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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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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. One such psychomotor function involves information processing and cognition (IPC) and using reaction time (RT) and response time (RPT) as ways of inferring such ability. Reaction time is the ability to perform a quick motor response with respect to a definite stimulus. More precisely, RT is interpreted as the interval of time from the presentation of an unanticipated stimulus to the initiation of movement (usually as a burst in electromyographic [EMG] activity) and does not include the time it takes to complete the movement. This process consists of sensory and perceptual process. After a stimulus is perceived by our receptors, identification and recognition in the central nervous system commences. If we recognize a certain stimulus to be significant, we respond, or if not significant, we ignore and do not respond.

The speed of identifying the stimulus is an essential factor in this process. The last stage of the response to the stimulus is a motor reaction which involves a culminating movement in concert with the specific environmental context. This period from the onset of muscle activity to the completion of the movement is often referred to as movement time (MT). The entire process from stimulus initiation to movement completion is referred to as response time (RPT) and constitutes the combination of RT and MT. It is important to note that some researchers use differing terminology in fractionating RPT as they define RPT as RT and fractionate this into premotor time (time interval between the onset of the stimulus and the onset of the EMG activity of the relevant muscle) and motor time (time interval

between the onset of EMG activity and completion of the actual motor task). Response time and RT are frequently used as an index of central nervous system functioning and it implicates information processing that is stimulus perception and preprogramming of the response prior to the execution of the desired action. Prolongation of RT reflects impairments in cognitive processing (Ozyemisci-Taskiran, Gunendi, Blukbasi, & Beyazova, 2008).

Since the 1980s, there have been a number of investigations showing improvement in IPC during acute bouts of exercise at intensities ranging from as low as 35% to upwards of 90% of aerobic capacity (e.g., Arcelin, Delignières, & Brisswalter, 1998; Audiffren, Tomporowski, & Zagrodnik, 2008; Chmura, Krysztofiak, Ziemba, Nazar, & Kaciuba-Uscilko, 1998; Davranche, Audiffren, & Denjean, 2006; McMorris & Graydon, 1996; McMorris & Hale, 2012; Ozyemisci-Taskiran, Gunrndi, Bolukbasi, & Beyazova, 2008; Paas & Adam, 1991; Pesce, Capranica, Tessitore, & Figura, 2002; Pesce, Casella, & Capranica, 2004). 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 these stimuli, understanding the mechanisms involved in this process is essential for practitioners involved with the training or rehabilitation of athletes and nonathletes alike.

Furthermore, better understanding the mechanisms involved in RT and RPT becomes particularly important for understanding the underlying mechanisms of the elderly population at risk of falling (Rosado, Bravo, Raimundo, Carvalho, Marmeleira, & Pereria, 2021). The aging process leads to biological and physiological changes in the brain, with measurable effects on RT and dual-task performance. Researchers have established that there is a strong inverse relationship between cognitive functioning and the risk of falling (lower cognitive functioning leading to an increased risk of falling), and that the association between RT and falling is so compelling that it is reported as one of the most important and sensitive indicators of

changes in the central nervous system related to falls in the elderly population (Graveson, Bauermeister, McKeown, & Bunce, 2016).

Mechanisms for Improved IPC with Exercise

Arguably, the most prevalent mechanism attributed to the enhancements in IPC 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 (e.g., Audiffren, Tomporowski, & Zagrodnik, 2008; Davey, 1973; e.g., Heckler & Croce, 1992; Lambourne & Tomporowski, 2010; McMorris & Graydon, 2000; Näätänen, 1973; Thayer, 1987). The first to offer a theoretical rationale for increased arousal being the mediator for the facilitatory effects of exercise on IPC was Davey (1973) who, drawing on Yerkes and Dodson's (1908) arousal–performance interaction theory, reasoned that exercise was a stressor which could induce changes in arousal levels. He hypothesized an inverted-U effect of acute exercise on cognitive performance, with moderate intensity exercise producing significantly better performance than lower or high intensities. Meta-analyses have shown small, yet significant mean effects sizes for this inverted-U exercise effect on IPC (Etnier et al., 1997; Lambourne & Tomporowski, 2010; McMorris & Hake, 2012); however, this effect has not been found universally (Brisswalter, Collardeau, & Rene', 2002; McMorris & Graydon, 2000; Tomporowski, 2003).

Although there appears to be a relationship between the inverted-U theory and the effects of acute exercise on IPC and despite the strength of some of the existing evidence on the topic, there nonetheless was a lacking in our understanding of (1) the intrinsic mechanisms by which the facilitatory effects of exercise work, (2) the way in which these mechanisms influence the components of the information processing-response system, and (3) the time-points throughout an exercise bout or throughout post-exercise recovery that exercise influences the components of the information processing-response system (Tomporowski, 2003). To this end, additionally theories have been espoused to explain the effects of aerobic exercise on IPC.

Expanding on the work of Sternberg (1969, 1998), Sanders (1983, 1998) proposed a cognitive-energetical model in which he articulated that there are three mechanisms (i.e., arousal, activation, and effort) influencing IPC. He argued that arousal is linked to the feature extraction stage, activation influences the motor adjustment stage, and effort is involved in the response-selection stage. Results of experiments endeavoring to isolate the locale of the exercise-induced arousal effects on these stages of IPC have been, however, inconsistent, and inconclusive.

For example, some authors were unable to localize the facilitating effect of moderate aerobic steady-state exercise on RT (Arcelin et al., 1998; Davranche & Audiffren, 2004; Jin, Easson, & Loftin, 2015). In contrast, Audiffren et al. (2008) supported a selective effect of exercise on the motor adjustment stage of IPC. Further, in their meta-regression analysis of exercise-induced arousal and cognitive performance, Lambourne and Tomporowski (2010) concluded that exercise-induced arousal enhanced performance on tasks that involve rapid decisions and automated behaviors, and that cognitive performance was affected differentially by exercise mode, with cycling being associated with enhanced performance during and after exercise. Their conclusion was that IPC performance may be enhanced or impaired depending on when it is was measured, the type of cognitive task that was used, and the type of exercise mode that was performed.

Similarly, in two reviews on the subject, McMorris and Hale (2012) and Tomporowski (2003) both concluded that information processing, which in many of the studies included reaction time responses, is best enhanced by acute submaximal exercise and further noted that exercise bouts up to one hour were most effectual and

that longer exercise bouts adversely affected information processing and memory. It appears that moderate steady-state exercise increases central nervous system arousal, enhancing performance by making the individual more sensitive to stimuli, and by increasing the speed at which sensorimotor processing occurs. The mechanism for this relationship is most likely an interaction of several dynamics, of which arousal is but one factor. This has led to numerous other interpretations into the causal effect of exercise on IPC.

One such theory is the reticular activating hypofrontality (RAH) model espoused by Dietrich (Dietrich, 2003; Dietrich & Audiffren, 2011). According to this theory, during moderate intensity exercise the reticular system will increase alertness and arousal leading to improved performance of well-learned tasks. However, heavy exercise requires greater activation of the premotor and supplementary motor cortices and if exercise intensity is to be maintained, these areas will be activated at the expense of the prefrontal cortex, which would lead to poorer cognitive performance on tasks requiring prefrontal cortical activation. Thusly, the mediating role of resource allocation and arousal could explain the observed improvements in cognitive performance resulting from exercise (Brisswalter, Collardeau, & Rene, 2002; Nanda, Balse, & Manjunatha, 2013; Du Rietz et al., 2019).

Another theory, which is related to the reticular system activation theory, is the catecholamine hypothesis originally espoused by Cooper (1973). According to Cooper, three main systems of neuromodulators have been distinguished as being possibly explanatory for increased arousal: The noradrenergic, the dopaminergic, and the serotonergic systems (McMorris, Tomporowski, & Audiffren, 2009). The catecholamine hypothesis stipulates that immediately preceding and during exercise the hypothalamus and other brainstem areas activate the sympathoadrenal system (Miyashita & Williams, 2006). As exercise intensity increases from low-to-moderate-to-intense levels, there is a release of epinephrine and norepinephrine into the blood

from the adrenal medulla, which centrally activates primary, premotor, and supplementary motor cortices, as well as influencing other brain networks responsible for information processing. Moderate increases in the concentration of these two neurotransmitters influence pre-frontal attentional systems by enhancing evoked responses, or by suppressing "background activity", or by a combination of the two (Masulam, 1990; Patil, Patkar, & Patkar, 2017).

Similarly, the dopaminergic modulatory system has projections modulating neural in the ventral striatum, which is part of the cortical-striatal network that activates premotor and primary motor cortices (motor planning and execution) and the medial prefrontal cortex (modulates executive functions), energizing neuronal outputs. Lastly, the serotonergic modulatory system dampens the actions of each of the two preceding systems and promotes behavioral inhibition and cortical deactivation (McMorris et al., 2009; Patil, Patkar, & Patkar, 2017).

The result of Increases in brain concentrations of catecholamines during and/or following moderate-intensity exercise would theoretically facilitate IPC. During and/or following low-intensity aerobic exercise IPC performance would be subdued due to limited activation in the relevant brain areas. During and/or following high-intensity exercise, much larger increases in catecholamines would lead to neural noise, which in turn would lead to decrements in performance (Arnsten, 2011; Arnsten & Goldman-Rakic, 1985). As observed in the inverted-U theory of arousal and IPC, this theoretical framework would favor moderate-intensity exercise as most beneficial on IPC. McMorris and Hale (2015) in their investigation, although not fully supporting the concept that there is a physiological/biochemical trigger point which induces increased speed of cognition, nevertheless concluded that moderate intensity exercise can induce increased speed of cognition, which is due to both physiological and biochemical changes

peripherally, as well as increased central neurochemical activity resulting from exercise-induced perceptions of stress.

Lastly, adequate levels of Brain-Derived Neurotrophic Factor (BDNF) and Irisin have emerged as potential mediators for the acute exercise-induced enhancements on IPC performance (Ferris Williams, & Shen, 2007; Hwang et al., 2016; Tsai et al., 2021). Brain-Derived Neurotrophic Factor is one of several growth factors found in the pre-frontal cortex, basal forebrain, and hippocampus where decision making takes place and priority is given to important information processing tasks. Brain-Derived Neurotrophic Factor and Irisin work synergistically to bring about the observed beneficial effects of exercise on IPC by facilitating attentional processes and enhancing stimulus selection and decision making (Basso & Suzuki, 2017; Janseen, Toussaint, vanMechelen, & Verhagen, 2014; Tsai et al., 2021). It is possible that some of the improvements in IPC observed with aerobic exercise is the direct result of increased levels of brain growth factors. Although previous research does suggest that exercise induced BDNF increases are associated with improved cognitive performance, results are equivocal (Hwang et al., 2016).

PURPOSE

In the present investigation, we investigated the role of three intensities of aerobic exercise (Low Intensity [LI], Moderate Intensity [MI], High Intensity [HI]) on IPC using a unique method to fractionate RPT into three components: (1) RT, which is the interval between the onset of the stimulus signal and the onset of muscle activity in the responding muscle (cognitive-decision making component), (2) movement time (MT), which is the time interval between the onset of muscle activation and completion of the required motor response, and (3) RPT, which encompasses both RT and MT. Movement time reflects more the muscular

components of the stimulus-response action, whereas RT reflects the duration of all earlier stages of information processing.

Analysis of RT and MT provided a way of determining whether the facilitating effect of exercise occurs prior to or after the onset of muscle activity or whether the facilitatory effects occur both prior to and after the onset of muscle activity, and directly isolates early cortical-integration processes from later motor-movement processes (Hasbroucq et al., 2001). Limited research using EMG to fractionate RPT has provided some evidence that acute aerobic exercise differentially impacts RT and MT (Davranche et al., 2005, 2006). Moreover, according to Ozyemisci-Taskiran et al. (2008) and Ito (1997), RT is a more valid indicator of programming time than looking at RPT (Ito, 1997). Ito posited that future studies performed by fractionating total RPT would better reflect the effect of exercise on one's reactions.

What makes this investigation unique is that we investigated the effects of exercise on fractionated RPT from multiple viewpoints. Firstly, we assessed the effects of three different intensities of aerobic exercise on simple (1-choice), complex (5-choice), and dual-task (DT; 5-choice plus counting backwards by 3) conditions. Secondly, we assessed whether the facilitating effect of these three exercise intensities influenced either RT, MT, or both of RT and MT. Lastly, we assessed temporal changes in RT and MT performances immediately (1-min post-exercise) and short-term (20-min post-exercise).

Further, as exercise influences both central and peripheral processes differently during simple and multichoice tasks (Burle, Vidal, Tandonnet, & Hasbroucq, 2004; Davranche et al., 2006), it was imperative that we investigated both conditions. For example, according to Burle et al. (2004) and Schapkin, Raggatz, Hillmert, and Bockelmann (2020), inhibition, or the suppression of unwanted responses, is widely proposed to account for data obtained in choice RT tasks with two structures, the anterior cingulate cortex and supplementary motor area, being

integral to the process of neural inhibition. This process of neural inhibition becomes less of a mitigating factor in simple (1-choice) tasks. Therefore, one might expect to see potential differences in how aerobic exercise influences simple and multichoice tasks. Based on the work of McMorris and Hale (2012, 2015) and McMorris et al. (2011), accuracy as a dependent variable does not show improvement with an acute bout of exercise; therefore, we investigated solely speed of IPC rather than investigating both speed and accuracy in this investigation.

METHODS

Study Participants

Twenty-seven participants (16, male; 11, female) from the University of New Hampshire between the ages of 18-25 (mean age = 21.9 years) took part in 1-choice, 5-choice, and DT conditions prior to and after an acute bout of either LI, MI, or HI of 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 such as asthma 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 reaction time 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 hours prior to each session, not consuming any alcohol within 24 hours prior to each session, and not consuming caffeine the day of each session as these can influence HR and exercise performance.

Stimulus and Response Time (RPT) 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-degree semicircle, each 8 inches on center from the start button on the bottom of the apparatus. The components are encased in a 17″x13″x2″ 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 a one-choice task, the color white is displayed; for a 5-choice task, colors red, yellow, white, green, and blue are displayed (Figures 1 & 2). Colors for the multiple-choice tasks 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 10-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-sec to 2-sec 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 (see Figures 1 & 2). [CoolTerm software is a tool that's geared towards hobbyists and professionals with a need to exchange data with hardware connected to serial ports such as servo controllers, robotic kits, GPS receivers, and microcontrollers.)

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, 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.

Procedures

In the first session (about 30-40-min) 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 the pre-participation health screening questionnaire, participants were randomly assigned into one of the following three groups for session-2 when participants engaged in the acute exercise bout: (1) a low intensity exercise group (LIE), where participants exercised for 12-min between 35-40% max HR; (2) a moderate intensity exercise group (MIE), where participants exercised for 12-min between 55-60%% max HR; or (3) a high intensity exercise group (HIE), where participants exercised for 12-min between 75-80% max HR. All exercise sessions in session-2 included a 2-min warm-up and 1-min cool down, leading to a total exercise time of 15-min, which corresponds to several previous investigations. According to Chang, Labban, Gapin, and Etnier (2012),

changes in cognition after exercise are observed following bouts lasting at least 11-min, with no enhancements observed for bouts lasting 10-min or less. Further, Lambourne and Tomporowski (2010) determined that cognitive enhancements following physical activity were greater for cycling exercise than for running-based exercise. These two factors were used in determining exercise duration and mode of exercise used in this investigation.

In perusing the literature there have been numerous approaches to characterize intensity of exercise, including using different physiological (cardiac capacity vs. energy expenditure) or psychological parameters (perceived exertion). According to Pontifex et al. (2019), the approach used by an investigator should reflect the research question of interest and the context and external relevance in which the research question exists. Further, those investigations focusing on feasibility or clinical relevance of acute bouts of exercise, are better served using intensity measures such as heart rate reserve. Accordingly, in this investigation heart rate reserve (using the Karvonen method) was used to measure exercise intensity.

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, Wagner, & Heyward, 2019), participants were brought to their designated target heart rate range (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, if 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 bike

ergometer with their knees at between 30- to 35-degrees for maximum efficiency and minimal knee- and ankle-joint stress (Ferrer-Roca, Bescós, Roig, Galilea, Valero, & García-López, 2014). The last part of session 1 included having participants perform 10 practice trials of each condition (1-choice, 5-coice, DT) to become familiar with the RPT apparatus and each choice condition.

In the second session participants were pre-tested (prior to exercise and used as baseline measurements) in each of the three conditions (1-choice, 5-choice, and DT [5-choice RT while counting backwards by 3]). The order of testing was counterbalanced to control for potential learning effects. Before baseline testing, participants engaged in 10 practice trials of each condition to minimize practice-related improvements in RT and MT over the course of testing sessions (Del Rossi, Malamute & Del Rossi, 2014).

After baseline measurements were taken, participants engaged in a 12-min bout of aerobic bike exercise at their designated heart rate, which also included a 2-min warmup and a 1-min cool down. One-min (immediate effects) and then again 20-min (short-term effects), participants were again tested on the three conditions (1 choice, 5-choice, and DT) in the same order tested in pretesting. Participants performed 10-trials in each of the RT conditions at each of the test times (pre, post 1-min, post 20-min). For data analysis, high and low RT scores were omitted, and the middle eight trials were averaged. It took participants approximately 2-min to complete the RT tasks during each testing session.

STATISTICAL ANALYSIS

For each test measurement (1-choice, 5-choice, DT), TRT, PMT and MT time scores (msec) were analyzed via separate 3 (Group [LIE, MIE, HIE]) x 3 (Test Blocks [pre, post 1-min, post 20-min]) repeated measures ANOVA. To control for type-1 error the Bonferroni correction factor was used determining significant alpha levels

($p > 0.05$). To adjusting 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. The following parameters were used to determine effect size: a value of 0.2 represented a small effect size, a value of 0.5 represented a medium effect size, and a value of 0.8 represented a large effect size.

RESULTS

For the 1-choice condition, there were no significant between group (LI, MI, HI) and within group differences (BL, 1-min, 20-min) 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 5-choice condition there were no significant between group differences for RT ($p = 0.38$), MT (0.69), and RST ($p = 0.34$), but there were significant within group differences for RT ($p \leq 0.001$, $r = 0.55$) and RSP ($p < 0.01$; $r = 0.47$), but not for MT ($p = 0.47$). Like the 5-choice condition, in the DT condition there were no significant between group differences for RT ($p = 0.17$), MT (0.84), and RST ($p = 0.48$), but there were significant within group differences for RT ($p < 0.05$, $r = 0.46$) and RSP ($p < 0.05$; $r = 0.45$), but not for MT ($p = 0.17$). *Post-hoc* analysis for both the 5-choice and DT conditions indicated that there were significant decreases in RT and RST time values from BL to 1-min and 20-min post-exercise and that decreased time values were maintained from 1-min to 20-min post-exercise (Figures 4-6).

Therefore, regardless of the exercise intensities undertaken by participants – LI, MI, and HI – there was a positive effect on the speed of IPC in the more complex RST conditions (5-choice and DT conditions) and that this faciliatory effect was seen in central nervous system processing of the stimulus and choice selection (i.e., RT) and not in the actual movement per se (i.e., in MT or the time from initiation of the muscle response to the completion of the task [button press]). However, this facilitatory effect of exercise on IPC was not observed in the simpler RST condition (i.e., 1-choice condition).

DISCUSSION AND CONCLUSIONS

In the present investigation we investigated the role of three intensities of aerobic exercise (Low Intensity [LI], Moderate Intensity [MI], High Intensity [HI]) on IPC, by analyzing RPT and its fractionated components RT and MT. Based on the statistical analyses, three major findings emerged: (1) participants improved RT and RPT in the more complex 5-Choice & DT tasks but not in the simple 1-Choice task; (2) the primary improvement in RPT occurred as a result of decreased RT (Premotor time) and not MT (movement to target-time); and (3) all exercise intensities improved RT and RPT in the 5-Choice and DT tasks both immediately post-exercise (1-min) and short-term (20-min);. As RT represents more CNS mechanisms than movement per se, the facilitatory effects of exercise on RPT involved more speed of cortical processing than speed in completing the task. Each of these effects will be discussed separately.

IPC Improvement in Complex but not Simple Response Tasks:

Different models of choice RPT and RT tasks have been developed and tested using both behavioral and electrophysiological (EEG) techniques. All of them treat information processing as a gradual process based on the accumulation of information that is time sensitive and most of these models are comprised of at least two processing levels: one stimulus-related and one response-related. In such models, 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 (Spencer & Coles, 1999). Reaction time

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 aforementioned RT model and accounts for the extended time need to complete tasks involving multiple response alternatives. This concept of inhibition of responses is often considered a functional counterpart of neural activation; however more importantly to this discussion, neural inhibition is defined not only as an absence of excitation but as an active process involving suppression of an excitatory action, or more descriptively as the 'suppression of inappropriate responses or the suppression of interfering memories during retrieval' (Burle, Vidal, Tandonnet, & Hasbroucq, 2004; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Zhang, Ding, Wang, Qi, & Luo, 2015). In the context of our investigation inhibition is an intermediate variable that increases processing time and engages cortical mechanisms that are not employed in simple one-choice situations. It would appear that in simple response situations, the responding mechanics are simplified and because of this simplified process, the impact of exercise on IPC is minimal compared to that encountered in more complex, multichoice and dual task situations.

Results of a series of experiments by Burle et al. (2004) exemplify these differences. Burle et al. (2004) found that the activation of the motor structures involved in the required response was accompanied by an inhibition of the structures involved in the 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 and that response competition is implemented through a balance of activation and inhibition of possible responses. Similarly, Zhang et al. (2015) posited that inhibition of a response is an essential executive function which enables us to suppress inappropriate actions in a given

context. 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.

Schapkin, Raggatz, Hillmert, and Bockelmann (2020) found in a multichoice, high-load working memory reaction time task changes in in alpha, beta, delta, and theta EEG frequencies, which were observed in multiple, functionally distinct regions and that were either positively (beta) or negatively (alpha and theta) related to task complexity. They concluded that increases in theta power indicated efficient information processing in working memory resulting in improvements of higher-order executive control over all the sub-processes including motor preparation and execution. They postulated that this may reduce a compensatory over-activation of the motor system (lowering of beta activity) and facilitate motor responses (shortening of RT). Conversely, enhanced beta activity may be an index of impairments in WM and lowering of executive control, resulting in compensatory over activation of the motor system and a lengthening of RT.

But what neural system would be responsible for balancing activation and inhibition of the possible responses in multichoice situations and potentially be the site through which exercise imbues its effects. 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; Schapkin et al., 2020). Although the prefrontal cortex (PFC) provides both excitatory and inhibitory input to distributed neural circuits throughout the cortex and is required for diverse functions, the parietal cortex is most involved in task-related attentional processes.

When an individual is engaged in a task requiring focused attention, an increase in 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. Those internal factors guiding attention and response selection are typically referred to as the top-down control of attention and response selection (Malik, Schamiloglu, & Sohal, 2022). In this control process cognitive factors such as goals, knowledge, and expectations are used to direct the focus of attention and external influences involving relevant stimuli that are behavioral applicable are often referred to as stimulus driven.

Inhibitory control has for a long time been associated with the FPN and both the dorsal (dPFC) and medial (mPFC) PFC have been offered as key structures involved in this process. 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 top-down control. The cingulo-opercular control system shows maintenance across trials and acts as stable background maintenance for task performance. The frontoparietal system, in contrast, showing mostly start-cue signals, 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 IPC observed in multichoice compared to simple-choice tasks is a direct result of increased processing time throughout this network due, at least in part, to the engagement of inhibitory processes involved in stimulus processing and response selection/inhibition and that exercise in some way facilitates this processing. As simple reaction time tasks involve less stimulus processing and response selection/inhibition, exercise has a minimal effect compared to more complex 5-Choice and DT conditions.

IPC Improvement in RT and RPT but not MT

The reduction in RT that resulted in reduced RSP were seen in both 5-choice and dual choice. RT represents CNS mechanisms in the participants response to the stimulus (Ito, 1997; Ozyemisci-Taskiran et al. 2008). This is because once a stimulus occurs, it must be registered through sensory and perceptual processes. Once perceived through the senses, the information passes to the central nervous system to be identified and recognized. Only then does the brain determine if this stimulus is significant and initiate a response (Malhotra et al., 2015). Therefore, an improvement in RT is in line with exercise improving CNS processing and in turn, improving overall RSP and IPC.

There was no statistically significant change in MT which means the speed of the motor movement to the stimulus remained constant. This supports the information processing model that aerobic exercise impacts the motor adjustment processing stage through the activation mechanism not through the arousal mechanism (Sanders, 1983; Audiffren et al., 2008). Previous literature has found that with a fractionated reaction time model, there were improvements in the RT component (Davranche et al., 2006; Ozyemisci-Taskiran et al., 2008). Additionally, some studies found improvements in both RT and MT (Clarkson 1978; Baylor and Spirduso, 1988; MacRae et al., 1995). However, Audiffren et al. found only an improvement in MT which indicates increased arousal, but had a smaller sample size than this study (Audiffren et al., 2008). The statistically significant reduction in RT and not MT is consistent with previous literature and overall signifies improved CNS functioning and IPC.

Exercise Improves IPC in Complex tasks Immediately and short-term Post-Exercise

The improvement in RT was seen both immediately, at 1-minute, and short-term, at 20-minutes post exercise. This shows that the effects of exercise on RT in this

study were maintained over the 20-minute period post exercise. Previous literature reports that the greatest effects on RT are seen 15 minutes post exercise (Pontifex et al., 2019). However, Basso et al. found that improvements in cognitive performance after exercise were maintained for 2 hours (Basso et al., 2015). One explanation for these longer lasting effects is BDNF release and increased arousal as a result of the bout of exercise. While BDNF was not looked at in this study, previous literature has found that BDNF has been found to increase in concentration after a single bout of aerobic exercise (Piepmeier et al., 2015; Hwang et al., 2016; McMorris et al., 2016; Tsai et al., 2021). Since BDNF is important for synaptic transmission and neuroplasticity-related processes, this increase in concentration has led to the hypothesis that it is responsible for changes in cognition following exercise at short term.

Additionally, exercise has been shown to be a stressor that results in an increase of arousal. The inverted-U theory of arousal states that exercise increases arousal with the greatest improvement seen with moderate intensities (Yerkes and Dodson, 1908). Arousal refers to changes to physiological, cognitive and affective aspects that occur after a stressor (Eysenck, 1982). Malhotra et al. reported not only a significant decrease in reaction time after an acute bout of exercise, but also improvements in the participant's mood, circulation and mental alertness (Malhotra et al., 2015). By measuring how the participants felt paired with the RT task, these results were indicative of an increase in arousal after a bout of exercise. One aspect of increased arousal is increased attention. It is reasonable to assume the improvement seen in the RT times but not the MT was a result of increased arousal which overall increased attention. Additionally, increased arousal would most likely cause the maintained improvements seen short term at 20-minutes post exercise.

Future Directions of Study

There are several potential avenues of future research to pursue in regard to the effect of exercise on reaction time. One would be to repeat this study with EEG to see where exactly in the brain is more active after a bout of exercise. The area of focus in this situation would be the PFC. Additionally, the biochemical effects could be analyzed to see if there is a change in neurotrophic hormone release. This would explore both the catecholamine and neurotropic models and how exactly exercise improves IPC performance. This study could also be done on different age groups including children and the elderly. For children, an improvement with exercise could have implications for improving performance in the classroom. For the elderly, an improvement with exercise could have implications for reducing fall risk and maintaining independence. Additionally, different conditions could be studied such as autism and other neurologic disorders. This study could also be repeated with different exercise models to see if the type of exercise impacts IPC performance, such as HIIT training. Lastly, further research could include testing executive functioning to investigate if exercise causes improvement in IPC with more complex tasks. The potential for improvement in IPC performance with exercise is an exciting possibility that could have a strong positive impact on all age groups and improve cognitive functioning.

Conclusion

The results of our study have led to three major conclusions. The first being that regardless of exercise intensity, there was an improvement in IPC in the 5-choice and dual task. The second being that the improvement in RSP was seen in the RT component which is directly related to IPC and CNS processing. The third being that the improvement was seen at 1-minute post exercise and lasted short term at 20-minutes. Overall, our investigation was seminal in showing that exercise improves IPC with dual task conditions. Exercise and reaction time has several important

implications in everyday life with basic reaction time intensive tasks such as driving, and athletic performance. While there are several future potential research avenues under this topic, our investigation provided important insight on how exercise impacts reaction time in more complex tasks, and that it occurs within the RT component of RSP.

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<u>Figure-1</u>. Configuration and sequencing of the reaction-time apparatus.

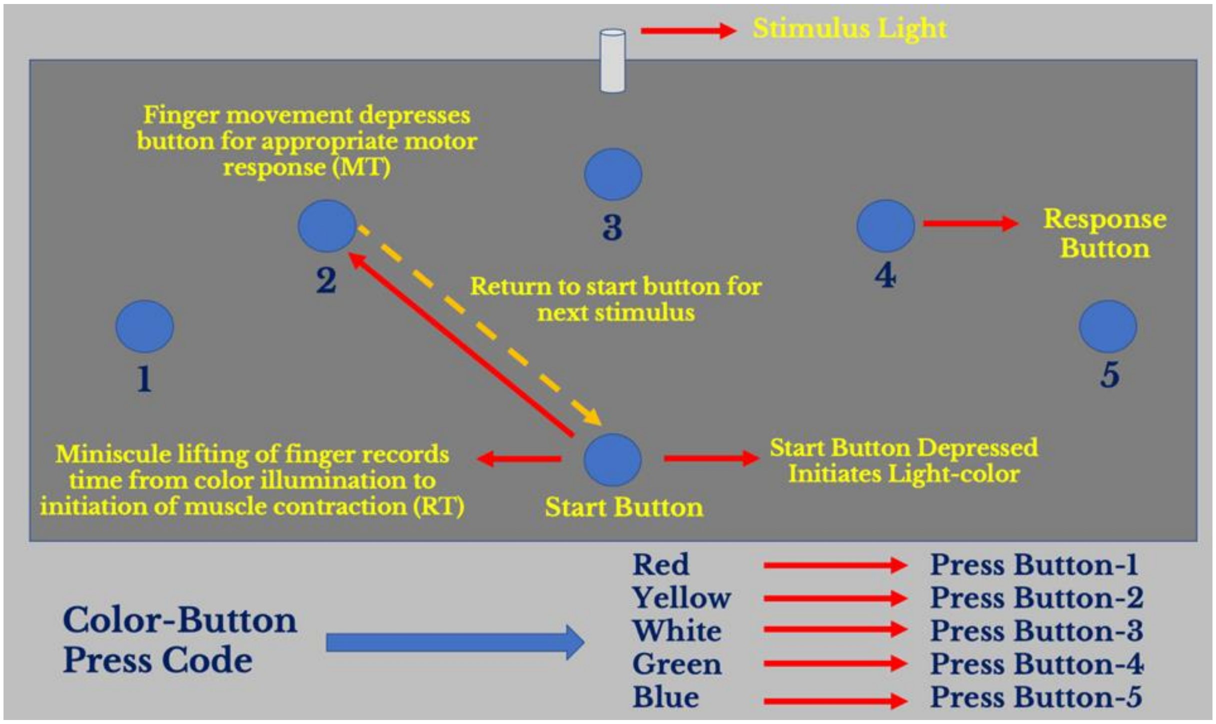
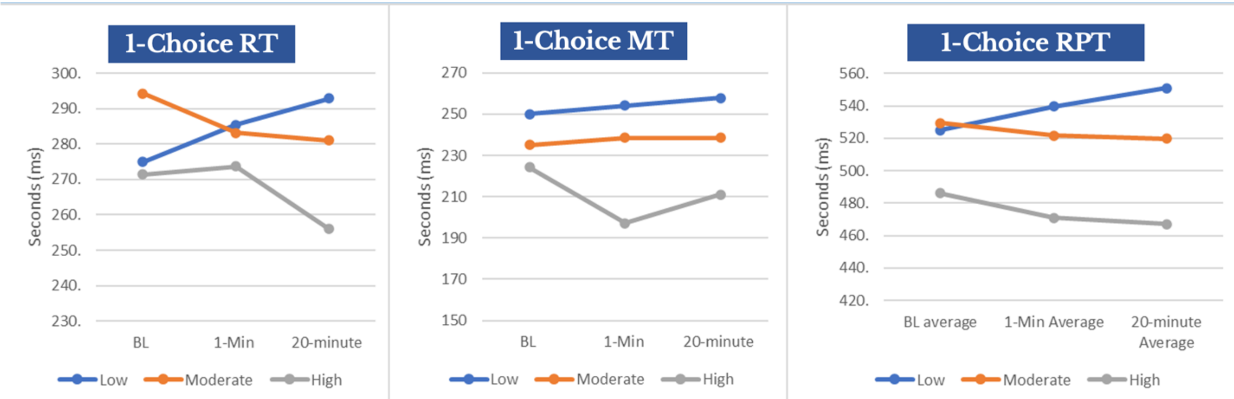


Figure-2. Participants seated at the reaction-time apparatus.

Figure 3. Participant seated on the Monarch Bike Ergometer.

<u>Figure 4</u>. Results of the 1-Choice Response Time Task.

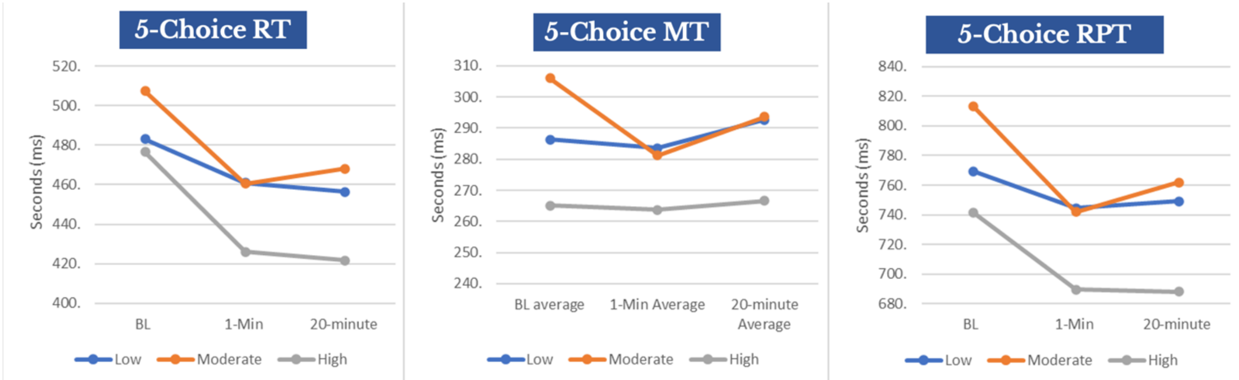


Groups	BL	1-Min	20-minute	Groups	BL	1-Min	20-minute	Groups	BL	1-Min	20-minute
LI	274.92	285.43	292.88	LI	250.00	254.22	257.97	LI	524.92	539.65	550.85
MI	294.36	283.14	281.08	MI	235.18	238.68	238.60	MI	529.54	521.82	519.68
HI	271.46	273.76	255.99	HI	224.32	197.13	211.11	HI	486.21	470.89	467.10

<u>*Code*</u>: LI = Low Intensity Exercise; MI = Moderate Intensity Exercise; HI = High Intensity Exercise. RT = Reaction Time; MT = Movement Time; RPT = Response Time.

<u>*Note*</u>: There was NSD ($p > 0.05$) amongst groups or across trial blocks.

Figure 5. Results of the 1-Choice Response Time Task.

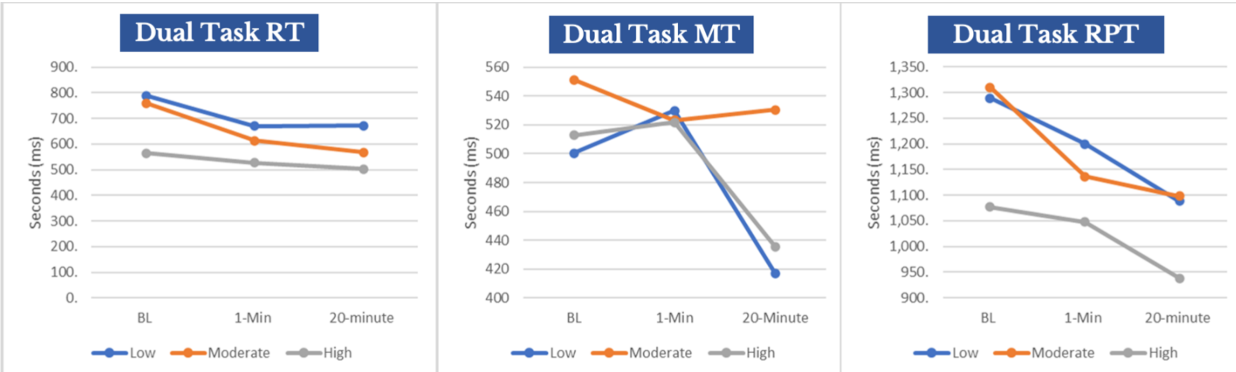


Groups	BL	1-Min	20-minute	Groups	BL	1-Min	20-minute	Groups	BL	1-Min	20-minute
LI	483.10	460.89	456.50	LI	286.38	283.60	292.65	LI	769.47	744.49	749.15
MI	507.40	460.56	468.17	MI	306.00	281.29	293.68	MI	813.40	741.85	761.85
HI	476.49	426.00	421.63	HI	265.14	263.71	266.67	HI	741.63	689.71	688.29

Code: **LI = Low Intensity Exercise; MI = Moderate Intensity Exercise; HI = High Intensity Exercise. RT = Reaction Time; MT = Movement Time; RPT = Response Time.**

Note: **There was NSD ($p > 0.05$) amongst groups; there was a SD across trial blocks for RT ($p \leq 0.001$) and RPT ($p \leq 0.01$), but not for MT ($p > 0.05$).**

<u>Figure 6</u>. **Results of the Dual Choice (DT) Response Time Task.**



Groups	BL	1-Min	20-minute	Groups	BL	1-Min	20-minute	Groups	BL	1-Min	20-minute
LI	788.61	669.86	671.68	LI	500.38	530.00	417.07	LI	1288.99	1199.86	1088.75
MI	759.54	613.03	567.56	MI	551.24	523.32	530.56	MI	1310.78	1136.35	1098.11
HI	564.40	526.36	502.14	HI	512.69	521.81	435.63	HI	1077.10	1048.17	937.76

***<u>Code</u>*: LI = Low Intensity Exercise; MI = Moderate Intensity Exercise; HI = High Intensity Exercise. RT = Reaction Time; MT = Movement Time; RPT = Response Time.**

***<u>Note</u>*: There was NSD ($p > 0.05$) amongst groups; there was a SD across trial blocks for RT ($p \leq 0.05$) and RPT ($p \leq 0.01$), but not for MT ($p > 0.05$).**