BJMB
Brazilian Journal of Motor Behavior

Research Article

Acute low- and higher-volume resistance circuit training improves immediate and short-term cognition in young adults

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https://doi.org/10.20338/bjmb.v18i1.445

HIGHLIGHTS

• Both low- and higher-volume circuit training incorporating resistance exercise improves performance in complex but not simple information processing tasks in young adults.
• Only higher-volume circuit training incorporating resistance exercise improves executive functioning in young adults.
• Acute exercise facilitates correct choice response and inhibits competing choices in multichoice and dual-task conditions, increasing cortical processing speed.
• Previous investigations support these findings, showing that acute exercise improves executive and non-executive functioning in adults.

ABBREVIATIONS

BNDF	Brain-Derived Neurotrophic Factor
CON	Non-exercise-control
DT	Dual-task
FPN	Frontoparietal Network
HRR	Heart rate reserve
HV-RCT	Higher Volume RCT
IGF-1	Insulin Growth Factor-1
LV-RCT	Low Volume RCT
MC	Multichoice
METs	Metabolic Equivalents
MMSE	Mini-Mental State Exam
MT	Movement time
η^2	Eta square
PFC	Prefrontal cortex
RCT	Resistance circuit training
RPT	Response time
RT	Reaction time
SC	Single choice
TMT	Trail Making Test
1-RM	1-repetition maximum

PUBLICATION DATA
Received 10 11 2024
Accepted 02 01 2025
Published 05 01 2025

BACKGROUND: Exercise's significance in promoting health and fitness cannot be overstated. In addition, various exercises have been shown to enhance cognition. The combination of aerobic and strength benefits in resistance circuit training (RCT) offers a unique opportunity to study how two different outcomes of exercise interact to enhance cognitive function. Such research could lead to new recommendations for improving cognitive and motor performance.
AIM: The present study investigated the role of two volumes of resistance circuit training (Low Volume [LV-RCT] of approximately 11 min and Higher Volume [HV-RCT] of approximately 23 min) on information processing speed and executive function.
METHOD: Thirty adult male and female volunteers (18, male; 12, female) between the ages of 18-25 (mean [± standard deviation]: 22.37 ±2.06) were randomly recruited and assigned to either a non-exercise-control (CON), an LV-RCT, or an HV-RCT group. Participants took part in an introductory session followed one day later by an exercise session. During the exercise session, participants participated in timed single-choice, multichoice, and dual-task response-time tasks to ascertain information processing and the Trail Making Test to ascertain executive functioning. Information processing was analyzed by fractionating total response time into reaction and movement times. In the exercise session, measurements were taken pre-exercise, 1 min (immediately), and 20 min (short-term) postexercise. The observed benefits in the intervention groups were compared to those in the control group using repeated measures ANOVA.
RESULTS: The following outcomes were found: (1) on the single-choice task, there were no significant differences among groups; (2) on the multichoice task and dual-task, both RCT groups displayed decreased reaction ($p < 0.05$, $\eta^2 = 0.04$, $p < 0.01$, $\eta^2 = 0.04$, respectively) and response times ($p < 0.05$, $\eta^2 = 0.05$, $p < 0.001$, $\eta^2 = 0.10$, respectively) postexercise, with no differences between RCT groups; and (3) On the Trail Making Test, participants in the HV-RCT condition, and not the LV-RCT condition, improved their executive function scores ($p < 0.05$, $\eta^2 = 0.06$).
CONCLUSION: Despite small effect sizes for some data, results indicated that resistance circuit training can improve young adults' cognitive processing speed on complex stimulus-response tasks and executive functioning. The combination of aerobic and strength benefits found in circuit training emerges as a unique opportunity to study how two different outcomes of exercise interact to enhance cognitive function.

KEYWORDS: Circuit training | Executive function | Information processing | Cognition | Response time

INTRODUCTION

Exercise's significance in promoting health and fitness cannot be overstated. Regular physical activity is a cornerstone of health and well-being [1]. Beyond the physical realm, exercise's mental health and cognitive benefits are also significant [2]. Although most research in this area has focused on chronic physical activity and its relationship to cognition, more recent investigations have investigated how acute exercise affects various components of cognitive functioning [3].

One important cognitive function involves information processing and using reaction (RT), movement (MT), and response (RPT) times to infer such capacity [3]. Reaction time is when the stimulus is recognized and processed; MT is the time from the conclusion of RT to completing the motor response; and RPT is the entire process from stimulus recognition to completion of the motor task. One may think of RPT as the capacity to rapidly respond to a stimulus and involves sensory, perceptual, and motor processes.

Another important cognitive function is executive functioning. Executive function is generally conceptualized as 'higher level' or 'metacognitive' functioning that oversees other more basic cognitive functions such as regulating emotions and attention and is often described as the brain's internal management system [4]. Executive function includes three core domains: inhibitory control (the ability to make appropriate decisions without being affected by internal tendencies or external distractions), cognitive flexibility (the ability to use inhibitory control and working memory to alter or redress one's perspective of, and approach to, a given situation), and working memory (the ability to store or update specific information in response to task demands). Both speed of information processing and executive function are associated with academic performance, vocational achievement, and positive social relationships and are key determinants of successful aging [5].

Researchers have demonstrated that aerobic exercise can improve information processing and the core domains of executive functioning [2,6]. Although not as prevalent as aerobic exercise, resistance exercise [5] and exercise using a combination of aerobic and resistance exercise [7] have also been shown to enhance these functions. Exercise is believed to improve cognitive performance because it acts as a 'physiological stressor,' elevating concentrations of lactate [7], catecholamines, and/or brain-derived neurotrophins [2,8], such as Brain-Derived Neurotrophic Factor (BDNF), Insulin Growth Factor-1 (IGF-1), Vascular Endothelial Growth Factor (VEGF), and Irisin, that are involved in attention and cognitive processes.

According to Martineau et al. [3], the elevation of these key biochemicals in the cortex can influence the functioning of the Frontoparietal Network (FPN), which is involved in many functions, including decision-making, task-switching, response inhibition, attention, and executive function during goal-directed tasks. The prefrontal cortex (PFC) is responsible for the flexible allocation of cognitive resources and helps prioritize information based on task relevance. Concurrently, the parietal cortex maintains and shifts attention across different stimuli. This coordination ensures that individuals can focus on pertinent tasks, suppress distractions, and engage in goal-directed movements. In addition, the FPN directly interacts with the basal ganglia and motor and premotor regions and is involved in planning, coordinating, and executing voluntary motor actions. Overall, exercise appears to increase concentrations of key biochemicals in the cortex and influence cortical areas that impact sensorimotor behavior [2,3].

A particular type of exercise that has not been investigated sufficiently as affecting cognition is resistance circuit training (RCT). Circuit training is a popular, time-efficient exercise mode and is an excellent way of simultaneously improving cardiovascular fitness, body composition, muscular strength, and muscular endurance [9]. Circuit training programs can either incorporate resistance exercises exclusively, cardiovascular exercises exclusively, or a combination of both resistance and cardiovascular exercises. Resistance circuit training routinely involves rotating through up to 12 exercises targeting different muscle groups. In RCT regimens, participants complete a series of exercises for a certain number of repetitions (typically 12-20) or for a certain amount of time (typically between 30- to 60 s), moving from one exercise to another exercise for the same number of repetitions or time with little or no rest between exercises. When performed properly, RCT routines can elevate heart rate and keep it elevated throughout the entire circuit session, thereby creating an aerobic effect [9]. Moreover, like traditional resistance exercise programs, RCT programs can be differentiated by volume and intensity, where volume describes how much work is performed throughout a training session (e.g., number of repetitions performed and/or the number of circuits performed), and where intensity describes the difficulty or the amount of resistance used.

Purpose

Research into the relationship between circuit training and cognition is important for several reasons: Firstly, it may offer insights into how exercise influences brain health, provide alternative methods for enhancing cognitive performance, and contribute to preventing or mitigating cognitive decline. Secondly, the effect of RCT on an individual's speed of responding and decision-making to an external stimulus has several important implications for understanding the interaction between cognition and motor performance. Improving response time is crucial in sports, as well as being important in performing activities of daily living. The combination of aerobic and strength benefits of RCT offers a unique opportunity to study how two different outcomes of exercise interact to enhance cognition and motor behavior.

According to Chen et al. [7], further research into the acute effects of exercise with aerobic and resistance exercise components on cognitive processes and executive function is warranted. No studies were found investigating the impact of volume-based RCT programs on cognition and executive functioning. Accordingly, this investigation explored the acute effects of low and higher-volume RCT protocols (LV-RCT and HV-RCT, respectively) on cognition and executive functioning in young adults. It was hypothesized that such an exercise routine would be a potent stressor facilitating cognition in young adults.

METHODS

Participants

Using an effect size of $\eta^2 < 0.14$ as an estimate for a power analysis (1-ß = .80) based on repeated measures ANOVA, a power analysis suggested a minimum sample size of 40 participants; however, due to logistical problems encountered in accessing the circuit training area, a smaller number of participants engaged in the experiment. Thirty participants (18, male; 12, female) between the ages of 18-25 (mean [± standard deviation]: 22.37 ±2.06) were randomly recruited from seacoast New Hampshire and took part in single choice (SC; participants responded to a stimulus light by pressing a response button), multichoice (MC, 5-choices: participants responded to differently colored stimulus lights by pressing the appropriate corresponding response buttons), and dual-task (DT: counting backward by seven whilst performing the MC task) conditions to assess information processing [3] and the Trail Making Test Parts A and B (TMT-A and B) to assess executive function [4], before and after an acute bout of one of three volumes of RCT: a non-exercise Control [CON] condition, in which participants did not exercise and solely sat quietly in the circuit training exercise space; (2) an LV-RCT condition, in which participants completed one circuit of the prescribed exercises; or (3) an HV-RCT condition, in which participants completed two circuits of the prescribed exercises. Each group contained equal numbers of male (6) and female (4) participants.

Participants were recreationally active, exercising 3-5 days/week for approximately 1 hr/session, and based on a physical and mental health questionnaire and the Mini-Mental State Exam (MMSE), had normal cognitive function. Participants were excluded from taking part in the study if they: (1) scored below 25 points on the MMSE; (2) participated competitively in endurance or weight training-related activities; (3) had a serious chronic mental, central nervous system, or cardiac issues; (4) were on antidepressants or anxiolytics; (5) had respiratory, orthopedic, or arthritic conditions that may impede performing the RCT programs; and/or (6) had a history of traumatic brain injuries or attention-deficit/hyperactivity disorder. Exclusion criteria before partaking in both session one and session two included not performing moderate to strenuous aerobic activity within 12 hours before each session (moderate [3–6 Metabolic Equivalents] to vigorous [> 6 METs]) and not consuming alcohol or caffeine within 12 hr before each session. There was no effort to control nutrition other than informing participants to have a normal breakfast. This investigation adhered to ethical standards in the Declaration of Helsinki and was approved by the University of New Hampshire Institutional Review Board for Research with Human Subjects. Subjects provided written consent before participation.

Instrumentation

The stimulus-response apparatus used to measure RT, MT, and RPT was developed by the Electrical Engineering and Kinesiology Departments at the University of New Hampshire and has been described in detail previously [3] (Figure 1). The TMT was used to measure executive function [10,11]. The TMT is a timed neuropsychological test of visual-spatial search, task-switching inhibition, and cognitive flexibility. It comprises two components: TMT-A (visuospatial abilities) and TMT-B (cognitive flexibility, task-switching, and task inhibition). The time difference to complete TMT-B and TMT-A is calculated to measure executive function [11] (Figure 2).

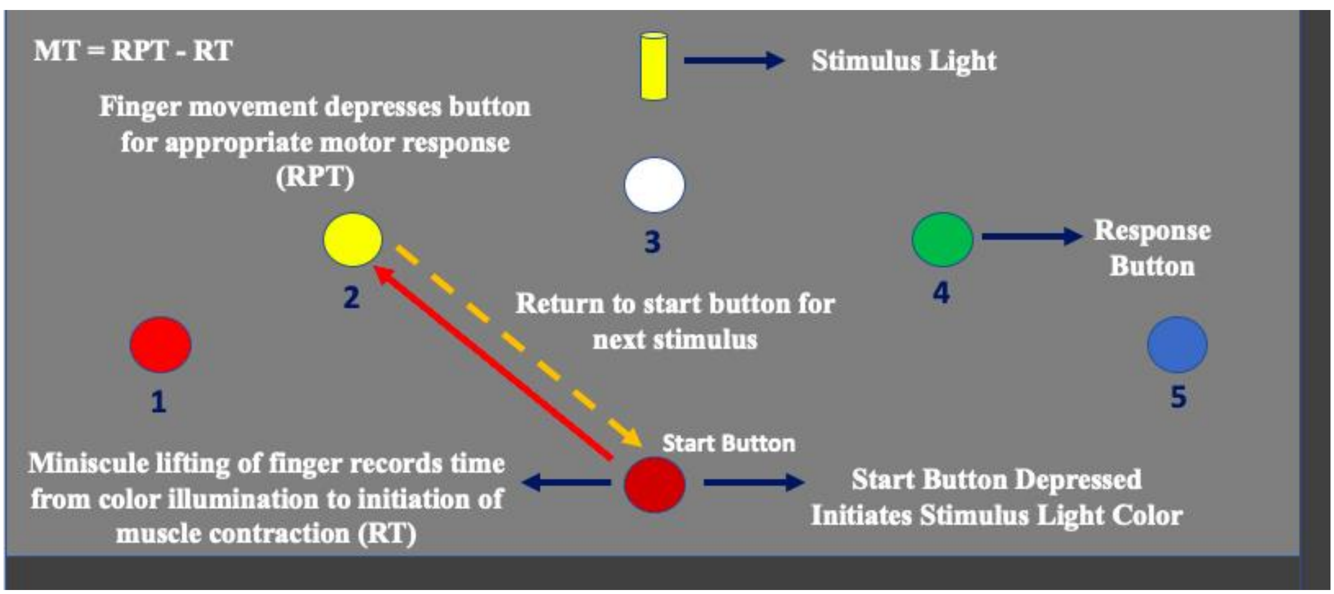

Figure 1. Configuration of the response-time apparatus.

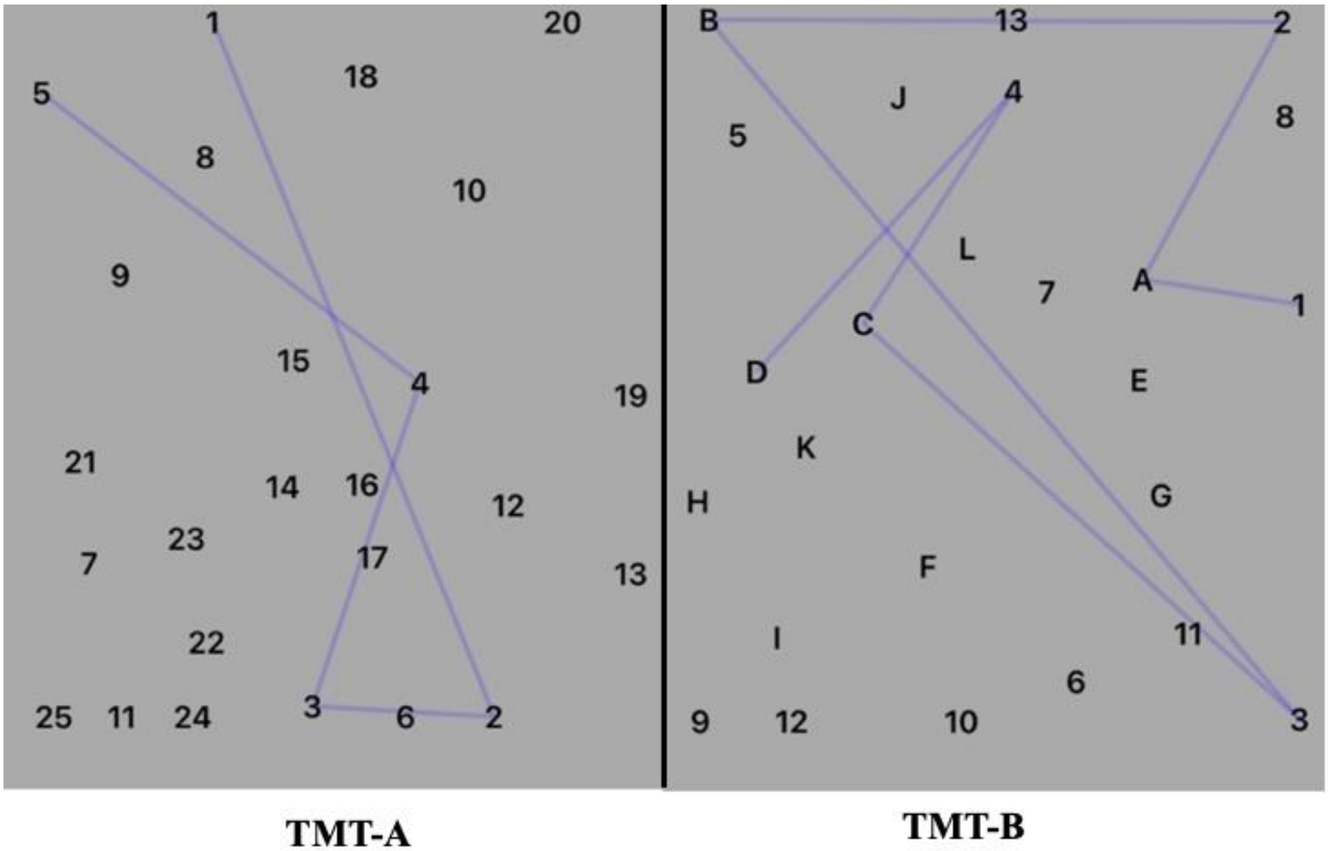

Figure 2. Example of sequencing in the Trail Making Test Part-A (TMT-A) and Part-B (TMT-B).

Experimental Design and Procedures

In Session 1, participants were explained the study's purpose and importance, the TMT, SC, MC, and DT tests, and the three exercise conditions. After reading and signing informed consent, they were given a physical and mental health questionnaire and MMSE to determine if they had physical, cognitive, or psychological characteristics that might exclude them from participating. After completing the questionnaire, participants were randomly assigned to one of the three treatment groups, after which each participant's heart rate reserve (HRR) was determined using the Karvonen formula [1,3]. Participants were randomly assigned to groups using a random number generator computer program.

Afterward, participants in the exercise groups had their appropriate resistance per exercise calculated by determining 60% of a 1-repetition maximum (1-RM) performed for each exercise. The only exception to this resistance level was the body squat exercise, where each participant's body weight was used as the resistance. The last part of the session included having participants perform 30 practice trials on the response time apparatus for each condition tested and two practice trials on the TMT to become familiar with each test.

Session 2 occurred on the following day. In Session 2, participants were fitted with a Polar heart monitor and sensor (Polar Fit1, 15 Grumman Road West, Bethpage, NY 11714) to determine pre- and postexercise heart rates and at what percent HRR participants reached at the end of their respective exercise sessions. Participants then performed 30 practice trials on each response time condition and two on the TMT to obtain truer pre-exercise baseline measurements and minimize learning effects across testing sessions [3].

Following practice trials, participants were pretested on the three response-time conditions and the TMT. The order of testing was counterbalanced. After completing their respective exercise protocols, participants were retested at 1 min and 20 min postexercise to determine the immediate and short-term exercise effects. Participants performed 8 trials in each response-time condition per test. High and low scores were omitted in the data analysis, with the middle six trials averaged [3]. If a participant had a mishit during one of the 8 trial test blocks, that trial was counted as the high score and omitted from the averaging processes. No participant had more than one mishit at any testing session. Participants performed one trial of the TMT per test session.

The RCT program consisted of the following 12 exercises sequentially performed for 40 s/exercise at a cadence of 2 s/repetition with a 14 s rest between each exercise (exercise time 11 min) in the following order: chest press, leg press, latissimus pulldown, military press, knee extension, elbow flexion, knee flexion, elbow extension, back rows, pectoralis flies, body squat, and abdominal crunch. For individuals engaged in the HV-RCT program, there was a 1 min rest between circuits (exercise time 23 min).

Participants' heart rates were recorded immediately after exercise. This value was used to determine pre- to postexercise heart rate changes and the percentage of HRR attained from exercise.

Data Analysis

According to Martineau et al.,[3] pre-exercise performance is a variable influencing the effects of acute exercise on cognitive performance and should be considered when determining the impact of exercise regimens on cognitive performance. Therefore, repeated measures ANOVAs incorporating pre-exercise tests were used in the analyses. To measure the aerobic effects resulting from RCT, participants' pre- to post-exercise heart rate changes were calculated via a 3 x 2 (Group x Heart Rate) repeated measures ANOVA. Reaction time, MT, and RPT scores (msec) were analyzed via separate 3 x 3 (Group x Test Trial Blocks) repeated measures ANOVA. Results on the TMT-A were subtracted from TMT-B to determine executive function and were analyzed via a 3 x 3 repeated measures ANOVA. The Bonferroni correction factor was used to determine significant alpha levels ($p < 0.05$), and the Greenhouse-Geisser correction was used to adjust for the lack of sphericity in repeated measures ANOVA. Eta square (η^2) was used to determine effect size. the Shapiro-Wilk test (W) was used to determine normal data distribution, and Levene's test was used to determine whether the homogeneity assumption of the variance was met. Both normal data distribution ($W = 0.95$, $p < 0.05$) and homogeneity of variance assumptions ($p > 0.05$) were met.

RESULTS

Heart Rate Changes

Significant group ($F_{2,27} = 215.84$, $p < 0.0001$, $\eta^2 = 0.09$), heart rate ($F_{1,27} = 1001.28$, $p < 0.0001$, $\eta^2 = 0.10$), and group x heart rate interaction ($F_{2,27} = 225.86$, $p < 0.0001$, $\eta^2 = 0.09$) effects were found, with LV-RCT and HV-RCT groups displaying greater heart rate changes attained at the culmination of their respective exercise sessions (Table 1). There were no significant differences between LV- and HV-RCT groups. Based on the Karvonen formula [1], CON participants reached 1.92% (±1.51) HRR, LV-RCT participants reached 55.15% (±6.95) HRR, and HV-RCT participants reached 58.24% (±8.24) HRR. Therefore, both RCT routines elicited a moderate aerobic effect [1].

Table 1. Means (M) and Standard Deviations (±SD) for post-circuit heart rates and percent of predicted heart rate reserve (percent HRR*).

	Pre-Circuit HR		Post-Circuit HR		Percent HRR*	
Group	M	SD	M	SD	M	SD
Control	74.50	±4.09	76.90	±3.84	1.92	±1.51
Low Volume	74.00	±4.89	142.90	±7.75	55.15	±6.95
Higher Volume	75.00	±3.79	146.10	±8.78	58.24	±8.23

Note: There were significant group ($p \leq 0.0001$, $\eta^2 = 0.09$), heart rate ($p \leq 0.0001$, $\eta^2 = 0.010$), and group x heart rate interaction effects ($p \leq 0.0001$, $\eta^2 = 0.09$). *HRR was determined using the Karvonen formula (also known as the heart rate reserve (HRR) formula), which considers a person's resting heart rate when calculating the heart rate maximum.

Information Processing

For the SC task, there were no between-group and within-group effects for RT ($p = 0.73$ and $p = 0.83$, respectively), MT ($p = 0.99$ and $p = 0.56$, respectively), and RPT ($p = 0.86$ and $p = 0.90$, respectively) (Table 2, Figure 3). For the MC task, there were no between-group effects for RT ($p = 0.36$), but there were within-group ($p < 0.01$, $\eta^2 = 0.03$) and interaction ($p < 0.05$, $\eta^2 = 0.04$) effects (Table 3, Figure 4). *Post-hoc* analysis indicated both RCT groups displayed decreases in RT at 1 min and 20 min postexercise, with no differences between RCT groups. For MT, there were no between or within-group effects ($p = 0.80$ and $p = 0.20$, respectively). For RPT, there were no between-group effects ($p = 0.53$), but there were within-group ($p < 0.01$, $\eta^2 = 0.04$) and interaction ($p < 0.05$, $\eta^2 = 0.05$) effects. *Post-hoc* analysis indicated decreases in RPT at 1 min and 20 min postexercise for RCT groups at 1 min and 20 min postexercise, with no differences between RCT groups.

Table 2. Means (M) and standard deviations (SD) for processing time (msec) across testing times on the single-choice condition.

	Processing Time (msec)					
	Reaction Time		Movement Time		Response Time	
Group	M	SD	M	SD	M	SD
Control						
Pre-exercise	250.40	73.24	218.08	52.12	468.48	104.47
1 min Postexercise	262.00	73.68	234.36	52.99	496.36	120.05
20 min Postexercise	279.70	89.90	206.81	82.63	486.51	114.44
Low Volume						
Pre-exercise	247.99	53.96	215.93	56.69	463.91	75.16
1 min Postexercise	239.90	60.27	222.04	47.19	461.94	70.78
20 min Postexercise	246.93	49.07	216.54	55.25	463.46	88.43
Higher Volume						
Pre-exercise	256.49	58.22	215.74	54.98	472.23	96.36
1 min Postexercise	247.58	64.38	211.59	47.22	459.16	101.27
20 min Postexercise	240.55	49.47	223.75	49.81	464.30	93.55

Note. There were no significant group or test differences for reaction, movement, and response times.

Table 3. Means (M) and standard deviations (SD) for processing time (msec) across testing times on the multichoice condition.

	Processing Time (msec)					
Exercise	Reaction Time		Movement Time		Response Time	
Intensity	M	SD	M	SD	M	SD
Control						
Pre-exercise	473.14	77.54	266.76	53.38	739.90	101.69
1 min Postexercise	482.41	81.07	275.74	58.09	758.15	99.99
20 min Postexercise	480.05	88.84	269.40	65.40	749.45	104.35
Low Volume						
Pre-exercise	476.64	82.49	297.40	37.03	774.04	87.71
1 min Postexercise	427.38	66.96	265.53	48.46	693.50	90.07
20 min Postexercise	421.93	81.77	282.33	74.34	704.25	136.45
High Volume						
Pre-exercise	459.91	90.38	283.55	67.95	743.46	122.86
1 min Postexercise	412.06	72.42	256.26	56.74	668.33	101.94
20 min Postexercise	424.56	84.88	262.39	57.70	686.95	115.05

Note: There were significant test ($p \leq 0.01$, $\eta^2 = 0.03$) and group x test interaction ($p \leq 0.05$, $\eta^2 = 0.04$) effects for RT and significant test ($p \leq 0.01$, $\eta^2 = 0.04$) and group x test interaction ($p \leq 0.05$, $\eta^2 = 0.05$) effects for RPT.

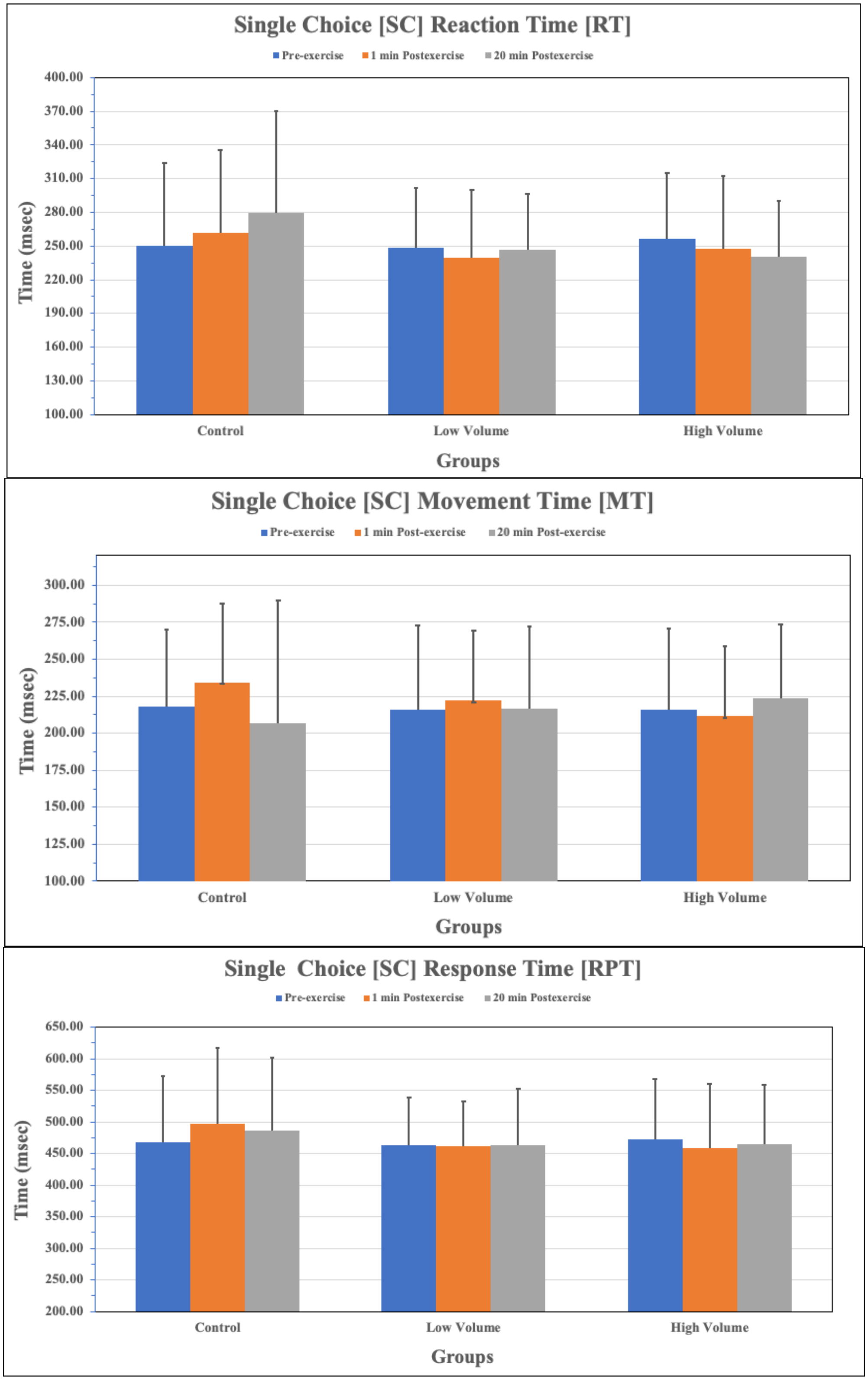

Figure 3. Single choice reaction, movement, and response times (msec) across measurement time blocks.

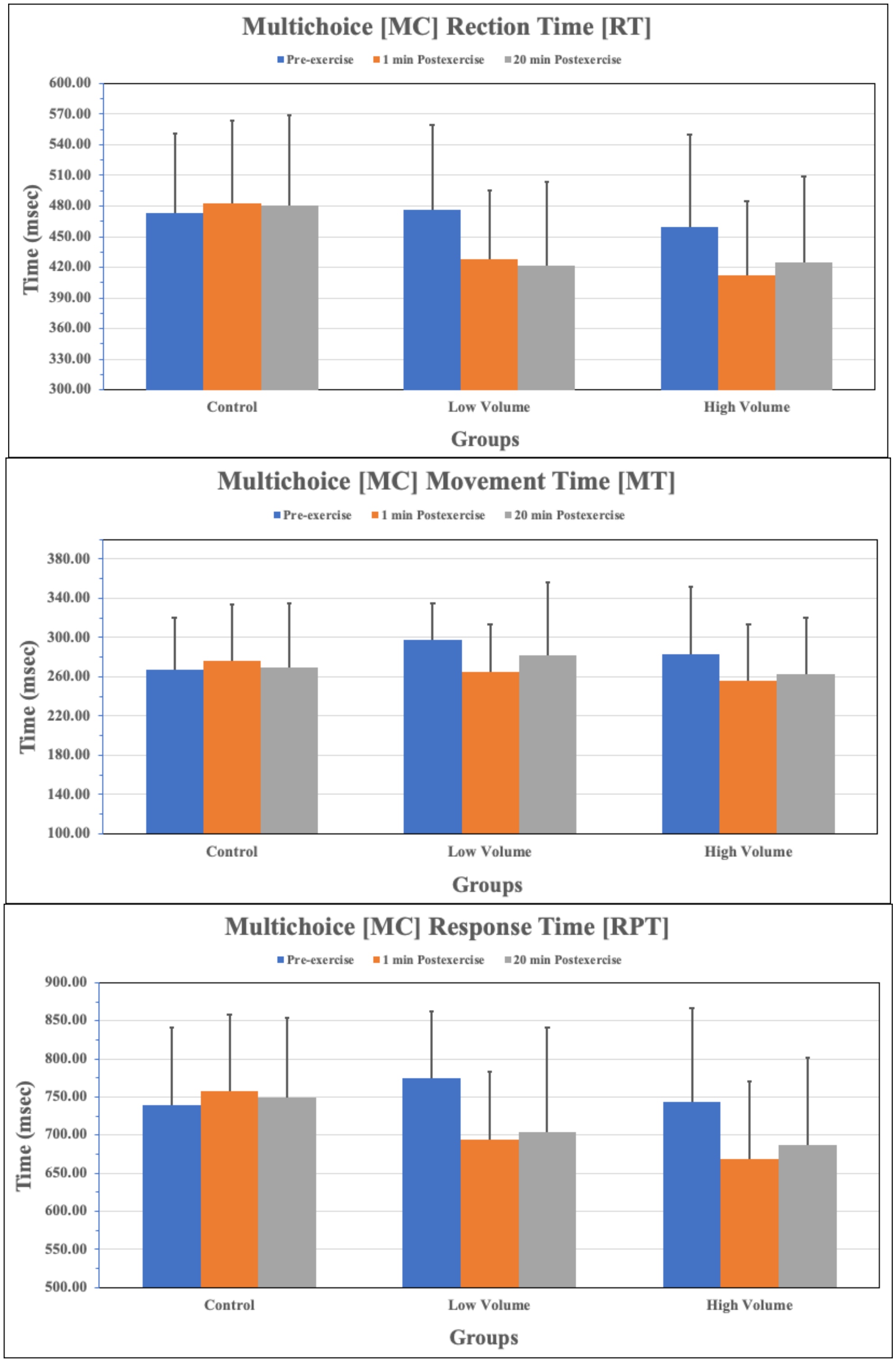

Figure 4. Multichoice reaction, movement, and response times (msec) across measurement time blocks.

For the DT task, there were no between-group effects for RT ($p = 0.17$), but there were within-group ($p < 0.001$, $\eta^2 = 0.05$) and interaction ($p < 0.01$, $\eta^2 = 0.04$) effects (Table 4, Figure 5). *Post-hoc* analysis indicated decreases in RT at 1 min and 20 min post exercise for RCT groups, with no differences between RCT groups. For MT, there were no between or within-group effects ($p = 0.90$ and $p = 0.39$, respectively). For RPT, there were no within-group effects ($p = 0.11$), but there were between-group ($p < 0.05$, $\eta^2 = 0.12$) and interaction ($p < 0.001$, $\eta^2 = 0.10$) effects. Post-hoc analysis indicated decreases in RPT at 1 min and 20 min postexercise for RCT groups, with no differences between RCT groups.

Table 4. Means (M) and standard deviations (SD) for processing time (msec) across testing times on the dual-task condition.

Exercise Intensity	Processing Time (msec)					
	Reaction Time		Movement Time		Response Time	
	M	SD	M	SD	M	SD
Control						
Pre-exercise	741.69	154.94	472.21	138.41	1213.90	113.17
1 min Postexercise	768.05	147.87	564.06	263.27	1332.11	180.37
20 min Postexercise	758.59	146.59	505.34	155.23	1263.98	105.02
Low Volume						
Pre-exercise	750.25	148.51	484.55	102.21	1234.80	143.67
1 min Postexercise	653.46	174.91	482.41	127.50	1135.88	116.53
20 min Postexercise	645.53	173.02	494.83	118.47	1140.36	164.16
High Volume						
Pre-exercise	694.69	116.51	521.66	181.21	1216.35	118.68
1 min Postexercise	601.91	111.08	516.50	143.41	1118.41	107.76
20 min Postexercise	611.45	135.89	502.96	159.73	1114.41	108.19

Note: There were significant test ($p \leq 0.001$, $\eta^2 = 0.05$) and group x test interaction ($p \leq 0.01$, $\eta^2 = 0.04$) effects for RT and significant group ($p \leq 0.05$, $\eta^2 = 0.12$) and group x test interaction ($p \leq 0.001$, $\eta^2 = 0.10$) effects for RPT.

Executive Functioning

Analysis of TMT data (TMT-B [-] A) indicated that there were no between-group differences ($p = 0.09$), but there were within-group ($p < 0.05$, $\eta^2 = 0.05$) and interaction ($p < 0.05$, $\eta^2 = 0.06$) effects, (Table 5, Figure 6). *Post-hoc* analysis indicated improvements in TMT performance only in the HV-RCT group. This occurred at both 1 min and 20 min postexercise.

Table 5. Means (M) and standard deviations (SD) for completion time (sec) on the Trail Making Test across testing times.

Exercise Intensity	Processing Time (sec)					
	TMT Part B		TMT Part A		Part B (-) A	
	M	SD	M	SD	M	SD
Control						
Pre-exercise	55.29	9.94	38.94	7.44	16.35	8.15
1 min Postexercise	55.36	9.27	37.96	5.12	17.40	6.31
20 min Postexercise	55.94	9.15	38.83	3.58	17.11	8.12
Low Volume						
Pre-exercise	54.11	12.32	38.65	11.68	15.46	6.51
1 min Postexercise	42.68	10.88	32.73	6.78	9.96	7.86
20 min Postexercise	49.63	8.98	34.08	7.51	15.55	8.55
High Volume						
Pre-exercise	53.31	9.01	38.63	9.05	14.68	4.88
1 min Postexercise	44.53	9.01	35.48	7.25	9.05	3.74
20 min Postexercise	46.46	8.20	36.58	7.05	9.88	5.68

Note: There were test ($p \leq 0.05$, $\eta^2 = 0.05$) and group x test interaction ($p \leq 0.05$, $\eta^2 = 0.06$) effects.

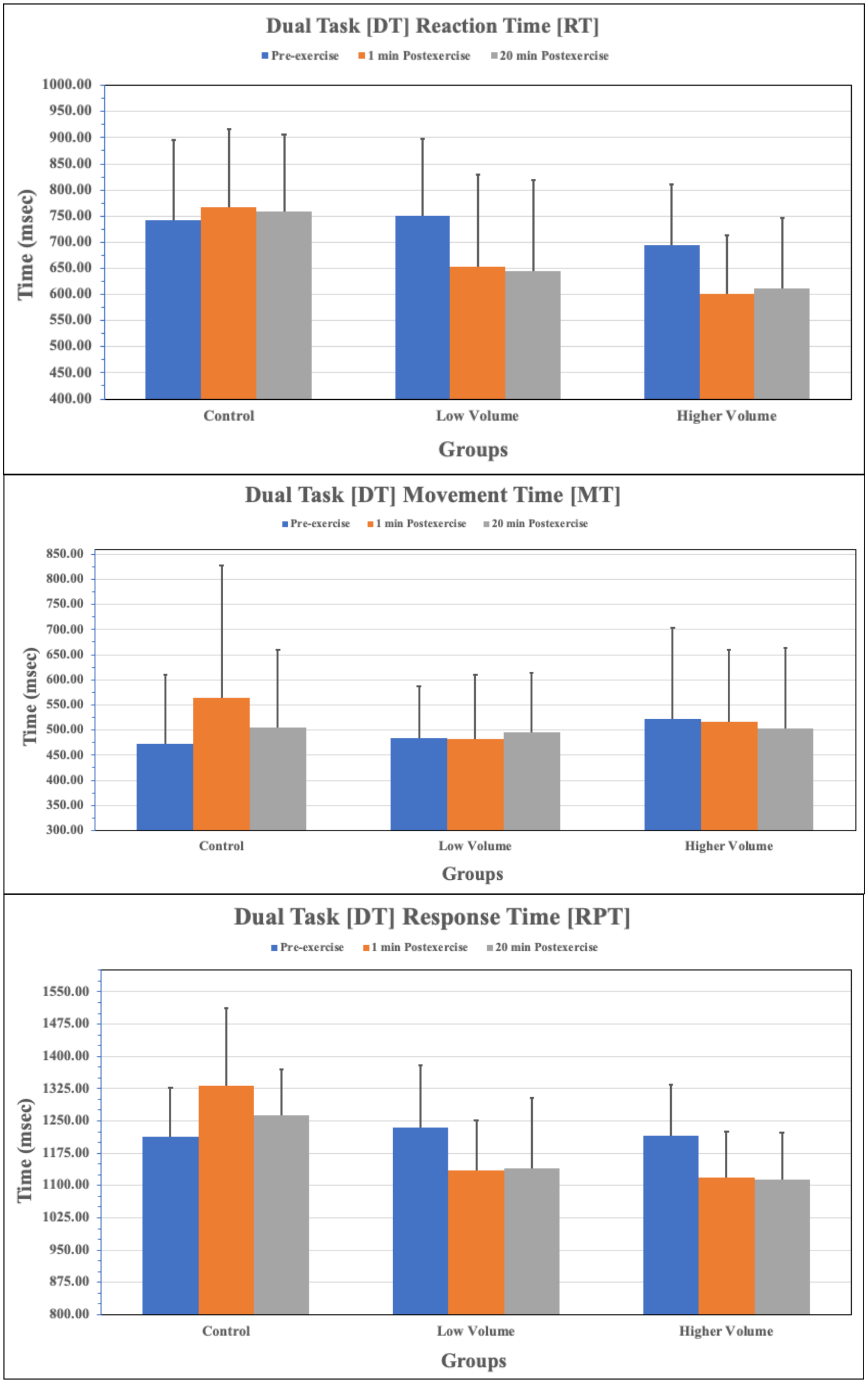

Figure 5. Dual Task reaction, movement, and response times (msec) across measurement time blocks.

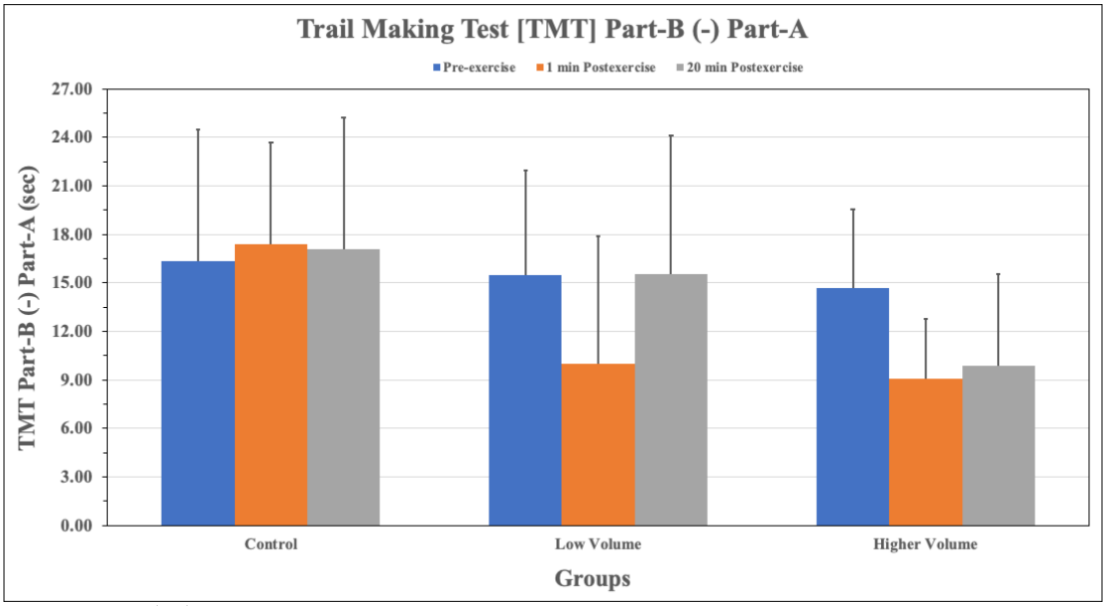

Figure 6. Trail Making Test times (sec) across measurement time blocks.

DISCUSSION

The presence of statistical significance despite the low effect sizes found in this investigation requires careful interpretation. Although statistical significance indicated that the observed results were unlikely to have occurred by chance, the low effect sizes found in several of the results suggest that the magnitude of the relationship is small, even if statistically significant. Therefore, caution is warranted when interpreting results at the risk of overstating the practical significance of the findings.

Results indicated that RT and RPT improved in MC and DT conditions but not in the SC condition; however, other than response time in the dual-task condition (group $\eta^2 = 0.12$ and interaction $\eta^2 = 0.10$), effect sizes for RT and RPT were small, ranging from $\eta^2 = 0.03$ to $\eta^2 = 0.05$). Nonetheless, the statistical significance found is supported by previous investigations showing that acute aerobic [2], resistance [5], and combined aerobic and resistance [12] exercise improve executive and non-executive functions. Moreover, dose-response studies mostly illustrate an inverted-U-shaped relationship between aerobic and resistance exercise and information processing, with optimal effects occurring at moderate intensity levels [8,13-16]. In the present investigation, the aerobic effect at the termination of exercise for the exercise groups (55 and 58% of HRR postexercise for LV- and HV-RCT groups, respectively) would be regarded as moderate [3], and the resistance used in the circuit training routines (60% of 1-RM) would be regarded as moderate as well [5]. The observation that low- and higher-volume RCT regimens enhanced reaction and response times in the more complex MC and DT response-time tasks but not in the SC response-time task aligns with previous research [3,17], suggesting that complex cognitive tasks are more likely to be affected by acute exercise than simpler tasks.

In all stimulus-response models, information processing is seen as a process based on the accumulation of time-sensitive information. At the central nervous system level, there are information accumulators, with every accumulator being associated with its unique response alternative. A given response is emitted once one accumulator or the difference between multiple accumulators reaches a predefined threshold. Reaction time is a function of the time necessary to reach this threshold and is an active process involving the suppression of inappropriate responses during retrieval [18]. Reaction time is often considered to involve suppressing inappropriate responses during response selection and retrieval [3,18,19]. Therefore, response inhibition acts as an intermediate variable, increasing processing time during multichoice conditions and engaging cortical mechanisms not employed during single-choice conditions.

Consequently, in the SC condition, information processing mechanics are simplified, which in turn, renders the impact of exercise on processing speed minimal compared to that encountered during the more complex MC and DT conditions. It is reasonable to believe that delays in information processing observed in MC and DT tasks and not the SC task result from increased processing time involved in response selection and inhibition, and the acute RCT programs decreased the time needed for these processing tasks. Recent investigations [3,18,19] similarly found acute exercise decreases processing time during tasks involving inhibitory control, facilitating response time speed.

Because there were no changes in MT, the motor response to the button press remained relatively constant. This, along with reductions in RT, supports the position that the effects of the RCT routines on RPT occurred primarily through cortical mechanisms rather than motor response mechanisms. Previous research has been mixed in this area, with research showing improvements occurring in RT

[20], RT and MT [21], or MT [22]. Like Martineau et al. [3], our data indicated that increases in the speed with which the cortex processed information were the primary reason for the observed improvements in RPT and not the improved speed in movement.

Both volumes of RCT improved participants' information processing speed when performing MC and DT tasks; however, only the HV-RCT improved executive functioning in participants. Results on the TMT should be interpreted cautiously, however, as effect sizes were low (η^2 = 0.05 and η^2 = 0.06). Nonetheless, significance was found. One plausible explanation for the differing effects of RCT on response time and executive functioning could be that the executive function task necessitated a greater level of cortical processing than did the simpler response-time tasks and that participants who engaged in HV-RCT sustained a higher level of 'physiological stress' than participants in LV-RCT due to a greater time engaged exercising (23 min versus 11 min). It is conceivable that this additional time was needed to promote the facilitatory effects of RCT on executive functioning. As no meaningful measures of physiological stress were collected (e.g., cortisol levels), this rationale is reasonable but speculative.

What is most interesting regarding the results of this investigation is that participants in the HV-RCT group displayed improvements on both DT and TMT tasks. Dual-tasking refers to the concurrent execution of two distinct tasks, whilst task-switching involves rapidly shifting attention between two or more tasks. In the DT condition, individuals were not only engaged in dual tasking -- counting backward by 7 while performing the MC task -- they also had to task switch from counting backward to reacting to the stimulus and executing the appropriate button press. Monsell [23] emphasized the role of cognitive control in dual-tasking and task-switching, underscoring that the brain must disengage from one task and rapidly shift attention to another, incurring a switch cost in terms of time and efficiency. Both dual-tasking and task-switching rely heavily on cognitive control processes that govern the ability to regulate attention, inhibit irrelevant information, and flexibly shift between tasks [24]. As the TMT is more involved in measuring task-switching and cognitive flexibility than working memory [11], it is reasonable to observe improvements in both DT and TMT performances resulting from RCT.

Although analyses of lactate or neurochemicals were not performed in this investigation, the literature supports the premise that the facilitatory effects of RCT on attention and cognitive functioning are most likely due to increased levels of lactate [7], neurotrophic factors, and/or catecholamines released during or following exercise [25-28]. As a result, cognition on tasks requiring executive functioning, task-switching, and multichoice responses were facilitated.

It is important to note that while acute exercise is purported to stimulate the release of lactate, neurotrophic factors, and/or catecholamines, this effect is not universal. Factors such as exercise type, intensity, and individual fitness levels play significant roles in determining whether these substances are released in response to exercise [29,30]. For instance, Rojas Vega et al. [29] found that only moderate-to-high-intensity exercise resulted in elevated BDNF levels, suggesting that low-intensity or shorter durations of exercise may not be sufficient to stimulate this neurotrophic chemical. Additionally, individual fitness levels and baseline neurochemical states can influence the release of these substances. Ferris et al. [30] observed that individuals with higher fitness levels experienced a greater increase in BDNF in response to exercise compared to less fit individuals, indicating that exercise-induced neurochemical responses may vary based on conditioning.

There were two primary limitations of this investigation. Firstly, a larger sample size is warranted to more precisely investigate the impact of differing volume-based circuit training programs on cognition. Secondly, as the TMT primarily measures cognitive flexibility, task-switching, task inhibition, and not working memory, additional executive function tests (e.g., Stroop Color and Word test that better evaluates working memory) should be used to obtain a more inclusive look at executive functioning.

CONCLUSION

Aerobic and resistance exercises have been linked to improved cognition and executive functioning, albeit with potential differences in the domains affected. For example, aerobic exercise interventions are particularly effective in enhancing cognitive functions such as attention, processing speed, and memory, whilst resistance exercise showed greater benefits in executive functions, such as impulse inhibition and cognitive fluidity. Combining both forms of exercise into a comprehensive fitness routine may offer synergistic benefits. Resistance circuit training should be considered as adjuvant therapy for improved brain health and cognition and to treat age- or disease-related cognitive declines.

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Citation: Croce RV, Horvat M. (2024). Acute Low- and Higher-Volume Resistance Circuit Training Improves Immediate and Short-Term Cognition in Young Adults. *Brazilian Journal of Motor Behavior*, 18(1):e445.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors and did not involve clinical trials.
Competing interests: The authors have declared that no competing interests exist.
DOI: https://doi.org/10.20338/bjmb.v18i1.445