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Effect of an Acute Bout of Low-, Moderate-, and High-Intensity Aerobic Exercise on Immediate and Delayed Fractionated Response Time

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ABSTRACT

Background: Information processing and cognition can be enhanced in various ways. The present study investigated the role of three intensities of aerobic exercise (low intensity [LIE], moderate intensity [MIE], high intensity [HIE]) on information processing speed using a response time paradigm. **Methods:** Twenty-seven adult male and female volunteers (16, male; 11, female) ages 18 to 26 years (Mean age = 21.9 years) were randomly assigned to LIE, MIE, and HIE exercise groups. Exercise was performed on a bike ergometer. Participants took part in single choice (SC), multichoice (MC), and dual task (DT) performance tasks before exercise and 1 min and 20 min postexercise. Information processing speed was analyzed by calculating total response time (RPT), reaction time (RT), and movement time (MT) on a response time apparatus. **Results:** For each performance task, the impact of three intensities of exercise on RPT, RT and MT were analyzed using separate 3 (Group [exercise intensity]) x 3 (Test Block [pre-exercise, 1 min postexercise, 20 min postexercise]) repeated measures ANOVA. Data analyses indicated: (1) participants in each exercise condition improved RT and RPT on MC ($p < 0.001$; $p < 0.01$, respectively) and DT ($p < 0.05$, $p < 0.05$, respectively) tasks but not on the SC task and these improvements were observed both immediately (1 min) and short-term (20 min) postexercise. **Conclusions:** As RT represents more CNS mechanisms than movement per se, the faciliatory effect of exercise on the speed of task completion involved more speed of cortical processing than speed of movement when completing the task. All exercise intensity levels investigated had a positive impact on the time required to complete MC and DT tasks.

1. Introduction

Physical exercise provides multiple physiological benefits to an individual. It is known that exercising regularly can prevent coronary artery disease, hypertension, obesity, and improve muscle tension and elasticity (Gibson, Wagner, & Heyward, 2019). The effects of exercise on psychomotor functions, however, are far more parsimonious (Malhorta, Goel, Ushadhar, Tripathi, & Garg, 2015). One such psychomotor function involves information processing and cognition and using reaction time (RT), movement time (MT), and response time (RPT) as ways of inferring such ability (Ozyemisci-Taskiran, Gunendi, Blukbasi, & Beyazova, 2008; Prabu et al., 2020). Reaction time is interpreted as the interval of time from the presentation of an unanticipated stimulus to the initiation of movement and consists of sensory and perceptual process (cognitive decision-making component). The last stage of the stimulus-response cycle involves a culminating movement within the specific environmental context. This period from the onset of muscle activity to the completion of the movement is referred to as MT. The entire process from stimulus initiation to movement completion is RPT and constitutes the combination of RT and MT (Ozyemisci-Taskiran et al., 2008).

Since the 1980s, there have been several investigations showing improvement in information processing consequent to an acute bout of exercise at intensities ranging from as low as 35% to upwards of 90% of aerobic capacity (Audiffren, Tomporowski, & Zagrodnik, 2008; Davanche & Audiffren, 2004; Davranche, Audiffren, & Denjean, 2006; McMorris & Hale, 2012). As sports and activities of daily living require individuals to engage cognitive processes to respond to a variety of stimuli, sometimes simultaneously interpreting and responding to them, understanding the mechanisms involved in this process is essential.

Arguably, the most prevalent mechanism attributed to the enhancements in information processing and cognition observed following an acute bout of physical exercise is the arousal induced by the exercise bout, with moderate intensities facilitating a greater immediate and sustained effect than lower or higher intensities, the supposed inverted-U theory of arousal and cognition (Audiffren et al., 2008; Lambourne & Tomporowski, 2010). Although there appears to be a small relationship between the inverted-U theory and the effects of acute exercise on information processing and cognition, the mechanisms for this relationship are most likely an interaction of several dynamics, of which arousal is but one factor. This has led to numerous other interpretations of this relationship.

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Presently, the leading theories as to why aerobic exercise improves information processing and cognition include: (1) the reticular activating hypo-frontality (RAH) model, which stipulates that exercise engages arousal mechanisms through the reticular-activating system (Dietrich, 2003; Dietrich & Audiffren, 2011); (2) the catecholamine hypothesis (McMorris, 2021; McMorris, Tomporowski, & Audiffren, 2009), which stipulates that preceding and during exercise the hypothalamus activates the sympathoadrenal system activating brain networks responsible for information processing (Basso & Suzuki, 2017; Miyashita & Williams, 2006); and (3) the brain-derived neurotrophic hypothesis, which stipulates that certain brain chemicals such as Brain-Derived Neurotrophic Factor (BDNF) and Irisin act as mediators for the acute exercise-induced enhancements in information processing and cognitive performance (Hwang et al., 2016; Tsai et al., 2021).

Based on the aforementioned theories, during and/or following low-intensity aerobic exercise information processing and cognitive performance would be subdued due to limited activation in relevant brain areas. During and/or following high-intensity exercise, higher levels of activation would lead to neural noise, which in turn would lead to decrements in performance. However, as postulated in the inverted-U theory of arousal and information processing, moderate-intensity exercise is the most beneficial as there is less neural noise seen in higher activation levels with nevertheless significant activation in relevant brain areas (Cantelon & Giles, 2021; McMorris & Hale, 2012; Tomporowski, 2003). McMorris and Hale (2012) and Tomporowski (2003) concluded that information processing is best enhanced by acute submaximal exercise with exercise bouts of minimally 10 min to maximally 60 min being the most effectual.

Based on the literature reviewed, we investigated the role of three intensities of exercise (Low Intensity [LIE], Moderate Intensity [MIE], High Intensity [HIE]) on information processing speed during single choice, multichoice, and dual task conditions and analyzing RPT and its fractionated components, RT and MT. Analysis of both RT and MT was essential to this investigation as it provided a way of isolating early cortical-integration processes (RT) from later movement processes (MT) (Hasbroucq, Burle, Bonnet, Possamai, & Vidal, 2001).

Moreover, as Lambourne and Tomporowski (2010) indicated, the role of dual task demands on attentional allocation during and after acute exercise is significant. According to the hypo-frontality hypothesis proposed by Dietrich (2003), the neural circuitry involved in information processing during dual task performance and the initiation, control, and maintenance of movements requires considerable resources. Therefore, available resources are drawn from cortical networks that control less immediately critical behaviors. Given the paucity of research investigating the impact of aerobic exercise on dual task performance, it was essential that DT performance was investigated. We posited that all three exercise conditions would have positive effects on RT and RPT, especially during the performance of the more complex multichoice and dual task conditions investigated.

2. Materials and Methods

2.1. Participants

Twenty-seven participants (16, male; 11, female) from the University of New Hampshire between the ages of 19-26 (mean age = 22.44 years, SD = 2.10, range 18-26 years) took part in single choice (SC), 5-choice (multichoice, MC), and dual (DT) tasks prior to and after an acute bout of either LIE, MIE, or HIE aerobic exercise on a bike ergometer. Participants were recreational active in that they exercised 3-5/wk for approximately 1 hr/ session. Participants were not allowed to take part in the study if they: (1) participated competitively in an endurance-related sport or activity, (2) had a serious chronic mental illness, (3) had serious cardiac issues, (4) were on antidepressants or anxiolytics, (5) had respiratory problems that may compromise exercising on a bike ergometer, (6) had orthopedic or arthritic conditions that may impede exercising on a bike ergometer or moving the upper extremity when performing the RPT tasks, or (7) had a history of traumatic brain injuries, had a learning disability, had attention deficit/hyperactivity disorder, or had a psychiatric or neurological diagnosis. Exclusion criteria prior to partaking in both Session 1 and Session 2 included not performing strenuous aerobic activity within 12 hr prior to each session, not consuming alcohol within 24 hr prior to each session, and not consuming caffeine the day of each session.

2.2. Task and Apparatus

The stimulus and response time apparatus was built by the Electrical Engineering and Kinesiology Departments at the University of New Hampshire. In the design an Arduino Mega microcontroller (Arduino IDE 2.02, https://www.arduino.cc) was used to control the reaction time tasks. Five stimuli in the form of a multicolored LED using the colors red, yellow, white, green, and blue, were used along with 5 response arcade buttons laid out in a 100 deg semicircle, each 20.3 cm on center from the start button at the bottom of the apparatus. The components are encased in a 43.5 cm x 33.2 cm x 5.1 cm aluminum box. The apparatus is connected to a Dell XPS 13 9310 computer via USB. The desired reaction time program is then opened with Arduino IDE and uploaded to the apparatus.

Participants committed to memory prior to testing the following stimuli-response pattern (Stimulus Color Red = Button-1, Yellow = 2, White = 3, Green = 4, Blue = 5). When the start button is pushed, a pulse is sent to the apparatus and computer and a color-number code is generated. For the SC task, the color white is displayed; for the MC task, colors red, yellow, white, green, and blue are displayed (Figure 1). Colors for the MC task were randomly generated. After the correct button was pushed, the participant repositioned over the start button and the process commenced again. This process was repeated until eight trials were completed. The cue time from pressing down on the start button until the color stimulus was generated was randomly sequenced between 0.5 s to 2 s to prevent anticipation by the participant. Using the application CoolTerm (Version 2.0, https://coolterm.en.lo4d.com/ windows), times were recorded on a text file and exported to an Excel spreadsheet for data analysis.

The device recorded two measurements: (1) RT, which was the time the LED light was displayed to when the participant initiated a release from the start button (a minuscule release of pressure from the start button initiated the recording time for RT), and (2) RPT, which was the time from when LED light was displayed to when the participant selected the correct response-button. Movement Time, or the time from initiation of the response to when the participant selected the correct response-button, was obtained from subtracting RT from RPT. All values were recorded in milliseconds and taken to three decimal places.

Prior to the investigation, the authors performed a pilot study (N = 15) to determine test-retest reliability and concurrent validity of the response time apparatus. Applying statistical procedures used in previous research (Croce, Horvat, & McCarthy, 2001), test-retest reliability of the apparatus was estimated using an intraclass correlation coefficient from a one-way analysis of variance. This statistic was the estimate of consistency of performance across trials; concurrent validity was estimated by calculating Pearson correlation coefficients between scores on the apparatus and a Lafayette Choice Reaction Time Apparatus (Model 63013). Analyses indicated that there was both high test-retest reliability (r = .93) and concurrent validity (r = .89).

2.3, Experimental Design and Procedures

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For each group (LIE, MIE, HIE) and task (SC, MC, DT), RPT, RT and MT times were analyzed across three test Blocks (pre-exercise, 1 min postexercise, 20 min postexercise). In the first session participants were given (1) an explanation of the study's purpose and importance, (2) a detailed explanation of the three choice conditions used in the experiment and how the RPT apparatus worked was given, and (3) an explanation of the three exercise intensities, one of which they would be placed, and how the bike ergometer worked. After reading the informed consent and consenting to participate, participants were given a pre-participation health screening questionnaire as explained previously.

After completing the informed consent and pre-participation health screening questionnaire, participants were randomly assigned into one of three groups for Session 2 when participants engaged in the acute exercise bout: (1) an LIE group, where participants exercised for 12 min between 35-40% max HR; (2) an MIE group, where participants exercised for 12 min between 55-60%% max HR; or (3) an HIE group, where participants exercised for 12 min between 75-80% max HR. All exercise sessions included a 2 min warm-up and 1 min cool down, leading to a total exercise time of 15 min, which corresponds to previous investigations (see Chang, Labban, Gapin, & Etnier, 2012). Further, Lambourne and Tomporowski (2010) determined that cognitive enhancements following physical activity were greater for cycling exercise than for running-based exercise. Thus, the mode of exercise used in this investigation was cycling.

After informed consent was signed and participants were placed into their respective exercise groups, determination of their appropriate exercise heart rate range commenced. This consisted of a bout of exercise on a stationary bike ergometer (MONARCH, Model 894E, http://www.hcifitness.com/Monark-894e-Wingate-Testing-Bike-Ergometer) in which participants were attached to a Polar heart monitor and sensor (Polar Fit1, 15 Grumman Road West, Bethpage, NY 11714) (Figure 3). Using the Karvonen Heart Rate Formula (Gibson, et al., 2019), participants were brought to their designated target heart rate range (that is, values for between 35-40% max HR, 55-60%% max HR, or 75-80% max HR) by pedaling at a rate of 70 rpm and when necessary, adding small weights to the bike until the desired heart rate range was achieved. This information was recorded and used for Session 2 when participants engaged in the acute bout of exercise.

Participants were seated on the bike ergometer with their knees at between 30- to 35-degrees for maximum efficiency and minimal knee- and ankle-joint stress (Ferrer-Roca et al., 2014). The last part of Session 1 included having participants perform 20 practice trials on the SC, MC, and DT tests to become familiar with each of the tests.

In Session 2 participants were tested in each of the three tasks both before and after exercising. The order of testing was counterbalanced to control for potential learning effects. Before pre-exercise testing, participants engaged in 10 practice trials of each RPT task to refamiliarize them with the tasks and to ensure more representative pre-exercise measurements in RT, MT, and RPT (Del Rossi, Malaguti, & Del Rossi, 2014).

After pre-exercise measurements were taken, participants engaged in their respective exercise bout. At 1 min (immediate effects) and again at 20 min (short-term effects) participants were again tested on the three RPT tasks in the same order as tested in pre-exercise. Participants performed eight trials in each of the RPT conditions at each of the test times. For data analysis, high and low RPT scores were omitted, and the middle six trials were averaged.

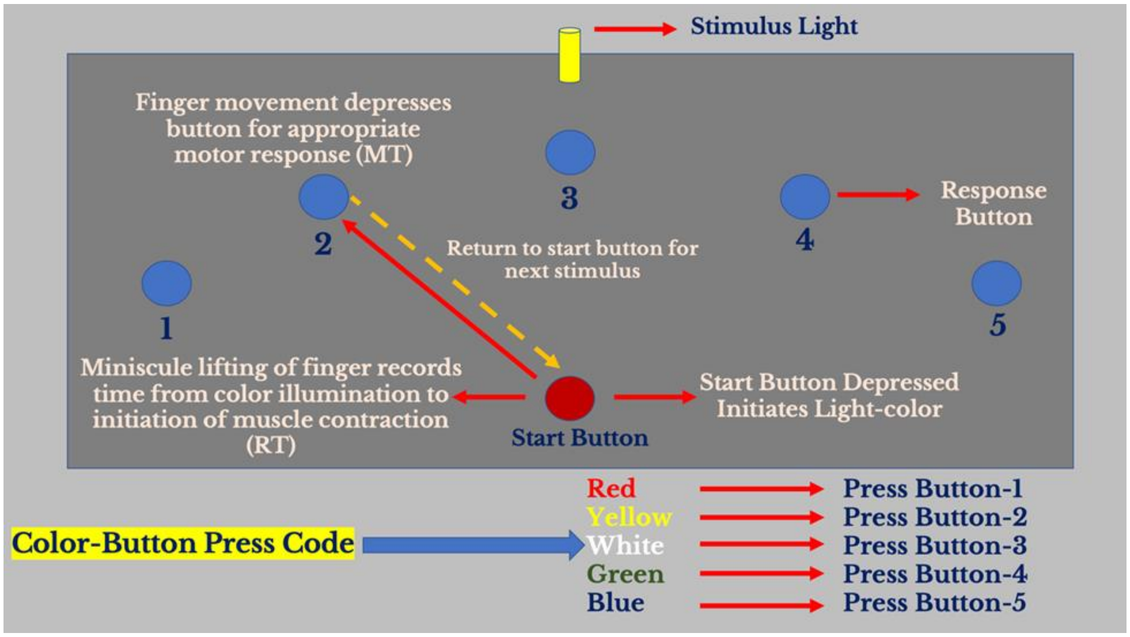

Figure 1. *Configuration and Sequencing of the Response-Time Apparatus*

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2.4. Data Analysis

For each task (SC, MC, DT), RPT, RT and MT times were analyzed via separate 3 (Group [LIE, MIE, HIE]) x 3 (Test Blocks [pre-exercise, 1 min postexercise, 20 min postexercise]) repeated measures ANOVA. In using a repeated measures design incorporating pre-exercise measurements, participants acted as their own controls, controlling for factors causing variability between subjects. Between group post hoc comparisons consisted of a Scheffe test; within-group comparisons consisted of planned orthogonal contrasts. To adjust for the lack of sphericity in repeated measures ANOVA, the Greenhouse-Geisser correction factor was used. Cohen's d (r) was used to determine effect size for all significant effects (Keppel & Wickens, 2004).

3. Results

For the SC task, there were no significant between group (LIE, MIE, HIE) and within group (pre-exercise, 1 min postexercise, 20 min postexercise) differences for RT ($p = 0.723$ and $p = 0.84$, respectively), MT ($p = 0.33$ and $p = 0.64$, respectively), and RPT ($p = 0.37$ and $p = 0.96$, respectively). For the MC task, there were no significant between group differences for RT ($p = 0.38$), MT (0.69), and RPT ($p = 0.34$), but there were significant within group differences for RT ($p < 0.001$, $r = 0.55$) and RPT ($p < 0.01$; $r = 0.47$), but not for MT ($p = 0.47$). Like the MC task, in the DT task there were no significant between group differences for RT ($p = 0.17$), MT ($p = 0.84$), and RPT ($p = 0.48$), but there were significant within group differences for RT

($p < 0.05$, $r = 0.46$) and RPT ($p < 0.05$; $r = 0.45$), but not for MT ($p = 0.17$). Post-hoc analysis for both MC and DT tasks indicated that there were significant decreases in RT and RPT times from pre-exercise measures to 1 min and 20 min postexercise. Consequently, all exercise intensities investigated had a positive impact on speed of processing in the more complex tasks tested (Tables 1-3 & Figures 2-4)

Table 1.

Means (M) and Standard Deviations (SD) for Processing Time across Measurement Trial Blocks on the Single Choice Response Time Task

	Processing Time (msec)					
Exercise Intensity	**Reaction Time**		**Movement Time**		**Response Time**	
	M	**SD**	**M**	**SD**	**M**	**SD**
Low Intensity (LIE)						
Pre-exercise	274.91	49.67	250.00	65.11	524.92	89.15
1-min	285.43	62.10	254.22	80.66	539.65	118.54
20-min	292.86	83.77	257.97	75.09	550.85	125.85
Moderate Intensity (MIE)						
Pre-exercise	294.36	64.87	235.18	60.45	529.54	105.05
1-min	283.14	61.23	238.68	68.91	521.82	117.36
20-min	281.08	59.30	238.59	75.18	519.68	106.05
High Intensity (HIE)						
Pre-exercise	271.45	51.88	224.32	31.70	486.21	72.95
1-min	273.76	59.74	197.12	55.42	470.89	97.41
20-min	255.99	42.98	211.11	54.85	467.10	92.02

***Note**. There were no significant between or within group effects found.*

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Table 2.

Means (M) and Standard Deviations (SD) for Processing Time across Measurement Trial Blocks on the Multichoice Response Time Task

	Processing Time (msec)					
Exercise Intensity	**Reaction Time**		**Movement Time**		**Response Time**	
	M	SD	M	SD	M	SD
Low Intensity (LIE)						
Pre-exercise	483.10	33.93	286.37	95.38	769.47	108.13
1-min	460.89	59.74	283.60	77.75	744.86	85.64
20-min	456.50	72.90	292.62	92.50	749.15	94.45
Moderate Intensity (MIE)						
Pre-exercise	507.40	104.44	306.00	58.38	813.40	113.83
1-min	460.56	79.83	281.30	87.56	741.84	153.77
20-min	468.17	63.75	293.68	86.25	761.85	126.97
High Intensity (HIE)						
Pre-exercise	476.49	70.11	265.14	53.32	741.63	67.98
1-min	426.00	36.58	263.71	72.80	689.71	84.60
20-min	421.63	66.44	266.67	62.84	688.29	108.33

Note. There was a significant within group effect for reaction time ($p \leq 0.001$) and response time ($p < 0.01$).

Table 3.

Means (M) and Standard Deviations (SD) for Processing Time across Measurement Trial Blocks on the Dual Task Response Time Task

	Processing Time (msec)					
Exercise Intensity	**Reaction Time**		**Movement Time**		**Response Time**	
	M	SD	M	SD	M	SD
Low Intensity (LIE)						
Pre-exercise	788.61	351.40	500.37	250.24	1288.99	527.74
1-min	669.86	217.55	530.00	234.45	1199.86	332.20
20-min	671.68	185.50	417.07	113.88	1088.75	274.64
Moderate Intensity (MIE)						
Pre-exercise	759.54	482.48	551.24	155.20	1310.78	537.87
1-min	613.03	223.20	523.32	243.02	1136.35	383.49
20-min	567.56	129.13	530.56	326.61	1098.11	404.13
High Intensity (HIE)						
Pre-exercise	564.40	108.99	512.69	212.79	1077.10	289.18
1-min	526.36	110.07	521.81	218.58	1048.17	293.59
20-min	502.14	100.10	435.63	274.44	937.76	319.81

Note. There was a significant within group effect for reaction time ($p \leq 0.05$) and response time ($p < 0.05$).

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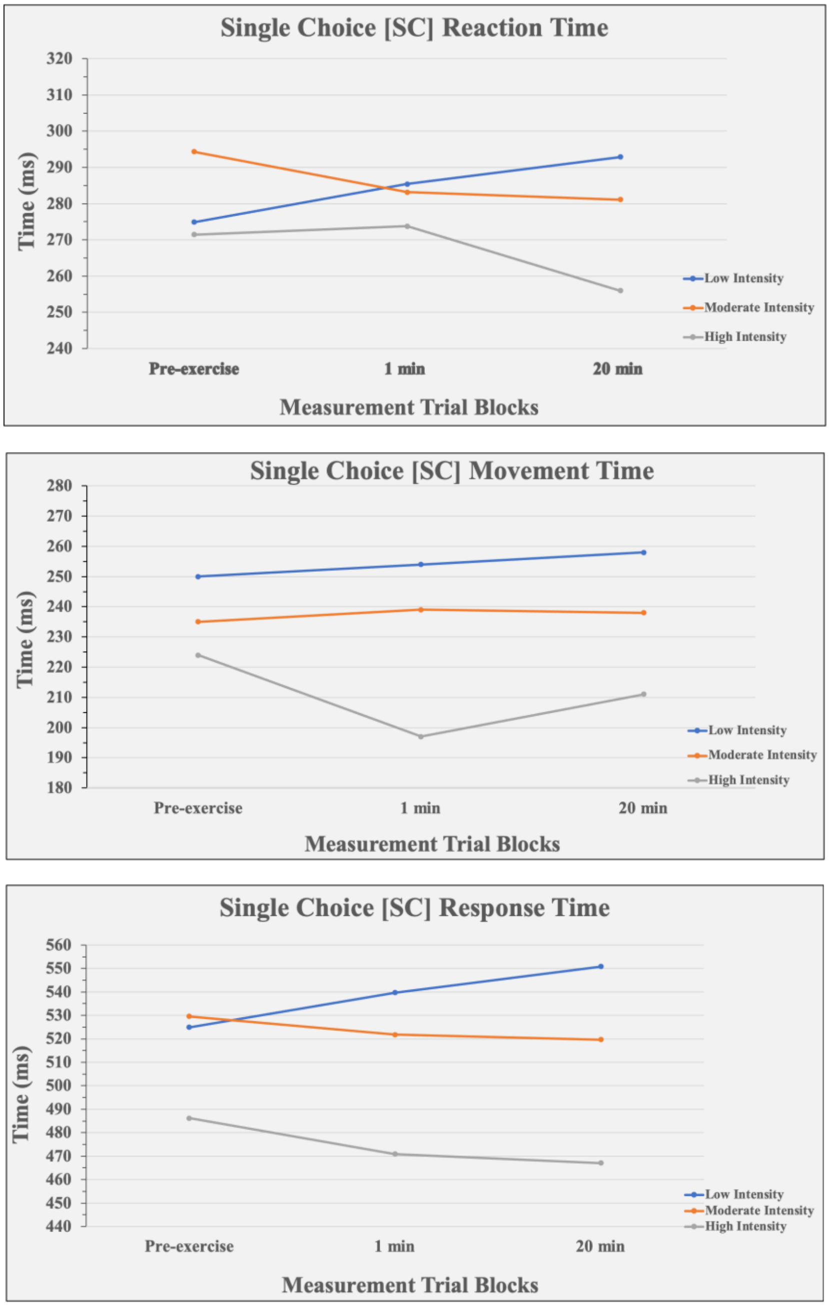

Figure 2. *Processing Time across Measurement Trial Blocks for the Single Choice Condition*. *Code: Pre-exercise = Pre-exercise measure; 1min = One-minute postexercise measure; 20 min = Twenty-minutes postexercise measure. Note: There was NSD (p > 0.05) amongst groups or across measurement trial blocks.*

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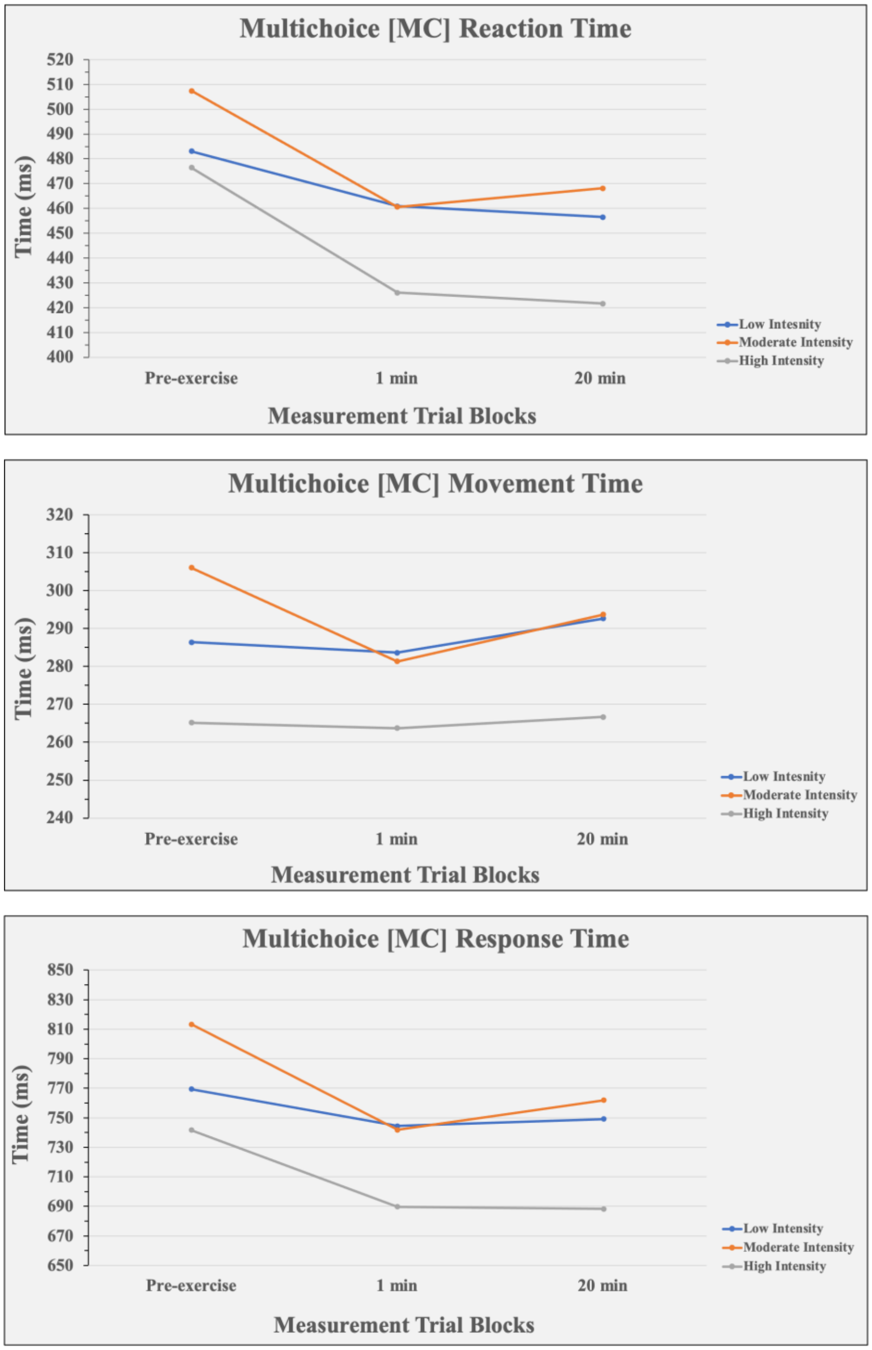

Figure 3. *Processing Time across Measurement Trial Blocks for the Multichoice Condition*. *Code: Pre-exercise = Pre-exercise measure; 1min = One-minute postexercise measure; 20 min = Twenty-minutes postexercise measure.* ***Note****: There was NSD ($p > 0.05$) amongst groups; there was a SD across measurement trial blocks for RT ($p \leq 0.001$) and RPT ($p \leq 0.01$), but not for MT ($p > 0.05$).*

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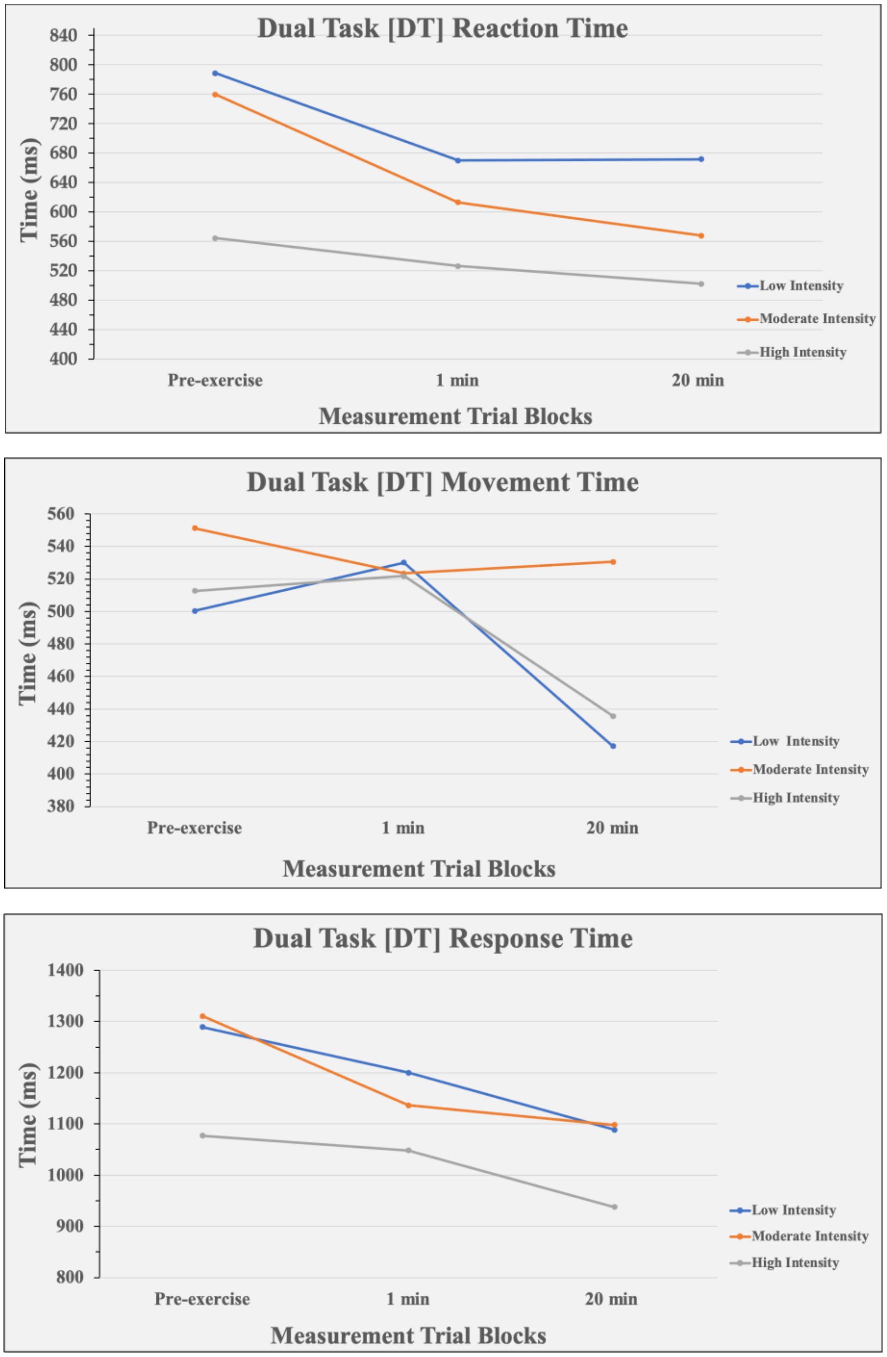

Figure 4. *Processing Time across Measurement Trial Blocks for the Dual Task Condition. Code:* Pre-exercise = Pre-exercise measure; 1min = One-minute postexercise measure; 20 min = Twenty-minutes postexercise measure. *Note:* There was NSD ($p > 0.05$) amongst groups; there was a SD across measurement trial blocks for RT ($p \leq 0.05$) and RPT ($p \leq 0.01$), but not for MT ($p > 0.05$).

[DOI: 10.61186/ijmcl.5.3.1]

4. Discussion and conclusion

In the present investigation the role of three intensities of aerobic exercise (LIE, MIE, HIE) on information processing speed using an RPT paradigm was investigated. Based on the statistical analyses and results, three major findings emerged, each of which will be discussed separately.

4.1. Exercise Influenced Complex but not Simple Response Tasks

Information processing and response to an external stimulus is often looked at as a gradual process based on the accumulation of information that is time sensitive with most models comprised of at least two processing levels (Petersen & Posner, 2012; Spencer & Coles, 1999): one stimulus related, and one response related. The response-related level is made of information accumulators or integrators, each accumulator being associated to one response alternative. A given response is emitted as soon as one accumulator, or the difference between two accumulators, reaches a predefined threshold. Speed of processing in this model is a function of the time (in model time units) necessary to reach this threshold. With only one response being correct on a given trial, the possible responses are thus in competition to reach the threshold first.

Inhibition is an intermediate variable found in the stimulus-response task model and accounts for the extended time needed to complete tasks involving multiple response alternatives. This concept of response inhibition is often considered a functional counterpart of neural activation; however, more important to this discussion, neural inhibition is defined not only as an absence of excitation but as an active process involving 'suppression of inappropriate responses or the suppression of interfering memories during retrieval' (Burle, Vidal, Tandonnet, & Hasbroucq, 2004; Zhang, Ding, Wang, Qi, & Luo, 2015). In the context of this investigation inhibition is an intermediate variable that increases processing time and engages cortical mechanisms that are not employed in one-choice situations. In simple response situations, the responding mechanics are simplified and because of this simplified process, it could be that the impact of exercise on processing speed is minimal compared to that encountered during more complex, multichoice and dual tasks.

Research by Burle et al. (2004) exemplify these differences. Burle et al. (2004) found that the activation of motor structures involved in the required response was accompanied by inhibition of the structures involved in alternative responses. Their results provided direct support for the theoretical notion of inhibition of competing responses as being integral to choosing a response from a multitude of choices. Similarly, Zhang et al. (2015) posited that inhibition of a response is an essential executive function which enables us to suppress inappropriate actions. In their study, Zhang et al. (2015) found that individuals with fencing expertise exhibit behavioral advantages on tasks with high demands on response inhibition. In a Go/ No-go task where frequent stimuli required a motor response while reaction had to be withheld to rare stimuli, fencers, compared with non-fencers, exhibited behavioral as well as EEG advantages when suppressing prepotent responses.

Most recently, Kao et al. (2022) found that a short bout of aerobic exercise counteracts time-related decrements in processing capacity as well as cortical processing of attention and conflict suppression that contribute to response outcomes of inhibitory control. They concluded that aerobic exercise can be seen as an effective strategy for transiently enhancing inhibitory control and suppressing irrelevant distractors while focusing on relevant information in facilitating goal-directed behavior.

The Frontoparietal Network (FPN), which is involved in a multitude of functions including, but not limited to, attention and executive function during goal-directed tasks, is the network most advanced as being involved in this process (Badre & Nee, 2018; Malik, Schamiloglu, & Sohal, 2022; Petersen & Posner, 2012; Schapkin, Raggatz, Hillmert, & Bockelmann, 2020). While the prefrontal cortex (PFC) provides both excitatory and inhibitory input to distributed neural circuits throughout the cortex serving diverse functions, the parietal cortex is most involved in task-related attentional processes. When an individual is engaged in a task requiring focused attention, increased neural processing is observed in brain regions that are task relevant and a decrease in neural processing is observed in brain regions that are task irrelevant.

Inhibitory control has for a long time been associated with the FPN. Moreover, all areas within the PFC are richly interconnected with the anterior cingulate cortex (ACC) (Peterson & Posner, 2012). Peterson and Posner (2012) suggested that two executive systems act relatively independently in producing and controlling movement. The cingulo-opercular control system shows maintenance across trials and acts as stable background maintenance for task performance, whereas the frontoparietal system, is thought to relate to task switching and initiation, to response inhibition, and to adjustments within trials in real time.

It is reasonable to believe that delays in information processing observed in MC and DT tasks compared to the SC task is a direct result of increased processing time throughout this network due to the engagement of inhibitory processes involved in stimulus processing and response selection/inhibition and that exercise in some way facilitates and shortens this processing. As simple reaction time tasks involve less stimulus processing and response selection/inhibition, exercise has a minimal effect on these tasks compared to that encountered in more complex motor tasks, such as the MC and DT tasks used in this investigation.

4.2. Exercise Improved Reaction and Response Times but not Movement Time

The reduction in RT resulting in an overall reduction in RPT was seen in both MC and DT tasks. Reaction time represents more CNS mechanisms in an individual's response to a stimulus than does MT (Ito, 1997; Ozyemisci-Taskiran et al. 2008). This is because once a stimulus occurs, it must be registered through sensory and perceptual processes and once perceived through the senses, information passes on to the central nervous system to be identified and recognized. Only then does the brain determine if this stimulus is significant and initiates a response (Malhotra, Goel, Ushadhar, Tripathi, & Garg, 2015).

As there was no statistically significant change in MT, the speed of the motor response to the button press remained relatively constant. This fact, along with the reduction in RT time, supports the position that to a greater extent the effects of aerobic exercise occur more through cortical activation and processing mechanisms than through the motor response mechanism in improving overall response time (Audiffren et al., 2008). It is important to note that previous research investigating where improvements in information processing occur consequent to aerobic exercise have been mixed. Using a fractionated response time model such as ours, the locale for improvements in information processing have been found in RT (Ozyemisci-Taskiran et al., 2008), in MT (e.g., Audiffren et al., 2008), and in both RT and MT (Baylor & Spirduso, 1988). The statistically significant reduction in RT and not MT observed in our investigation is, therefore, consistent with previous investigations and indicates that increased speed of CNS processing (RT) was the primary cause for the improvement in total response time observed in this investigation.

4.3. Exercise Improved Complex Reaction and Response Times Immediately and Short-Term

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Improvement in reaction and response times during multichoice and dual task conditions was observed both immediately, at 1 min, and short-term, at 20 min, postexercise and is supported by the literature (Lambourne & Tomporowski, 2010; Pontifex et al., 2019). One explanation for the observed lasting effects of aerobic exercise on speed of processing during multichoice and dual-task conditions could be the continuing effects of neurotrophic substances and/or catecholamines released during and following exercise. In previous investigations, researchers have found that concentrations of neurotrophic substances increase significantly after an acute bout of aerobic exercise (Hwang et al., 2016; Piepmeier & Etnier, 2015; Tsai et al., 2021). Since BDNF and Irisin are important for synaptic transmission and neuroplasticity-related processes, enduring concentrations of these substances could be responsible for the continued effects of exercise on speed of processing observed at 20 min postexercise.

Likewise, sustained higher levels of catecholamines provides a plausible explanation for the enduring effects of exercise on speed of processing observed at the 20 min postexercise period (McMorris, 2021, 2016). McMorris (2021) expanded on the basic catecholamine hypothesis by envisioning an interoception model for the facilitatory effects of exercise on information processing and cognition both immediately and short-term. According to McMorris (2021), during exercise and following the norepinephrine threshold, interoceptive feedback induces increased tonic release of extracellular catecholamines, which in turn facilitates phasic release of catecholamines and thereafter improved cognitive performance. As a result, long-term memory and cognition on tasks requiring switching and multichoice responses to new stimuli-response couplings are most likely facilitated. In the present investigation this could have translated into the sustained effects of exercise observed at 20 min postexercise.

Lastly, exercise has been shown to be a stressor that results in an overall increase in arousal and attention, which is most likely related to increased levels of the catecholamines norepinephrine, dopamine, and/or serotonin. Malhotra et al. (2015) reported not only a significant decrease in RT times after an acute bout of exercise, but also improvements in participants' mental alertness and attention. It is reasonable to assume that the observed improvements in speed of processing were in part the result of increased cortical arousal and attention.

In this investigation, all levels of exercise intensity improved participants' information processing speed when performing MC and DT tasks. On face value this appears to contradict the belief that the arousal and catecholamine induced effects of exercise on information processing should have an inverted-U affect, with moderate intensity having the greatest impact on information processing as espoused originally by Cooper (1973) and Davey (1973). However, meta-analyses have shown only small effects sizes for this inverted-U arousal effect on information processing (Lambourne & Tomporowski, 2010; McMorris & Hale, 2012), and this inverted-U effect has not been found universally (McMorris & Graydon, 2000; Tomporowski, 2003). Therefore, the potential of all levels of exercise intensity having an impact on information processing and cognition is not unprecedented.

The effect of exercise on an individual's speed of responding to an external stimulus has several important implications both in the performance of motor skills and in understanding the interaction between cognition and movement in motor performance. Improving reaction and movement time is crucial in sports, where quick responses and decision-making are essential for success. Moreover, with increasing age, information processing speed has been shown to slow dramatically. Thus, older individuals require more time to complete sensorimotor tasks when compared to younger adults. Lastly, processing speed is one of the most sensitive, albeit nonspecific, cognitive abilities demonstrating decline with varying types of cerebral dysfunction (e.g., autistic spectrum disorder, intellectual disabilities) (Cox et al., 2016). In this investigation, as well as in previous investigations, exercise has been shown to improve this essential component of motor performance and, therefore, has a wide range of potential applications.

Results from this investigation also suggest several opportunities for future research. One potential research venue would be to repeat this study using electrophysiological techniques to investigate what area (s) in the brain is (are) most active after an acute bout of aerobic exercise. One such area of focus might be the PFC and anterior cingulate cortex as they appear to be critical in inhibiting competing responses during multichoice tasks. Additionally, biochemical analysis ought to be employed to explore both catecholamine and neurotropic models and their relationship in improving information processing consequent to an acute bout of exercise. Lastly and most importantly, this investigation should be replicated using different age groups (comparing elderly, middle age, and pediatric populations) and populations (e.g., individuals with autistic spectrum disorder or intellectual disabilities).

Authors' contributions

R. C: Conceptualization, data curation, study supervision and administration, formal analyses, methodology, writing-original proposal, and writing-final draft and editing. **D. M**: Data curation and collection, assisted in writing final draft and editing. **W. S**: Construction and writing of response time apparatus software, electrical wiring of equipment and computer integration, assisted in writing-original proposal; editing of manuscript.

Conflict of interests

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