Online Processing software (Compumedics Neuroscan, Charlotte, NC). Electrode positions on the electrode cap were arranged in accord with the extended International 10–10 System. Continuous online EEG data were re-referenced to averaged left and right mastoid electrodes (M1 and M2) with the AFz electrode serving as the ground. The electrooculogram (EOG) activity was monitored through the additional electrodes located above and below the left-eye orbit and outer canthus of each eye. The impedance of electrodes was maintained below 10 kΩ throughout the EEG recording period.

Offline EEG processing and analysis adhered to ERP guidelines (Picton et al., 2000) including re-reference (M1, M2), automatic channel rejection, interpolation of bad channels, independent component analysis (ICA), automatic eye-blink ICA correction through "icablinkmetrics" (Pontifex et al., 2017), epoch (−200 to −1000 ms relative to the stimuli onset), baseline correction (−200 to −0 ms relative to the stimuli onset), artificial rejection (signals > ± 100 μV), bandpass filter (0.1–30 Hz, 500 Hz sampling rate), and notch filter (60 Hz). The time windows for P3 were determined from the grand-average waveforms (i.e., 350–550 ms). The mean amplitudes of P3 were obtained from the mean amplitude values of parietal electrodes (i.e., Pz, P3, and P4) within the corresponding time windows.

Lactate

Capillary blood samples (3μL) were collected from the participant's fingertip at three timepoints: Time 1 (prior to treatment), Time 2 (the treatment midpoint; ~17 min), and Time 3 (immediately after the treatment). A lactate analyser (The EDGE, Taipei, Taiwan) was used to assess concentrations of blood lactate (mmol/l).

Treatment

Concurrent Exercise Training (CET)

Each participant was instructed to complete a 5-min warm-up at 70 rpm. Initial resistance on a cycle ergometer (Corival cpet, Lode, Groningen, Netherlands) was set at 25 W/min and increased gradually until target heart rate (40%–59% HR reserve [HRR]) was reached. The participant was required to maintain the target HR for 12 min. They were then instructed to perform the resistance exercise, which comprised a series of eight single-set exercises (12 repetitions of each) at a moderate intensity (i.e., of the resistance was set at 70% 10-RM; Hsieh et al., 2016). The resistance exercise had a duration of ~13 min and the eight exercises were performed with a recovery interval of 2 min in between each. The participant was then asked to engage in a 5-min full-body stretch as a cool-down.

To monitor exercise intensity, objective (HR) and subjective measures (Rating of Perceived Exertion; RPE) were taken. HR was measured using a chest-worn HR monitor (H10; Polar Electro Oy, Kempele, Finland). Borg's (1982) 15-point RPE scale ranging from 6 (*no* exertion *at all*) to 20 (*maximal exertion*) was used to assess perceived exertion. Four HR indices were extracted: resting HR, pre-activity HR, treatment HR, and post-activity HR. Resting HR was represented by the average HR recorded while the participant sat quietly for 5 min. Pre-activity HR was the averaged HR assessed prior to the participant conducting the Task-Switching Test.

In the CET group, treatment HR represented the averaged HR assessed at 2-min intervals during AE and assessed before and after each resistance exercise. For the AE group, treatment HR represented the average HR assessed at 2-min intervals during exercise. In the RC group, treatment HR represented the average HR assessed at the beginning and end of the reading task. Post-activity HR represented the averaged HR assessed before and after the Task-Switching Test). The RPE scale was administered at intervals that corresponded with

measures of treatment HR.

Aerobic Exercise (AE)

Each participant was instructed to complete a 5-min warm-up, 25-min moderate aerobic exercise that ranged in intensity from 40%–59% HRR, and a 5-min cool-down. The protocol of warm-up, aerobic exercise (with the exception of the duration), and cool-down was consistent with that of the CET group (for which the second half of the exercise period was comprised of resistance exercise).

Reading Control (RC)

Each participant was seated in a comfortable chair and instructed to complete an exercise-related book-reading task for 35 min.

Procedure

Each participant was instructed to visit the laboratory on two occasions with an interval of at least 7 days (see Figure 1). During Visit 1, the participant was given a brief introduction to the experiment and provided their written informed consent. Thereafter, relevant anthropometric and physiological data were collated. After completing the baseline measurements, the participant's $\dot{V}O_{2\ peak}$ and 10-RM was assessed. The participant was asked to refrain from exercise participation as well as caffeine and alcohol consumption for 12 hr prior to Visit 2. During Visit 2, for a pretest, the participant was instructed to complete the Task-Switching Test while their neuro-electric activity was monitored. It was also monitored immediately after each treatment as a post-test.

Statistical Analyses

The statistical analysis was performed using SPSS version 26.0 (IBM Corp., Armonk, NY) and alpha was set at .05 prior to Bonferroni adjustment. Checks for univariate outliers ($Z > \pm 3.29$) and the relevant tests for normality assumptions were conducted (Tabachnick & Fidell, 2019). A one-way ANOVA was computed for anthropometric and

physiological data to facilitate comparison of the three groups (CET vs. AE vs. RC, presented with $M \pm SD$ throughout the results section). To determine the effects of acute exercise on behavioural measures of cognitive flexibility (i.e., response time and accuracy), one-way ANCOVA was computed for post-test scores on the Task-Switching Test on homogeneous, with the pretest Task-Switching Test score as the covariate. Similarly, one-way ANCOVA was computed for heterogeneous, non-switch, and switch conditions. Along similar lines, one-way ANCOVA was computed for mean P3 amplitudes to compare the four conditions. Mixed-model 3 (Group) × 4 (Timepoint: resting HR vs. pre-activity HR vs. treatment HR vs. post-activity HR) and 3 (Group) × 3 (Timepoint: Time 1 vs. Time 2 vs. Time 3) mixed-model ANOVAs were computed to determine the effect of acute exercise on HR and lactate, respectively. Multiple comparisons were examined where the interaction effect was significant. Greenhouse–Geisser-adjusted F ratios were used when the sphericity assumption was violated.

PROCESS Macro mediation analysis (Hayes, 2022) was applied with a simple mediation model (Hayes & Preacher, 2014) computed to determine the possible mediation of blood lactate. Specifically, “group” was converted into a dummy variable that served as the independent variable, with the RC group as a reference group. The incremental area under the lactate curve was selected as the mediator and was calculated through subtraction of the concentration of lactate at Time 1 from the concentrations at Time 2 and Time 3. Thereafter, the area under the concentration of lactate curve was calculated, with the value below Time 1 ignored and by application of the trapezoid rule (Narang et al., 2020). The post-test response time of each Task-Switching Test condition was the dependent variable, with the pretest response time was the covariate. The total effect (path c_1: CET vs. RC; c_2: AE vs. RC), the direct effect (c'_1: CET vs. RC; c'_2: AE vs. RC), the regression of group to lactate (a_1: CET vs. RC; a_2: AE vs. RC), the regression of lactate to cognitive flexibility (b), and the indirect

effect ($a_1 \times b$: CET vs. RC; $a_2 \times b$: AE vs. RC) were examined. The mediating role of blood lactate was supported when the indirect effect reached statistical significance. A confidence interval of 95% was adopted (95% CI) and the bootstrap method was used to resample the original sample 5000 times (Lacobucci, 2008). Similar mediation analyses were computed for mean P3 amplitude.

Results

Date Screening and Diagnostic Tests

Eight univariate outliers were identified and, in each case, the outlying score was modified by one unit that was either larger or smaller than the next most extreme score in the distribution (Tabachnick & Fidell, 2019). For data that were positively skewed and kurtotic ($p < 0.001$), either a square root or log transformation was applied to normalise the distribution (square root: IPAQ, the accuracy of Task-Switch Test in the homogeneous condition, and mean P3 amplitude of Task-Switch Test in the non-switch condition; log: lactate at Time 1, Time 2, and Time 3). The sphericity assumption was violated in the case of HR and lactate, so the relevant *F* tests were Greenhouse–Geisser-adjusted.

Anthropometric and Physiological Data

Analysis of the participant anthropometric and physiological data indicated no significant differences among the three groups (ps > .05; see Table 1).

Task-Switching Test

Response Time

With regard to the homogeneous condition, one-way ANCOVA indicated a significant effect of group ($p = .003$). Multiple comparisons indicated shorter response time for both CET and AE groups relative to the RC group ($p = .045$ and $p = .003$, respectively), with no difference between the CET and AE groups ($p = 1.000$). Similarly, a significant effect of group emerged in the heterogeneous condition ($p = .002$). Multiple comparisons indicated

shorter response times for both CET and AE groups relative to the RC group (p = .004 and p = .009, respectively), with no difference between the CET and AE groups (p = 1.000; see Figure 2). Full inferential and descriptive statistics are presented in the Supplementary Materials (Table S1 and Table S2).

With regard to the non-switch condition, a significant effect of group emerged (p = .002). Multiple comparisons indicated a shorter response time for both CET and AE groups relative to the RC group (p = .002 and p = .030, respectively), with no difference between the CET and AE groups (p = 1.000). Similarly, a significant effect of group emerged in the switch condition (p = .007). Multiple comparisons indicated a shorter response time for both CET and AE groups relative to the RC group (p = .035 and p = .011, respectively), with no difference between the CET and AE groups (p = 1.000).

Accuracy

One-way ANCOVA indicated no significant effects for group in the homogeneous (p = .703), heterogeneous (p = .574), non-switch (p = .672), or switch conditions (p = .766).

Mean P3 Amplitude

One-way ANCOVA indicated no significant effect of Group in the homogeneous condition (p = .304), but there was in the heterogeneous condition (p = .036). Multiple comparisons indicated a higher mean P3 amplitude for the CET group (p = .033) relative to the RC group (see Figure 2). No other differences emerged.

Along similar lines, while there was no significant effect of Group in the non-switch condition (p = .062), there was in the switch condition (p = .021). Multiple comparisons indicated a higher mean P3 amplitude for the AE relative to the RC group (p = .034). No other significant differences emerged. Stimulus-locked grand-average waveforms from parietal regions and topographic map are presented in Figure 2.

Heart Rate Manipulation Check and Lactate Change

Heart Rate

Two-way ANOVA for HR indicated a significant Group × Timepoint interaction ($p < .001$) as well as significant main effects of both group ($p < .001$) and timepoint ($p < .001$). Multiple comparisons used to examine the interaction indicated that, in the CET group, resting HR was the lowest, followed by pre-activity HR ($p < .001$), post-activity HR ($p < .001$), and treatment HR ($p < .001$). In the AE group, resting HR was the lowest, followed by pre-activity HR ($p < .001$), post-activity HR ($p < .001$), and treatment HR ($p < .001$). In the RC group, resting HR was lower than pre-activity HR ($p < .001$), treatment HR ($p = .019$), and post-activity HR ($p < .001$). There were no significant differences among pre-activity HR, treatment HR, and post-activity HR ($ps > .05$). Additionally, with regard to timepoints, there were no significant differences across groups in resting HR ($ps > .05$) and pre-activity HR ($ps > .05$). However, in post-activity HR, the CET and AE groups did not differ ($p = 1.000$), albeit both exhibited significantly higher HR than the RC group ($p < .001$). In treatment HR, the AE group exhibited the highest levels, followed by the CET ($p < .001$) and RC groups ($p < .001$).

Lactate

Two-way ANOVA for lactate, predicated on log-transformed data, indicated a significant interaction effect for Group × Timepoint ($p < .001$) as well as significant main effects of group ($p < .001$) and Timepoint ($p < .001$). For the interaction, multiple comparisons indicated that in the CET group, Time 3 exhibited the highest concentration, followed by Time 2 ($p < .001$), and Time 1 ($p < .001$). In the AE group, both Time 3 ($p = .001$) and Time 2 ($p < .001$) exhibited significantly higher concentrations than Time 1, with no differences between Time 2 and Time 3 ($p = .484$). In the RC group, no differences emerged ($ps > .05$). Moreover, with regard to timepoint, there was no significant difference

among groups at Time 1 (*p*s > .005). However, at Time 2, CET and AE groups did not differ ($p = 1.000$), but both were significantly higher than the RC group (*p*s < .001). At Time 3, the CET group exhibited the highest concentration, followed by the AE and RC groups (*p*s < 0.001).

Mediation Analysis of Blood Lactate in Acute Exercise Effect on Cognitive Flexibility

Response Time

There was no significant indirect effect of blood lactate in the effect of exercise on cognitive flexibility in the CET group (95% CIs: −71.89–5.11) and AE group (95% CIs: −35.16–2.43) in the homogeneous condition. In the heterogeneous condition, however, a significant lactate indirect effect emerged in both CET (95% CIs: −66.50 to −3.89) and AE groups (95% CIs: −36.41 to −1.44; see Figure 3 and Table 2).

Similarly, while a significant indirect effect of lactate was observed in terms of the exercise effect on cognitive flexibility in the CET (95% CIs: −61.46–2.89) and AE groups (95% CIs: −31.62–1.12) in the non−switch condition, a significant mediation of lactate emerged in both CET (95% CIs: −80.09 to −11.28) and AE groups (95% CIs: −44.79 to −3.90) in the switch condition.

Mean P3 Amplitude

A significant indirect effect of lactate in the effect of exercise on mean P3 amplitude did not emerge in both the CET and AE groups in the homogeneous (95% CIs: CET: −1.49–2.20, AE: −0.74–1.09), heterogeneous (95% CIs: CET: −1.27–0.60, AE: −0.61–0.30) non−switch (95% CIs: CET: −1.22–0.73, AE: −0.58–0.36), and switch conditions (95% CIs: CET: −1.56–0.46, AE: −0.79–0.23).

Discussion

The present study is among the first to examine the effects of acute exercise on executive function using CET. We assessed executive function using behavioural and neuro-

electric measures, while also determining the mediating role of blood lactate. The behavioural results indicate that both CET and AE reduce the response time across all conditions of the Task-Switching Test when compared to RC. Additionally, greater P3 amplitude was observed for the CET group in the heterogeneous condition and AE in the switch condition, when compared to RC (see Figure 2). Notably, while a significant mediation of lactate for response time emerged in both exercise modalities in the heterogeneous and switch conditions, the mediational role of lactate was not represented in P3 amplitude (see Table 2 and Figure 3).

Acute Exercise and Cognitive Function in Behavioural Measures

The finding of shorter response time with no difference in accuracy following exercise is indicative of improved executive function and not a consequence of the speed–accuracy trade-off (Fitts, 1992). The finding concurs with that of meta-analyses indicating that AE facilitates executive function (Chang et al., 2012; Ishihara et al., 2021; Ludyga et al., 2016). It also supports the findings of experimental studies that have reported increased cognitive flexibility following acute AE (Bae & Masaki, 2019; Tian et al., 2021; Tsai et al., 2016). It is worth noting that the present acute AE, structured within a 30-min moderate-intensity session (inc. warm-up and cool-down), replicated the PAGA recommendation in relation to eliciting enhancements in cognitive function (Erickson et al., 2019; Piercy et al., 2018).

The novelty in the present findings pertains to the observation that CET showed a similar facilitation for cognitive flexibility as AE. Past studies have demonstrated this facilitation immediately after aerobic *or* resistance exercise (Oberste et al., 2021; Wu et al., 2019), while this study extends the effect to the CET modality. Cognitive flexibility reflects rapid shifts in attentional focus to enable adjustment to new demands, rules, or priorities (Diamond, 2013; Friedman & Miyake, 2017). Improved cognitive flexibility might be implicated in other forms of executive function. Processing cognitive flexibility as a higher-

order facet of core executive function often engages the other core executive functions such as inhibition and working memory (Diamond, 2013). Inhibition serves to impede the interference of the previous rule, whereby working memory acts to respond the stimuli associated with the current rule while maintaining the preceding rule (Dajani & Uddin, 2015). It is the case that acute aerobic exercise and resistance exercise have been found to confer benefits to inhibition (Chang et al., 2015; Wang et al., 2019) and working memory (Pontifex et al., 2009; Weng et al., 2015). This, in turn, provides the possibility of improved cognitive flexibility from alterations in inhibition and working memory. More experimental work is needed to explore the role of inhibition and working memory on the improved cognitive flexibility induced by acute exercise.

While both acute aerobic and resistance-type exercise have both *independently* been shown to improve cognitive flexibility (e.g., Wu et al., 2019), CET is comprised, in equal measure, of two exercise modalities without increasing the total amount of exercise, relative to AE. The present results stands somewhat in contrast to those of a recent related study that was unable to detect inhibition alteration following an exercise protocol that involved both aerobic and resistance modalities (Wen & Tsai, 2020). While the discrepancy between studies might be attributed to the different aspects of executive function examined, the Wen and Tsai protocol entailed a 15-s break with 1-min aerobic or resistance exercise, which differs from the present protocol (continuous, not intermittent). Accordingly, the beneficial effects of CET-type protocols might be demonstrated through the seamless integration of aerobic and resistance-type modalities, which is a consideration for future practice.

Acute Exercise, Cognitive Function and Neuro-Electric Measures

Our neuro-electric findings show that the positive effect of acute exercise on cognitive flexibility is both exercise modality and amount-of-executive-control dependent. Specifically, larger P3 amplitudes of heterogeneous and switching conditions were observed

in both the CET and AE groups compared to RC, respectively (see Figure 2). Relative to the homogeneous and non-switch conditions that required stimulus response based on a single rule, possibly reflecting lower-order cognitive function (e.g., attention; Dajani & Uddin, 2015; Monsell, 2003), performing the heterogeneous and switch conditions made concurrent demands upon inhibition and working memory (i.e., the had higher cognitive demand; Monsell, 2003).

Although previous work has shown that acute AE has larger P3 amplitudes in switch conditions relative to a control group in tasks relating to cognitive flexibility (Bae & Masaki, 2019; Wu et al., 2019), as well as those associated with inhibition and working memory (Chu et al., 2015; Hsieh et al., 2018; Kao, Wang, & Hillman, 2020), the present findings serve to extend the beneficial effects from AE to CET. In contrast, previous studies have suggested the "general improvement hypothesis", which posits that acute exercise increases P3 amplitude regardless of cognitive demands (Aly & Kojima, 2020; Chang et al., 2017). It is worth noting that a recent meta-analysis has indicated that acute exercise enhances P3 amplitude specifically in terms of cognitive flexibility, rather than lower cognitive demand tasks (Kao et al., 2022). Given that P3 amplitude is an indicator of attentional resource allocation and superior cognitive performance (Polich, 2007), the results suggest that both CET and AE would facilitate allocation of attentional resources, particularly under conditions with higher executive function demands.

Mediation of Lactate

Another novel finding is that the improved cognitive flexibility following acute CET and AE was mediated by blood lactate in both the heterogeneous and switch conditions. Lactate has traditionally been thought of as a metabolic waste product and an index of exercise fatigue; latterly, however, its role in energy supply has been coming to the fore (Ferguson et al., 2018). Specifically, that lactate facilitates the use of energy substrate in

extracellular space for the energy requirements of synaptic activity (Hashimoto et al., 2021; Xue et al., 2022). Accordingly, the lactate induced by acute exercise might satisfy the requirements of neuronal metabolism in the brain. Lactate also activates the sympathetic nervous system through stimulating the adrenal glands and releasing peripheral epinephrine. This further induces phosphorylase secretion, which promotes glycolysis and produces lactate (Burnley et al., 2006). Nonetheless, activation of the sympathetic nervous system elevates psychomotor arousal (c.f., the fight or flight response; Waxenbaum et al., 2022), which engenders acceleration of mental processes that include an increase in memory storage and retrieval (Lambourne & Tomporowski, 2010).

Notably, acute CET elicited higher *t* values in the mediation analysis compared with AE (i.e., heterogeneous condition: −35.45 vs. −16.99 and switch conditions: −45.05 vs. −21.56). The discrepancy might be caused by lactate concentrations induced by different exercise modalities. Similar to earlier findings (Tsuchiya et al., 2015), our results show a higher lactate concentration induced by CET than AE. The differences in lactate concentration could well be associated with the different metabolic systems that are germane to these exercise modalities. Resistance exercise is dominated by the anaerobic system, which uses glycogen as an energy source in anaerobic glycolysis. A by-product of this metabolic process is lactic acid, meaning that there is an increase in the concentration of lactate in the blood. Contrastingly, AE is dominated by the aerobic system, which uses lactic acid as an energy source in gluconeogenesis. This results in a lower concentration of blood lactate (Kenney et al., 2022). The present results not only extend current literature by identifying the role of lactate as a mediating variable between acute exercise and executive function, but also confirm that CET differs from AE from a metabolic standpoint.

A direct effect, but not an indirect effect of lactate, emerged between acute exercise and P3 amplitudes. The direct effect represents the regression of acute exercise on P3

amplitudes without consideration of lactate and this finding implicates another mechanism. Specifically, that the Locus Coeruleus–Norepinephrine (LC–NE) system mediates the effect of acute exercise on neuro-electric activation. Norepinephrine, an essential neurotransmitter in the functional central neural system, is concentrated in *locus coeruleus*, which provides the energy source of norepinephrine to the cortex and hippocampus for higher cognitive and affective processes (Berridge & Waterhouse, 2003). Given that the P3 component is related to the enhancement of local neural responses evoked by the LC–NE system (Nieuwenhuis et al., 2005) and that acute exercise increased the cognitive performance and activation associated with the LC–NE system (Shigeta et al., 2021), the present findings suggest that the LC–NE system might be a possible candidate as a mediator in the effect of acute exercise on the neuroleptic activation elicited by executive function.

Strengths and Limitations

This is not only among the first studies to examine the effects of acute CET on executive function from a behavioural and neuro-electric perspective, but also to apply a mediation analysis to determine the mediating role of lactate in acute exercise. Additionally, the results are derived from a between-subjects design with a pretest cognitive measure used as a covariate to provide higher internal validity and moderate any potential underestimation of the facilitation effect that follows acute exercise (Ishihara et al., 2021).

There are, however, several limitations that warrant mention. First, the CET protocol was arranged in the order of aerobic followed by resistance exercise, which is likely to elicit a higher blood lactate concentration than the converse (Jones et al., 2017). Given that the present findings cannot be generalised to the resistance–aerobic exercise sequence, the positive effects associated with CET warrant further exploration to address any potential treatment order effects. Second, these researchers conducted separate statistical analyses for response time and accuracy, based on the approach of previous studies (Aly & Kojima, 2020;

Kao, Wang, & Hillman, 2020; Wu et al., 2019). Given the trade-off relationship between response time and accuracy, a multivariate approach (i.e., MANOVA) could be employed to examine both dimensions as a composite variable. Third, the lactate assayed from peripheral blood will not be entirely representative of lactate utilisation in the brain (Hashimoto et al., 2018). Lastly, rather than a being a unified concept, executive function embraces distinct components (inhibition, cognitive flexibility, and working memory) and so whether the present findings apply to inhibition and working memory is a question that will need to be addressed in future research.

Conclusions

The present findings suggest that acute concurrent exercise that combines aerobic and resistance-type exercise elicits behavioural and neuro-electric responses that are positively associated with the cognitive flexibility dimension of executive function. The benefits derived from CET were similar to those from AE. Additionally, blood lactate serves as a mediator of acute exercise on executive function from a behavioural perspective. Nonetheless, an alternative mediator of neuro-electric activation induced by acute exercise might be considered. CET is proposed as an exercise modality that can be adopted to engender enhancements in cognitive function. There is a need for further research to elucidate whether and how CET can affect the main components of executive function.

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Table 1

*Participant Anthropometric and Physiological Descriptive Data (*M ± SD*)*

	CET (*n* = 26)	AE (*n* = 26)	RC (*n* = 26)	*p*
Sex (male/female)	12/14	13/13	13/13	
Age (years)	22.81 ± 2.00	22.85 ± 1.54	22.81 ± 1.90	1.00
Height (m)	1.66 ± 0.08	1.67 ± 0.09	1.68 ± 0.10	.69
Weight (kg)	58.63 ± 7.54	57.21 ± 9.13	61.77 ± 10.00	.18
BMI (kg/m^2)	21.25 ± 2.02	20.42 ± 2.42	21.72 ± 1.82	.09
Digit Span Test				
Forward	14.81 ± 1.30	15.08 ± 0.98	15.08 ± 0.98	.59
Backward	10.73 ± 2.33	10.65 ± 2.23	10.85 ± 2.62	.96
IPAQ (MET/min/week)	1162.67 ± 1157.58	745.12 ± 634.58	1056.21 ± 1274.07	.42
$\dot{V}O_{2\ peak}$ ($ml/kg^{/}min$)	35.81 ± 6.06	33.65 ± 3.90	35.25 ± 5.92	.33
10-RM (lb)				
Chest press	56.77 ± 32.69	56.64 ± 33.48	58.86 ± 31.37	.96
Rowing	84.70 ± 23.53	87.42 ± 31.53	90.72 ± 31.34	.76
Lat pull down	63.15 ± 21.21	63.78 ± 21.14	64.92 ± 21.05	.95
Shoulder press	60.06 ± 19.85	58.54 ± 20.84	60.34 ± 20.97	.94
Arm curl	40.94 ± 17.05	38.00 ± 18.63	41.78 ± 18.08	.73
Leg extension	102.94 ± 28.35	103.62 ± 39.13	105.89 ± 27.86	.94
Leg press	201.46 ± 50.70	195.69 ± 60.38	208.40 ± 52.88	.71
Leg curl	66.77 ± 16.19	69.77 ± 23.90	69.86 ± 19.70	.82
RPE	12.84 ± 2.00	13.09 ± 1.86	-	.64

Note. The descriptive statistics are pre-transformation. The *p*-value for the forward component of the Digit Span Test relates to post-transformation data. CET = concurrent

exercise training group; AE = aerobic exercise group; RC = reading control group; BMI = body mass index; IPAQ = International Physical Activity Questionnaire; MET = metabolic equivalent; 10-RM = 10-repetition maximum; RPE = rating of perceived exertion.

Table 2

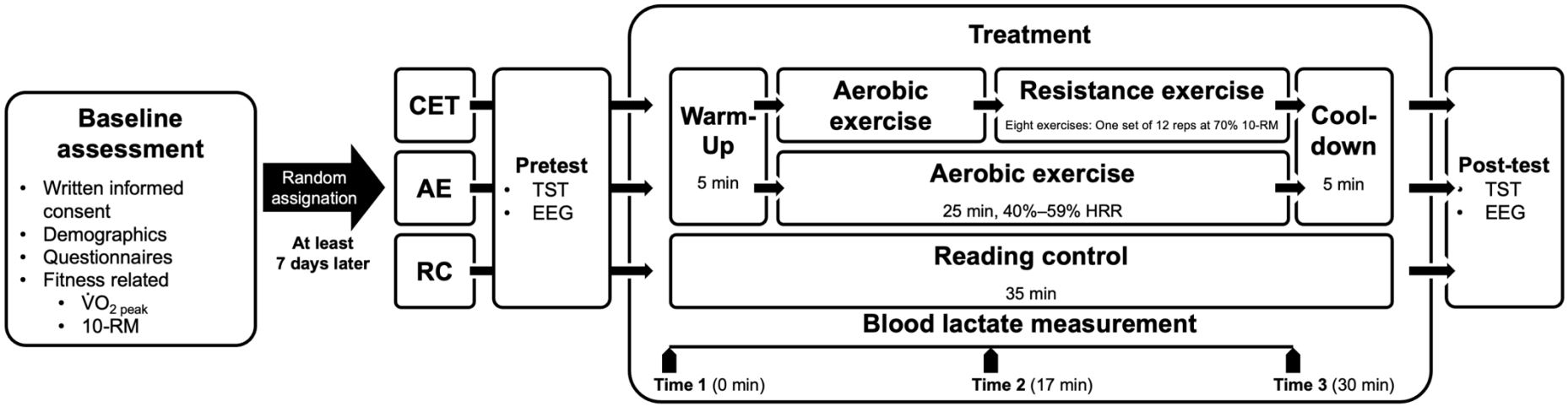
*The Mediation Effect of Blood Lactate Concentration in the Effect of Acute Exercise on Response Time and Mean P3 Amplitudes (*M ± SE *[*CI*])*

Group/Condition		Path *b*	Path *a*	Total effect (Path *c*)	Direct effect (Path *c*)	Indirect effect (Path *a* × *b*)
Cognitive flexibility						
CET	Homogeneous	−0.40 ± 0.25 [−0.89, 0.10]	73.04 ± 9.60 **[53.91, 92.18]**	−51.84 ± 20.80 **[−93.28, −10.40]**	−22.80 ± 27.47 [−77.56, 31.95]	−29.03 ± 19.65 [−71.89, 5.11]
	Heterogeneous	−0.49 ± 0.19 **[−0.87, −0.11]**	72.28 ± 9.64 **[53.07, 91.49]**	−55.50 ± 16.48 **[−88.33, −22.66]**	−20.04 ± 21.08 [−62.06, 21.97]	−35.45 ± 15.90 **[−66.50, −3.89]**
	Non-switch	−0.36 ± 0.20 [−0.75, 0.02]	72.07 ± 9.64 **[52.87, 91.27]**	−59.75 ± 16.45 **[−92.52, −26.98]**	−33.47 ± 21.44 [−76.19, 9.26]	−26.28 ± 15.99 [−61.46, 2.89]
	Switch	−0.62 ± 0.22 **[−1.05, −0.19]**	72.37 ± 9.65 **[53.14, 91.60]**	−48.86 ± 18.87 **[−86.45, −11.27]**	−3.81 ± 23.89 [−51.42, 43.80]	−45.05 ± 17.22 **[−80.09, −11.28]**
AE	Homogeneous	−0.40 ± 0.25 [−0.89, 0.10]	35.60 ± 9.63 **[16.41, 54.79]**	−70.48 ± 20.85 **[−112.03, −28.93]**	−56.33 ± 22.46 **[−101.10, −11.56]**	−14.15 ± 9.60 [−35.16, 2.43]
	Heterogeneous	−0.49 ± 0.19 **[−0.87, −0.11]**	34.64 ± 9.64 **[15.43, 53.85]**	−50.71 ± 16.48 **[−83.55, −17.87]**	−33.72 ± 17.23 [−68.05, 0.61]	−16.99 ± 8.96 **[−36.41, −1.44]**
	Non-switch	−0.36 ± 0.20 [−0.75, 0.02]	34.60 ± 9.63 **[15.42, 53.78]**	−43.50 ± 16.43 **[−76.24, −10.76]**	−30.88 ± 17.52 [−65.79, 4.02]	−12.62 ± 8.39 [−31.62, 1.12]
	Switch	−0.62 ± 0.22 **[−1.05, −0.19]**	34.63 ± 9.65 **[15.40, 53.87]**	−56.80 ± 18.87 **[−94.40, −19.19]**	−35.24 ± 19.58 [−74.14, 3.66]	−21.56 ± 10.36 **[−44.79, −3.90]**
Mean P3 amplitudes						
CET	Homogeneous	0.00 ± 0.01 [−0.01, 0.02]	72.23 ± 9.76 **[52.79, 91.67]**	−0.81 ± 0.83 [−2.46, 0.83]	−1.17 ± 1.10 [−3.36, 1.02]	0.36 ± 0.93 [−1.49, 2.20]
	Heterogeneous	−0.00 ± 0.01 [−0.02, 0.01]	65.43 ± 10.01 **[45.48, 85.38]**	1.61 ± 0.62 **[0.38, 2.84]**	1.93 ± 0.78 **[0.38, 3.48]**	−0.32 ± 0.46 [−1.27, 0.60]
	Non-switch	−0.00 ± 0.01 [−0.02, 0.01]	65.94 ± 9.97 **[46.08, 85.80]**	1.39 ± 0.66 **[0.08, 2.69]**	1.64 ± 0.83 [−0.02, 3.30]	−0.26 ± 0.49 [−1.22, 0.73]
	Switch	−0.01 ± 0.01 [−0.02, 0.01]	65.84 ± 10.02 **[45.88, 85.80]**	1.62 ± 0.69 **[0.24, 3.00]**	2.12 ± 0.87 **[0.38, 3.85]**	−0.50 ± 0.51 [−1.56, 0.46]
AE	Homogeneous	0.00 ± 0.01 [−0.01, 0.02]	34.55 ± 9.65 **[15.31, 53.78]**	−1.25 ± 0.82 [−2.88, 0.37]	−1.43 ± 0.89 [−3.20, 0.35]	0.17 ± 0.46 [−0.74, 1.09]
	Heterogeneous	−0.00 ± 0.01 [−0.02, 0.01]	31.50 ± 9.52 **[12.52, 50.47]**	1.01 ± 0.59 [−0.16, 2.18]	1.17 ± 0.63 [−0.09, 2.42]	−0.15 ± 0.22 [−0.61, 0.30]
	Non-switch	−0.00 ± 0.01 [−0.02, 0.01]	31.84 ± 9.51 **[12.88, 50.80]**	0.22 ± 0.63 [−1.03, 1.47]	0.35 ± 0.68 [−1.00, 1.69]	−0.12 ± 0.24 [−0.58, 0.36]
	Switch	−0.01 ± 0.01 [−0.02, 0.01]	31.57 ± 9.55 **[12.53, 50.60]**	1.72 ± 0.66 **[0.40, 3.03]**	1.96 ± 0.71 **[0.55, 3.36]**	−0.24 ± 0.25 [−0.79, 0.23]

Note. Bold typeface denotes those confidence intervals that do not contain zero. The data presented are pre-transformation.

Figure 1

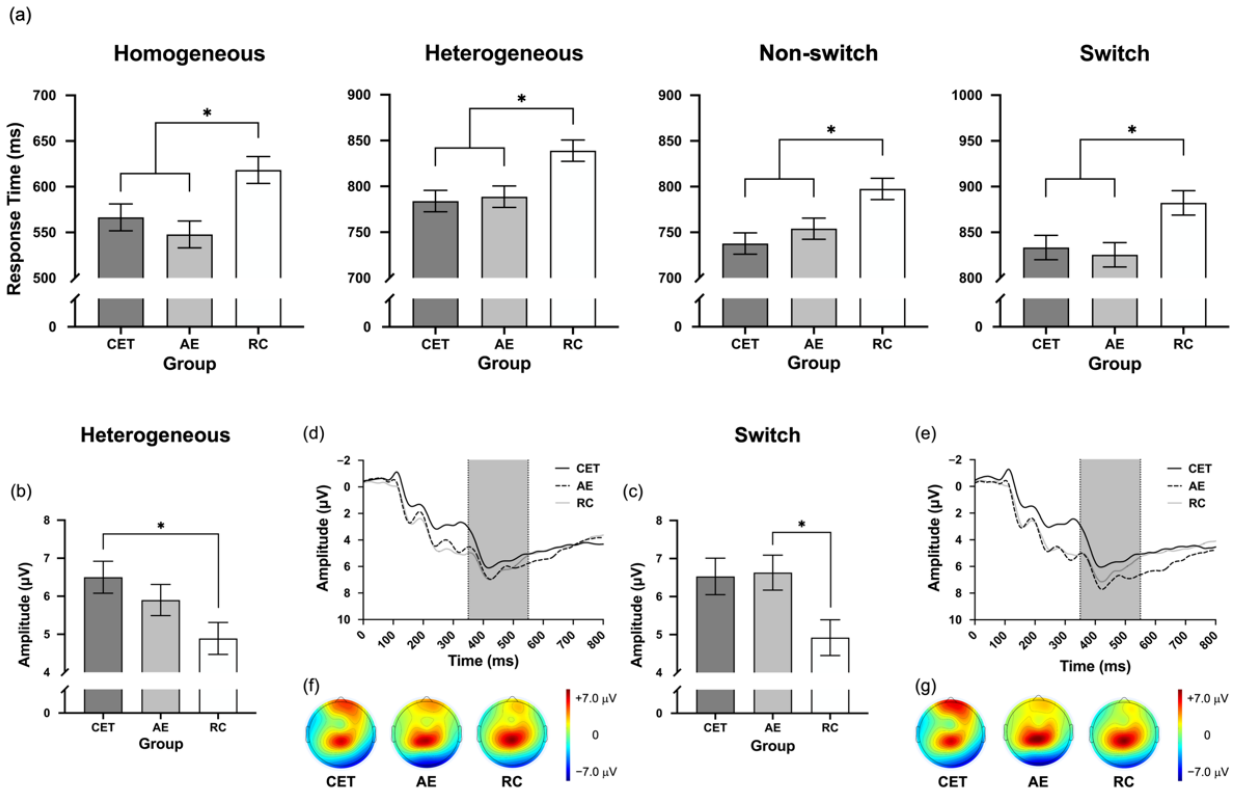
A Schematic of the Experimental Protocol



Note. CET = concurrent exercise training group; AE = aerobic exercise group; RC = reading control group; 10-RM = 10-repetition maximum; TST = Task-Switching Test; EEG = electroencephalography; rep = repetition; HRR = heart rate reserve.

Figure 2

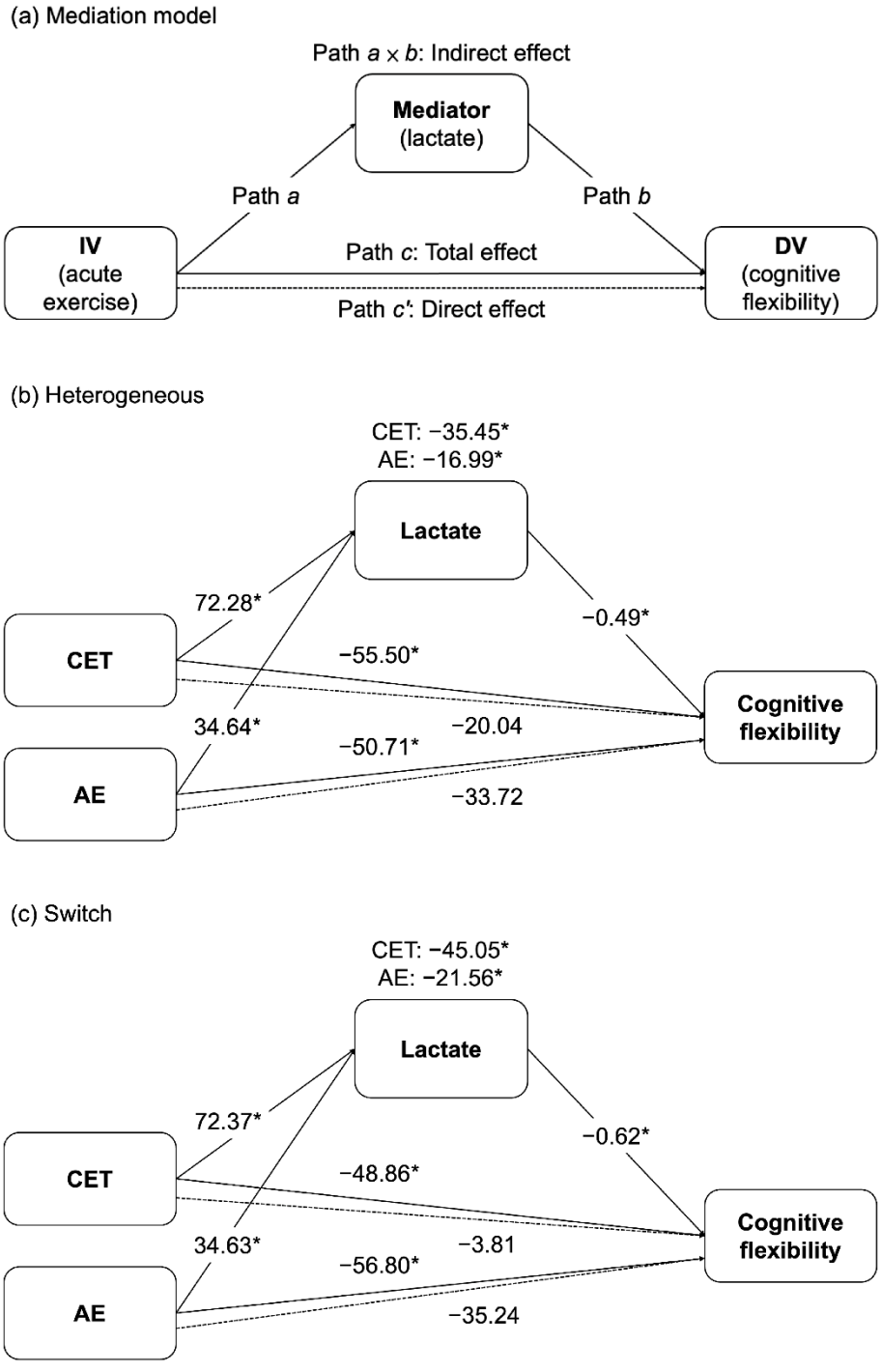
*(a) Response Time of the Homogeneous, Heterogeneous, Non-switch, and Switch Conditions Across Concurrent Exercise Training (CET), Aerobic Exercise (AE), and Reading Control (RC) Groups (M ± 1SE). Post-Test of Mean P3 Amplitude (*M ± *1*SE*) After Controlling for the Pretest Across Three Groups in (b) Heterogeneous and (c) Switch Conditions; Post-Test of Grand-Average ERPs Across Three Groups in the (d) Heterogeneous and (e) Switch Conditions; Post-Test of Topographic Distribution (350–550 ms) Across Three Groups in the (f) Heterogeneous and (g) Switch Conditions.*



Note. The data presented are pre-transformation. *$p < .05$.

Figure 3

The Mediation Model (a). The Mediation Effect of Response Time in the Task-Switching Test (b) Heterogeneous, and (c) Switch Conditions.



Note. The data presented are pre-transformation. IV = independent variable; DV = dependent variable; CET = concurrent exercise training group; AE = aerobic exercise group; RC = reading control group. *$p < .05$.

Supplementary Material

Table S1

Inferential Statistics Derived from ANCOVA and Mixed-Model ANOVA

Measures	*F*	*df*	*p*	η_p^2
Response time				
Homogeneous	6.13	2, 74	0.003	0.14
Heterogeneous	6.97	2, 74	0.002	0.16
Non-switch	7.06	2, 74	0.002	0.16
Switch	5.31	2, 74	0.007	0.13
Accuracy				
Homogeneous	0.35	2, 74	0.703	0.01
Heterogeneous	0.56	2, 74	0.574	0.02
Non-switch	0.40	2, 74	0.672	0.01
Switch	0.27	2, 74	0.766	0.01
Mean P3 amplitude				
Homogeneous	1.21	2, 74	0.304	0.03
Heterogeneous	3.49	2, 74	0.036	0.09
Non-switch	2.88	2, 74	0.062	0.07
Switch	4.05	2, 74	0.021	0.10
HR				
Group × Timepoint	275.298	5.36, 200.97	< 0.001	0.88
Group	66.49	2, 75	< 0.001	0.64
Timepoint	1155.23	2.68, 200.97	< 0.001	0.94

Lactate				
Group × Timepoint	16.55	3.59, 134.76	< 0.001	0.31
Group	37.16	2,75	< 0.001	0.50
Timepoint	32.09	1.80, 134.76	< 0.001	0.30

Note. The inferential statistics presented herein are derived from transformed data in the case of accuracy in the homogeneous condition, mean P3 amplitude in the non-switch condition, and lactate. HR = heart rate.

Table S2

*Descriptive Statistics for the Experimental and Control Groups (*M ± SE*)*

	CET	AE	RC
Response time (ms)			
Homogeneous	566.46 ± 14.67	547.82 ± 14.70	618.30 ± 14.72
Heterogeneous	783.97 ± 11.65	788.76 ± 11.66	839.46 ± 11.65
Non-switch	737.73 ± 11.63	753.98 ± 11.62	797.48 ± 11.62
Switch	833.32 ± 13.34	825.39 ± 13.34	882.18 ± 13.34
Accuracy (%)			
Homogeneous	98.12 ± 0.32	97.90 ± 0.32	98.01 ± 0.32
Heterogeneous	94.71 ± 0.63	94.27 ± 0.63	93.77 ± 0.63
Non-switch	95.20 ± 0.61	95.09 ± 0.61	94.48 ± 0.61
Switch	93.96 ± 0.74	93.55 ± 0.75	93.19 ± 0.74
Mean P3 amplitudes (μV)			
Homogeneous	4.65 ± 0.58	4.21 ± 0.58	5.47 ± 0.58
Heterogeneous	6.50 ± 0.42	5.90 ± 0.41	4.89 ± 0.42
Non-switch	6.35 ± 0.45	5.19 ± 0.44	4.96 ± 0.45
Switch	6.53 ± 0.48	6.63 ± 0.46	4.92 ± 0.47
HR (bpm)			
Resting	70.42 ± 1.37	71.00 ± 1.37	67.12 ± 1.37
Pre-activity	77.25 ± 1.68	79.44 ± 1.68	75.52 ± 1.68
Treatment	121.16 ± 1.37	130.67 ± 1.37	72.00 ± 1.37
Post-activity	89.14 ± 1.76	88.64 ± 1.76	72.56 ± 1.76

Lactate (mmol/l)			
Pre-activity	2.95 ± 0.32	3.09 ± 0.32	2.40 ± 0.32
Mid-activity	5.58 ± 0.41	5.27 ± 0.41	2.13 ± 0.41
Post-activity	8.94 ± 0.44	4.65 ± 0.44	2.44 ± 0.44

Note. These descriptive statistics are pre-transformation. CET = concurrent exercise training group; AE = aerobic exercise group; RC = reading control group.