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CHANGES IN FLANKER TASK PERFORMANCE FOLLOWING HIGH-INTENSITY EXERCISE IN ENDURANCE ATHLETES

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By

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Definitions

Aerobic exercise: As referred to by the American College of Sports Medicine (ACSM), any activity that uses large muscle groups, can be maintained continuously and is rhythmic in nature (Wahid et al., 2016).

Allocation of resources: Allocation of energy resources between the brain and the periphery, especially skeletal muscle (Peters et al., 2004).

Catecholamines: Physiologically active molecules that act both as neurotransmitters and hormones vital to the maintenance of homeostasis through the autonomic nervous system. The term “catecholamines” regroups the substances dopamine, norepinephrine, and epinephrine, that play an excitatory role (“fight or flight” response), notably to sustain a physical effort (Paravati, Rosani, & Warrington, 2024).

Cerebral cortex: Layer of gray matter that covers the outside of the cerebral hemispheres in the brain and is associated with higher cognitive functions, such as language, learning, perception, and planning (APA Dictionary of Psychology, 2018).

Cognitive functioning: Cognitive functioning refers to any mental operation involved in knowledge acquisition, reasoning, and manipulation of information. Cognitive functioning can be subdivided in a set of cognitive functions that can include the domains of perception, memory, learning, attention, decision making, and language abilities (Kiely, 2014).

Cognitive performance: Assessment outcome of any task relative to a its corresponding cognitive function (Harvey, 2019).

Congruency: Whether the trials in the flanker task are congruent or incongruent (or neutral). The purpose of congruent trials is to comparatively emphasize the changes in incongruent trials. They highlight incongruent trials by increasing the gap of difficulty to perform between both designs. The flanking arrows in the congruent design (looking to the same direction as the target) aim to facilitate decision making, while the incongruent flanking arrows (looking to the opposite direction) perturbate decision making. Congruent trials are meant to tend to more accurate and faster results than incongruent trials. However, the incongruent design is the one that reflects executive control, since fostering the inhibition of behavior (Eriksen & Eriksen, 1974).

Downregulation (physiology): Reduction of the magnitude or rate of a physiological response or biochemical or metabolic process (Lackie, 2010).

Energy resources (psychophysiological, physiological, neural): Referred to as “resources” in this study as any compound or substance that can be used as a source of energy by the brain or the skeletal muscles or is directly involved in their metabolism (Fehm, Kern, & Peters, 2006).

Executive function: Higher-level cognitive abilities that can be defined as a range of cognitive processes necessary for managing and controlling the behaviors that lead to the achievement of selected goals (Diamond, 2013).

Inhibition (cognitive sciences): Mental capacity to sort out and eliminate stimuli that are irrelevant to the ongoing task/process or to the current state of the mind (MacLeod, 2007).

Learning effect: Significant increase in cognitive test results as the number of repetitions increases, until results no longer change and become stable (Tao et al., 2019).

Maximal oxygen consumption (VO_{2max}): Maximal oxygen uptake (expressed in mL/min/kg, or L/min). It is reached at maximum exercise intensity when the oxygen uptake cannot be increased in spite of an increasing workload, and is thus used to define the limits of one's cardiorespiratory system (Hill & Lupton; 1923).

Physical Exertion: Expenditure of energy during physical activity. Intensity of exertion may be measured by rate of oxygen consumption; heat produced, or heart rate. This includes perceived exertion, a psychological measure of exertion (Medical Subjects Headings term, 2009).

Physical Exhaustion: Impossibility for a subject to sustain a physical load of equal or higher intensity due to physical exertion (Fery, Ferry, Vom Hofe, & Rieu, 1997).

Prefrontal cortex (PFC): Most anterior (forward) part of the cerebral cortex of each frontal lobe in the brain (APA Dictionary of Psychology, 2018).

Psychophysiology: The study of the physiological basis of human and animal behavior (Medical Subjects Headings term, 1996).

Recovery: In this study, we will refer to "short-term recovery" [Bishop et al., 2008] as the time period and physiological processes following the termination of exercise and driving the return to a resting or "recovered" state (Romero, Minson, & Halliwill, 2017).

Respiratory exchange ratio: Ratio of the volume of carbon dioxide eliminated from the lungs per minute to the volume of oxygen taken into the lungs during the same time. RER = Volume of CO_2 / Volume of O_2 (Kent, 2006).

Resistance training: Repetitive use of external resistance (or load) against muscle contraction to increase its strength, power, hypertrophy, local muscular endurance, motor performance, balance, or coordination (Kraemer & Ratamess, 2004).

Submaximal aerobic exercise intensities: Any intensity of exercise that does not exceed VO_{2max} intensity (Hill & Lupton; 1923). It can be formulated in percentage of VO_{2max}, and be arbitrarily subdivided in intensity categories such as follows:
Low-intensity aerobic exercise: < 60% VO_{2max}, such as below the first ventilatory threshold
Moderate-intensity aerobic exercise: > 60% - 80% VO_{2max} >, such as between the two ventilatory thresholds
High-intensity aerobic exercise: > 80% VO_{2max}, such as above the second ventilatory threshold

List of Abbreviations

ACC: accuracy

HI: High-Intensity (exercise)

MI: Moderate-Intensity (exercise)

LI: Low-Intensity (exercise)

PFC: Prefrontal Cortex

RAH: Reticular-Activating Hypofrontality model (Dietrich & Audiffren, 2011)

RT: Reaction Time

SRRME: Self-Reported Rating of Mental Effort

Abstract

Executive function performance following acute aerobic exercise can be influenced by multiple variables. However, little is known about the lasting effects of these exercise-induced changes. This study aimed to determine the extent to which exercise intensity impacts executive function. 14 young endurance-trained adults (5 female, 9 male) performed an Eriksen flanker task before and immediately after running high-intensity until failure and isochronal moderate-intensity (~12 min). Pre- to post-exercise-induced changes in reaction time (ms), accuracy (%), and self-reported mental effort (1-9 rating) were analyzed by overall tasks and through tasks subsections. Results showed improvement in reaction time following high- and moderate-intensity exercise, while only high-intensity suggested transient accuracy impairment alongside an increased self-reported mental effort. The main findings of this study indicated that high-intensity exercise-induced changes occurred within the 2 first min in the flanker task. Implications of this study might relate to contexts combining simultaneously physiological arousal and higher-order cognitive demands.

1 Overview

Physical exercise affects cognitive performance in multiple ways including immediate hindrance, immediate benefit, or long-term benefits. The long-term benefits have been widely documented and include a reduction in negative mental states such as anxiety or negative mood, and improvements in functions such as learning and attention. (Belcher et al., 2021; Meng, Lin, & Tzeng, 2020; Zhao et al., 2020). They are the result of the adaptations induced by multiple physical exercise inputs (Cabral et al., 2019). The short-term effects preceding those psychophysiological adaptations, however, are more complex (Y. K. Chang, Labban, Gapin, & Etnier, 2012; M. Jung, Ryu, Kang, Javadi, & Loprinzi, 2022; T. McMorris & Hale, 2012). Overall, it is generally agreed that the acute, short-term effects of exercise are more pronounced with higher intensity levels (Sudo, Costello, McMorris, & Ando, 2022).

Previous research suggests that acute exercise exertions result in improvement, deterioration, or no change in cognitive performance, particularly executive function, depending on specific conditions (Dietrich & Audiffren, 2011; Myungjin Jung, Kang, & Loprinzi, 2023; Sudo et al., 2022). Globally, the discrepancies seen between studies examining the short-term effects of exercise on cognitive performance are influenced by contextual factors including: 1) Timing of cognitive task with respect to the physical effort, 2) Exercise intensity and physical condition of participants, and 3) Type of task used to assess cognitive function (Myungjin Jung et al., 2023; Sudo et al., 2022). For example, several studies have included a considerable delay between termination of exercise and cognitive function assessment, while others have assessed cognitive function during exercise that may thus impact the exercise-induced changes (Y. K. Chang et al., 2012; T. McMorris & Hale, 2012). Furthermore, physical fitness of individuals also appears to impact the intensity of exercise required to elicit changes in cognitive performance (Labelle, Bosquet, Mekary, & Bherer, 2013; Stroth et al., 2009; Themanson & Hillman, 2006). Also, cognitive assessment displays different outcomes depending on the function investigated (e.g., memory, planning, information processing) (Sudo et al., 2022). One specific aspect of cognitive performance affected by exercise is executive function. Executive function refers to higher-level cognitive abilities that can be defined as a range of cognitive processes necessary for managing and controlling the behaviors that lead to the achievement of selected goals (Diamond, 2013). Executive function has been consistently reported to be impacted by moderate- and high-intensity acute exercise (Y. K. Chang et al., 2012; Sudo et al., 2022).

While our understanding of the effects of high-intensity exercise on executive function has grown through the last decades (Myungjin Jung et al., 2023; P. D. Tomporowski, 2003), there remain some lingering questions. Specifically, the time needed to return to a stable state of executive function close to baseline level after exercise-related changes is still unclear. Therefore, the purpose of this study is to determine the extent to which exercise intensity impacts cognitive performance. Specifically, we will assess cognitive performance before and after exercise and establish the time course of recovery.

To accomplish this, 20 endurance-trained young adults (8 female) were enrolled in the study. Participants attended 4 separate testing sessions. After completing the 2 preliminary visits used to determine appropriate running speed, the participants performed 2 testing sessions on 2 separate days at 90% and 60% of maximal exercise intensity. Before and immediately after exercise, participants performed a 7-minute flanker test to examine the potential effects of exercise on executive function. High-intensity exercise (HI) was compared to moderate-intensity (MI) to observe the effect size of intensity per se. Both intensities were compared to baseline tests to observe the effect size of exercise.

We hypothesized:

- H-1: Accuracy, as represented by the number of correct responses of the task, would decrease after high-intensity exercise, while improving after the moderate-intensity exercise.
- H-2: Reaction time would decrease after both moderate- and high-intensity close to termination of exercise. We expected this decrease in reaction time to be greater after high- than moderate-intensity.
- H-3: We further hypothesized that accuracy and reaction time would return to their baseline levels faster after moderate- than high-intensity.
- H-4: Performing the cognitive task would be self-reported as more effortful following high-intensity than following moderate-intensity, all the more in early task

2 Literature Review

2.1 Introduction

The human nervous system constantly receives information about the ever-changing world around it (Chiel & Beer, 1997; Lewis & Todd, 2007). The central nervous system (CNS) is responsible for continually interpreting this feedback from the rest of the body in order to make decisions and plan further actions (Shapiro & Spaulding, 2021). Cognition is a term that refers to a wide range of higher mental processes such as reasoning, perceiving, estimating, speaking, or planning (Ward, 2019). The traditional breakdown of cognition into multiple subparts that can be investigated independently (e.g. reductionism) corresponds to the conceptual perspectives that have evolved in cognitive science (Harvey, 2019). This traditional approach proposes multiple ways to conceive cognitive domains. Classification can be done into the hierarchical complexity of the brain operations (i.e. top-down vs bottom-up). It can also be categorized according to the brain structures involved (e.g., frontal lobe, temporal lobe, hippocampus), or under the scope of the general process involved, such as memory, language, or executive functions (Harvey, 2019) (Figure 1).

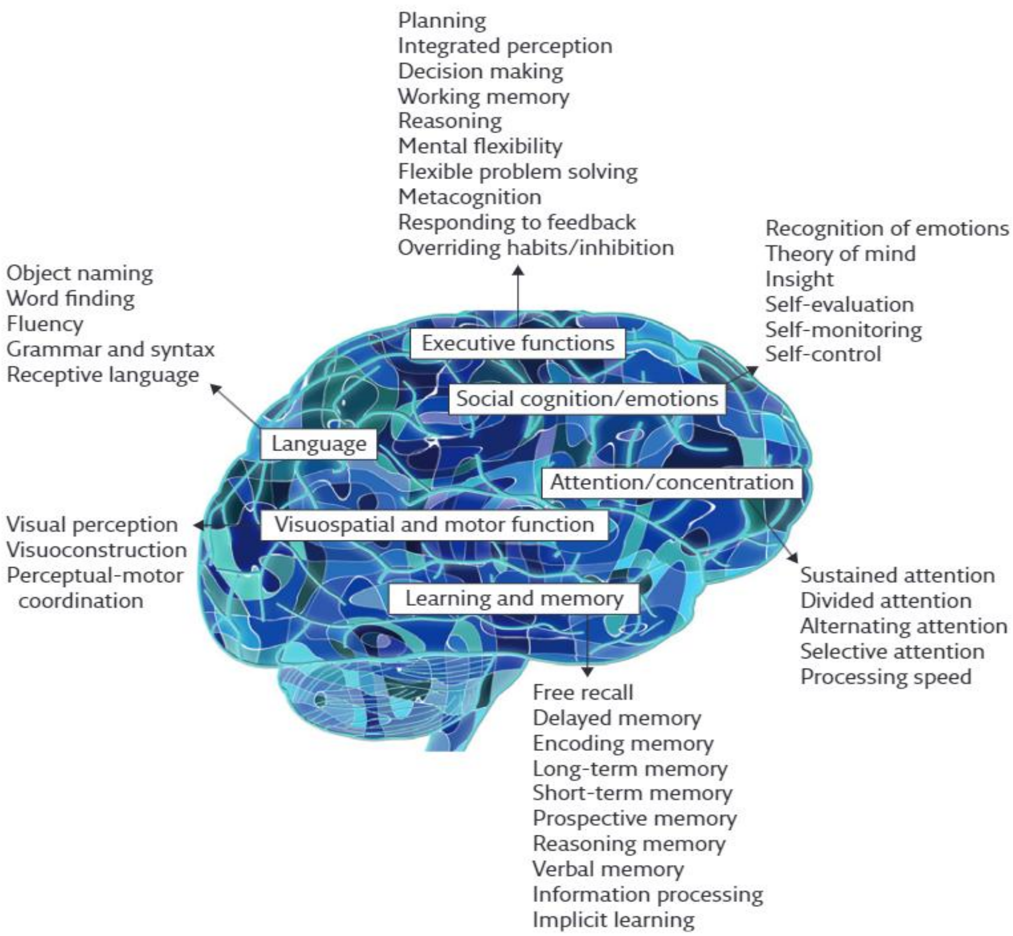


Figure 1. Major domains of cognitive function (Andrianopoulos, Gloeckl, Vogiatzis, & Kenn, 2017).

Reductionism has led to the use of tasks designed to assess specific subfunctions (abilities), functions, or brain structures associated with these functions (Harvey, 2019). However, there may be a strong intertwinement between cortical areas controlling movement, thinking, and physiological functions within common networks (Gordon et al., 2023). This network common to mental and physical tasks calls for the existence of a shared and limited pool of resources available to perform both types of tasks. There is evidence that this pool cannot be depleted, resulting in reduced performance (Michel Audiffren & André, 2015; T. McMorris, 2021).

Exercise can have both immediate and long-term effects on cognitive performance (Myungjin Jung et al., 2023; Meng et al., 2020; Sudo et al., 2022; Zhao et al., 2020). The literature investigating the causal relationship of acute exercise over cognitive functions refers often to the specific cognitive functions (or subfunctions) assessed (Y. K. Chang et al., 2012; Dietrich & Audiffren, 2011; T. McMorris, 2021; Sudo et al., 2022), and sometimes to their related brain structures (Myungjin Jung et al., 2023). The immediate effects of physical exercise on cognitive performance can lead to different outcomes depending on the circumstances surrounding the exercise. The mobilization of nervous and energetic resources for physical exercise can both support and conflict with those required for a cognitive task (Michel Audiffren, 2016; Michel Audiffren & André, 2015; Myungjin Jung et al., 2023). Beyond a certain threshold, the conflicting mobilization of two seemingly antagonistic tasks (i.e. mental task versus physical exercise) may require hierarchical adaptations to overcome the problem of limited shared resources (Dietrich & Audiffren, 2011; Sudo et al., 2022). Conversely, the resources elicited commonly may add up and benefit cognitive performance (Dietrich & Audiffren, 2011). The following sections review the current knowledge about the effect of acute physical exercise on cognitive function and describe the mechanisms underlying it.

2.2 Long-term effects of exercise on cognition

Physical activity has a positive long-term effect on cognitive function and mental health (Belcher et al., 2021; Christiansen et al., 2019; Herbert, Meixner, Wiebking, & Gilg, 2020; Meng et al., 2020; Zhao et al., 2020). Homeostatic disturbances induced by repeated physical activity result in changes in brain volume, perfusion, neuron plasticity, and neurogenesis (Herold, Muller, Gronwald, & Muller, 2019; Hwang et al., 2016; Zhao et al., 2020). These changes directly improve learning and attention, and overall cognitive functioning (Cabral et al., 2019; Law, Lam, Chung, & Pang, 2020). Long-term exercise has also been associated with reductions in anxiety, depression, and negative mood as well as improvement of self-esteem and better sleep (Callaghan, 2004). This is thought to be a result of psychophysiological adaptations including Zajonc's distraction theory (Zajonc, 1965), biochemical release, and the indirect perception of the overall exercise-induced benefits for health (Callaghan, 2004; Mikkelsen, Stojanovska, Polenakovic, Bosevski, & Apostolopoulos, 2017; Weinstein, Koehmstedt, & Kop, 2017).

2.3 Short-term Effects of Exercise on Cognition

Cognitive abilities are also affected by acute efforts of physical activity. The precise effects of these acute periods of exercise are not well characterized (Sudo et al., 2022). Previous research indicated mixed effects when investigating the impact of an acute exercise session on cognitive performance either during (i.e. while still performing the exercise) or after exercise (Y. K. Chang et al., 2012; M. Jung et al., 2022; T.

McMorris & Hale, 2012; T. McMorris, Hale, Corbett, Robertson, & Hodgson, 2015). Some studies found improvements in cognitive performance following or during aerobic exercise (Ando, Kokubu, Yamada, & Kimura, 2011; H. Chang, Kim, Jung, & Kato, 2017; Du Rietz et al., 2019; Finkenzeller, Doppelmayr, Wurth, & Amesberger, 2018; Hill, Walsh, Talbot, Price, & Duncan, 2019; O'Leary, Pontifex, Scudder, Brown, & Hillman, 2011; Samuel et al., 2017; Tempest, Davranche, Brisswalter, Perrey, & Radel, 2017). Multiple other studies found impairment after exercise (Coco et al., 2020; Komiyama et al., 2020; Labelle et al., 2013; Moore, Romine, O'Connor P, & Tomporowski, 2012; Smith et al., 2016; Stone et al., 2020; Zimmer et al., 2016). Conversely, several studies found no significant effect of exercise on cognitive function (Ando et al., 2011; Du Rietz et al., 2019; Hill et al., 2019; Samuel et al., 2017; Schmit et al., 2015; Sudo et al., 2017; Zimmer et al., 2016). The nature of the effect that exercise has on cognitive function depends on multiple factors including intensity and duration of effort, muscle mass involved, cognitive task and brain area involved, individual's fitness level and experience, and timing of the cognitive task with respect to the exercise (Dietrich & Audiffren, 2011; T. McMorris, 2021; Sudo et al., 2022; P. D. Tomporowski, 2003). These factors, which can be referred to as moderators or paradigms (Y. K. Chang et al., 2012; M. Jung et al., 2022) are discussed below (Table 1).

Table 1. Acute versus chronic exercise (Dietrich et Audiffren, 2011).

Type of effect	Mode of exercise	Type of change	Type of brain mechanism
Acute effect	Single bout of exercise	Transient	Physiological: modulation in the activity of neural networks
Chronic effect	Regular exercise	Durable	Anatomical: morphological changes in the brain structure

2.3.1 Timing Characteristics

Timing of cognitive assessment with respect to physical exercise directly affects the influence of exercise on cognitive ability (T. McMorris & Hale, 2012). Studies have examined the effect of exercise by performing the cognitive task during physical activity and at different moments after the termination of exercise (Y. K. Chang et al., 2012; Sudo et al., 2022). Therefore, the inertia of the mechanisms responsible for the changes in cognitive function varies over time. The changes in psychophysiological state immediately following exercise are more similar to their state during exercise than 30 minutes after termination of their physical effort (Sudo et al., 2022). When cognitive assessment is carried out during exercise, the immediate need to support exercise triggers different mechanisms (e.g., catecholamine release, oxygenation redirection) which may compete or be symbiotic with those helping to support the cognitive task (Dietrich & Audiffren, 2011). The conflict or mutualization of resources depends on other variables (e.g., exercise intensity, type of cognitive task being assessed, physical fitness of individuals) (Michel Audiffren, 2016; Myungjin Jung et al., 2023; Sudo et al., 2022).

These same variables come into play when cognitive performance is examined after exercise (Myungjin Jung et al., 2023; Sudo et al., 2022). Yet, the influence that each of these variables has on cognitive performance fluctuates depending on the amount of time that separates exercise cessation and beginning of cognitive task (Myungjin Jung et al., 2023). For instance, the results from a cognitive task performed close to the end of one HI bout seem to show regularly more impairment compared to measurements made longer after the subject stopped their effort (M. Audiffren, Tomporowski, & Zagrodnik, 2009; Y. K. Chang et al., 2012; Coco et al., 2020; Hill et al., 2019). Exercise-induced impairment was also shown by three of the aforementioned studies (Hill et al., 2019; Samuel et al., 2017; Tempest et al., 2017) due to deliberate variations of test conditions in cognitive task timing. This is believed to be reimbursement of the effort debt (Hill et al., 1924).

2.3.2 Exercise Characteristics

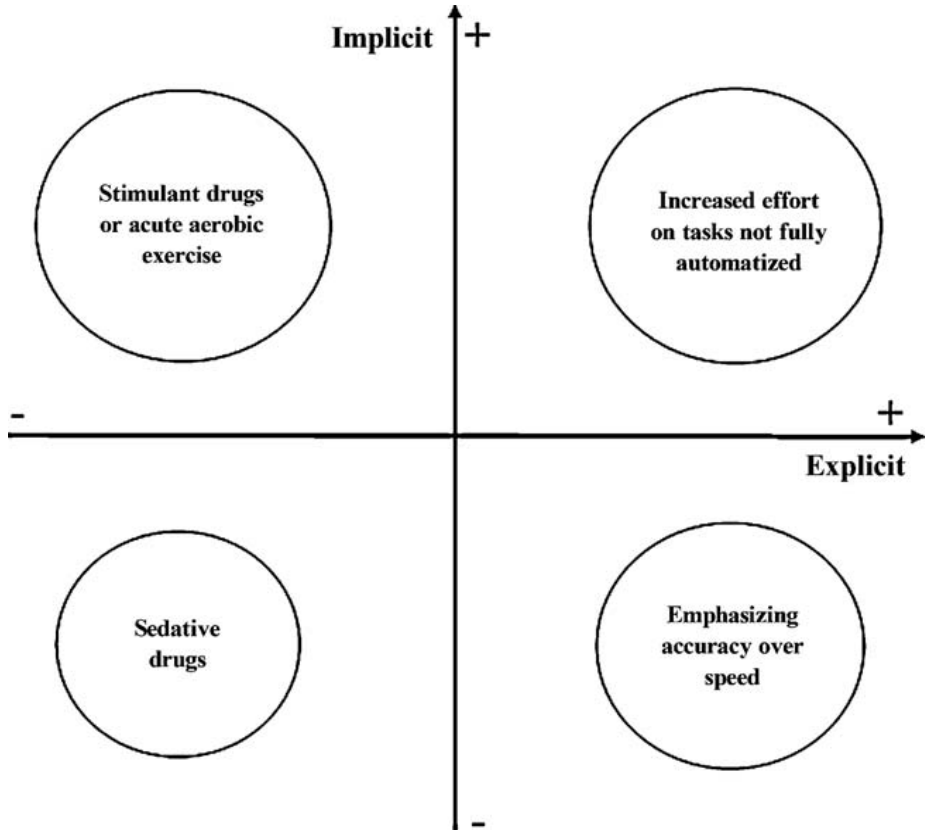
The intensity of exercise is another moderator of cognitive performance (Y. K. Chang et al., 2012; T. McMorris & Hale, 2012). Potential exercise-induced changes in cognitive performance seem to show consistent improvement (usually in RT) at MI, notably since this intensity elicits beneficial endocrine and circulatory acute adaptations, that positively impact cognitive performance (M. Jung et al., 2022; T. McMorris et al., 2015; P. D. Tomporowski, 2003). Positive effects of exercise are also thought to still occur to a lesser extent at lower-intensity exercise (Michel Audiffren, 2016; Y. K. Chang et al., 2012; Myungjin Jung et al., 2023). This suggests that at lower intensities, the exercise-induced stress is not significant enough to cause as much improvement (Sudo et al., 2022). In some cases, this may also result in no detectable change in cognitive function after low-intensity exercise (Ando et al., 2011; Hill et al., 2019; Tempest et al., 2017).

The effect of HI exercise on cognitive function is less clear. Generally, HI exercise (with a physical load exceeding the 2nd ventilatory threshold (~80% VO_{2max})) often shows impairments of cognitive function (Dietrich & Audiffren, 2011; Sudo et al., 2022). The influence of HI exercise on cognitive function appears to be more dependent on the context given by other moderators, such as the timing of cognitive task and the type of cognitive function assessed (Myungjin Jung et al., 2023; T. McMorris et al., 2015). The muscle mass involved during physical activity may influence the availability of cognitive resources: a larger muscle mass involved (by intensity and modality of exercise) elicits higher neural and physiological resources that can eventually be missing for cognitive performance (Michel Audiffren & André, 2015; Dietrich & Audiffren, 2011). Since the acute adaptations induced by physical effort require certain inertia to take place, exercise duration can influence cognitive performance (i.e. the time required for the physiological and endocrine mechanisms to settle down can vary, as well as fatigue) (Schmit et al., 2015; Tempest et al., 2017).

Modality of exercise also affects the extent of change in cognitive function. To date, most of the studies have used a cycle ergometer, which requires less coordination, postural control, and muscle mass involved at the same relative intensity than the use of a treadmill run to assess physical workload (Dietrich & Audiffren, 2011). Performing a physical task requiring a higher muscle mass or coordination may alter the pool of resources on which to draw in the next cognitive task (Michel Audiffren & André, 2015; T. McMorris, 2021). However, the immediate effects of an acute effort of resistance exercise (i.e. the effects of one set, rather than one session) have been consistently reported to improve cognitive performance, even transitorily (Anders et al., 2021; Huang et al., 2022; Wilke et al., 2019). The major cause for such improvement seems to be related to exercise-induced hormonal changes (release of catecholamines), as these latter would cause an enhanced state of arousal and alertness facilitating cognitive functioning (Huang et al., 2022; Tsai et al., 2014). While resistance training was not discussed in the present research in more detail, it is worth noting that those exercise-induced changes also occur during aerobic exercise, but at a lower extent (Hall, Ekkekakis, & Petruzzello, 2002; Terry McMorris, 2009).

2.3.3 Cognitive Task Characteristics

The cognitive task characteristics also play a role in outcome performance. Cognitive tests are designed to assess the performance of specific cognitive functions (Harvey, 2019). Executive function and inhibition have consistently been reported to be impacted by acute MI and HI exercise (Y. K. Chang et al., 2012; Sudo et al., 2022). However, Dietrich & Audiffren (2011) used the theory of explicit vs implicit cognitive systems as a different approach to explain which category of cognitive processes would be more prone to be impaired or improved given different contextual variables (Figure 2).



"The vertical axis represents implicit processes and the horizontal axis explicit ones. The positive sign represents a higher efficiency and the negative sign a lower one. Some stimulant drugs, such as amphetamines, or acute aerobic exercise improve the efficiency of the implicit system but have, at the same time, a negative effect on the explicit system. Motivational factors that increase mental effort to a task that is not fully automated, say, a tennis serve tend to improve the efficiency of both systems. Situations in which ACC is paramount, in science or any other task requiring careful deliberation for instance, emphasize explicit processes and reduce the involvement of implicit processes. Finally, a sedative drug is an example in which both of the brain's information-processing systems operate below par." (Dietrich & Audiffren, 2011)

Figure 2. Some examples of situational variables on the efficiency of explicit and implicit processes (Dietrich & Audiffren, 2011).

Studies measuring explicit, unautomated cognitive tasks (e.g., executive function tasks) are more incline to show impairment of cognitive performance, particularly following HI exercise (Michel Audiffren, 2016). This may be due to the downregulation of brain structures that are not primarily engaged in motor activity (Dietrich & Audiffren, 2011). Given the finite amount of available brain resources, this downregulation would reorient them to a lower-order modality (i.e. the fight or flight response). This discriminating mechanism can occur alongside an overactivity of the noradrenergic and dopaminergic tonic systems, detrimental to prefrontal cortex (PFC) function at higher doses (Michel Audiffren, 2016; Dietrich & Sparling, 2004). The PFC is generally associated with executive functioning (Yuan & Raz, 2014). PFC-dependent tasks, that are generally not directly involved with exercise performance, may be impaired at higher intensities (Myungjin Jung et al., 2023). This suggests a ceiling effect of some non-PFC-dependent tasks used to assess cognitive performance, that may be too simple to detect potential impairments (Browne et al., 2017; Myungjin Jung et al., 2023). On the other hand, highly automated, implicit, or any task mostly mobilizing subcortical regions are rather prone to show improvement at HI (Dietrich & Audiffren, 2011; T. McMorris & Graydon, 1997).

Timing of cognitive task can also play a role in the downregulation. For instance, the continuous involvement in the cognitive task, if started close to the beginning of exercise, may alleviate the downregulating processes and sustain the availability of brain resources that are needed to complete the cognitive task (Schmit et al., 2015). This suggests that both involvement in HI exercise and simultaneous standby of the brain areas involved in the cognitive function examined are necessary to observe cognitive impairment (Schmit et al., 2015).

Commonly used cognitive tests are numerous and touch a wide range of functions that differ in complexity and purpose (Dietrich & Audiffren, 2011; Myungjin Jung et al., 2023; Sudo et al., 2022). Each type of cognitive tests can be influenced differently by exercise, and so is the test used to assess it. For example, decision-making tasks in soccer, visual search tasks, or simple RT tasks often show performance improvement even at heavy intensity (or are not affected at all) (Myungjin Jung et al., 2023; Sudo et al., 2022). More explicit tasks (e.g., involving planning or inhibition, like the Eriksen flanker, Stroop, or Tower of London tasks) are more prone to show impairment when the other moderator variables are included (e.g., HI exercise, very short delay separating exercise and cognitive test) (Dietrich & Audiffren, 2011; Myungjin Jung et al., 2023; Sudo et al., 2022). Still, it appears that higher-order cognitive skills, including executive functions, are affected by exercise in a hierarchical manner, such as described by the downregulation process described by Dietrich & Audiffren (2011).

Executive function is one type of cognitive function that is often subject to assessment in studies investigating the impact of exercise on cognitive function (Y. K. Chang et al., 2012; Myungjin Jung et al., 2023; M. Jung et al., 2022; T. McMorris, 2021; T. McMorris et al., 2015). Executive function is impacted in various ways by physical exercise, depending on the moderators described previously (Y. K. Chang et al., 2012; Dietrich & Audiffren, 2011; Myungjin Jung et al., 2023).

Length of the cognitive task to be performed can also play a role in the overall impact that exercise has on cognition. For instance, some research using an ImPACT test (i.e. a concussion assessment test), that was ~ 25 minutes in duration immediately following HI reported a slight impairment at the beginning of the task (Covassin, Weiss, Powell, & Womack, 2007). This cognitive impairment was only observable in the first minutes of the test, and therefore, did not result in an overall impairment.

2.3.4 Participant Characteristics

The fitness and experience level of participants also affect cognitive task performance during or after exercise. Previous research suggests that debilitating effects observed at similar relative HI seemed stronger within less fit adults (Labelle et al., 2013; Stroth et al., 2009; Themanson & Hillman, 2006). Furthermore, the relative intensity of the MI exercise needs to be higher (i.e. closer to HI) to observe facilitation in aerobically fit compared to less fit adults (Labelle et al., 2013; Stroth et al., 2009; Themanson & Hillman, 2006). The level of task automation embedded in one's skills repertoire may also influence the relationship between cognitive function, fitness, and exercise. Particularly at moderate exercise intensities, exercise may benefit expert individuals while presenting a disadvantage to non-experts (Brisswalter, Arcelin, Audiffren, & Delignieres, 1997; T. McMorris & Graydon, 1997).

2.4 Underlying Mechanisms of Cognitive Function Changes

Theories were developed to explain the immediate effects of exercise on executive function through the tendencies given by the moderating variables surrounding executive function assessment (T. McMorris, 2021; Sudo et al., 2022). These theories and models that aim to describe the various outcomes are fairly general and extend to cognitive functioning as a whole (Dietrich & Audiffren, 2011; Myungjin Jung et al., 2023; Sudo et al., 2022). Even if no rationale is available to discriminate each of the cognitive functions independently, the theories discussed encompass executive functioning. Other potential explanations including exercise-induced dehydration, neural fatigue, and global body fatigue (Moore et al., 2012) may also play a role but appear to apply more to longer efforts, which were not considered here.

2.4.1 Hypofrontality

Hypofrontality theory refers to a shift of brain resources (i.e. glucose and oxygenation) (Ingvar & Franzen, 1974). In the context of conflict between physical exercise and cognitive functioning, hypofrontality occurs when the computation of motor (musculo-skeletal) processing requires these resources (Dietrich & Audiffren, 2011). Since the body has to prioritize some functions during HI, hypofrontality can be seen as a reallocation strategy of attentional resources that causes a transient impairment of executive function (Dietrich & Audiffren, 2011). This restriction means that during exercise over a certain intensity, a shift of brain resources (e.g., oxygen, glucose) would take place from higher-order brain areas (such as the PFC) to areas responsible for the management of exercise (Myungjin Jung et al., 2023; M. Jung et al., 2022). This prioritizes resources in a hierarchical order from the least to the most important functions relative to motor production (Michel Audiffren, 2016). Brain resources are allocated towards better-embedded brain schemes (e.g. automated skills, even complex, more often related to implicit mental tasks) and directly involve physiological systems and tissues necessary for the HI execution (Michel Audiffren, 2016).

2.4.2 Arousal

Changes in level of arousal may also help explaining the effects of exercise on cognition. Exercise-induced changes in the endocrine system, similar to the “fight-or-flight response”, may result in changes that cause an improvement in executive function thanks to the release of catecholamines. This increased signal-to-noise ratio (i.e. the selection and processing of relevant over irrelevant information by the CNS) is beneficial for cognitive processes (Dietrich & Audiffren, 2011; L. Tomporowski, 2010). However, over-arousal can occur at HI, if the homeostasis of this new high level of arousal fails to be maintained (Myungjin Jung et al., 2023). This over-arousal can lead to attention deficit and difficulty to maintain focus (Lupien, Maheu, Tu, Fiocco, & Schramek, 2007; Yerkes & Dodson, 1908).

2.4.3 Brain Lactatemia

The potential presence of brain lactatemia (i.e. the blood contenance in lactates within the brain) may also help explain the effect of exercise on cognition. The brain can use lactates as an energetic substrate that perfuses alongside their corresponding hydrogen ions (Deitmer, Theparambil, Ruminot, Noor, & Becker, 2019). However, lactate-induced acidosis disequilibrium from high-intensity exercise may affect cognitive function. However, there is limited evidence to support a correlation between exercise, lactate levels, and cognitive impairment (Coco et al., 2020; Zimmer et al., 2016).

2.5 Conceptual Models

Conceptual models were developed to help explain how these seemingly independent theories can respond to complementary mechanisms, bringing logic to the prior contradictory results (Sudo et al., 2022). These models link different theories together and present in which context (moderating variable) the psychophysiological mechanisms consecutive to physical exercise may affect cognitive functioning (Michel Audiffren, 2016; Myungjin Jung et al., 2023; Sudo et al., 2022). None of these models are competing. Instead, they can be put together in a concomitant way (Michel Audiffren, 2016; Myungjin Jung et al., 2023; Sudo et al., 2022).

The reticular-activating hypofrontality (RAH) model links the arousal and hypofrontality theories, as coactive processes that facilitate higher-order processes, or downregulates them in favor of a fight-or-flight psychophysiological state according to the exercise intensity (Dietrich & Audiffren, 2011). This model implies that individuals committing to acute exercise impacts their psychophysiological response.

Table 2. Hypothetical bidirectional effect of steady-state exercise on cognitive processes (Dietrich & Audiffren, 2011).

Improvement of performance	Impairment of performance
Implicit	Explicit
Stimulus-driven	Goal-driven
Automatic	Effortful
Bottom-up	Top-down
Unconscious	Conscious

“Note: Processes from the right column tend to be improved, while processes from the left column tend to be impaired by acute exercise. Each row should be viewed as a continuum. There is no dimensional overlap, that is, for instance, a top down process may be fully unconscious, while a stimulus-driven process may require allocation of effort.” (Dietrich & Audiffren, 2011)

The updated strength model of self-control (Audiffren & André, 2015; Muraven, Tice, & Baumeister, 1998) suggests that proximity of perceived exhaustion rather than exercise intensity determines the signal initiating the downregulating psychophysiological changes at high-intensity. It states that a conservation threshold is used as a conservative strategy to preserve some available resources for further additional tasks (Figure 3).

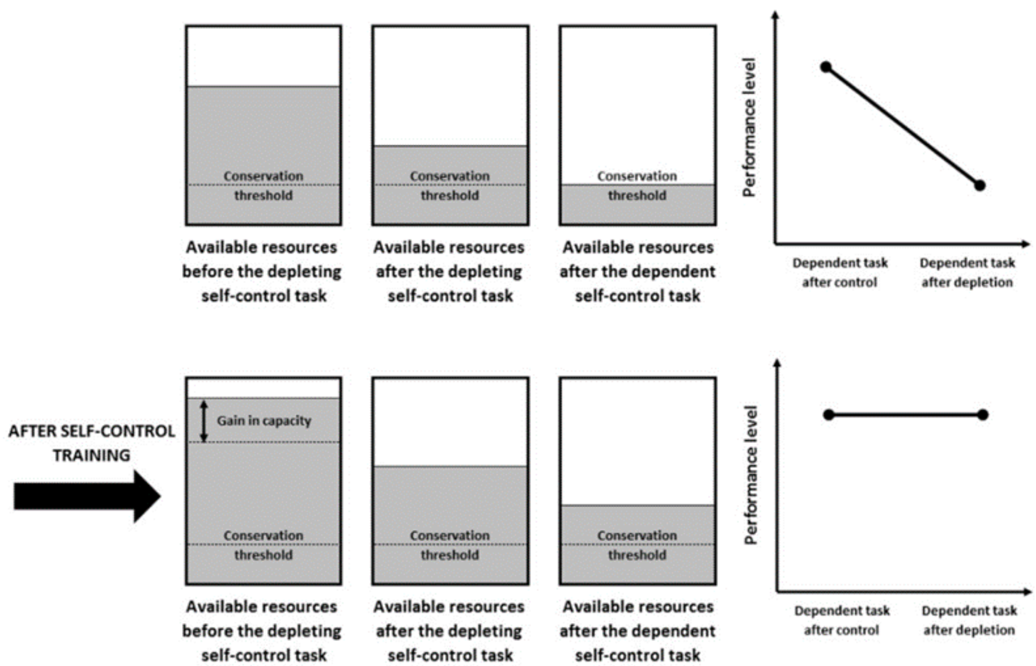


Figure 3. Illustration of the capacity hypothesis explaining a lower detrimental effect of self-control depletion after self-control training (Michel Audiffren & André, 2015).

Similarly, the interoceptive model (T. McMorris, 2021), limited to the arousal aspect only, proposes that interoceptive variables (i.e. mood, motivation, perceived effort costs, perceived availability of resources), modulate catecholaminergic activity in the brain. It requires ongoing and predicting estimations of those variables. Over-arousal is met when perceived available resources are insufficient to meet predicted effort costs (Figure 4).

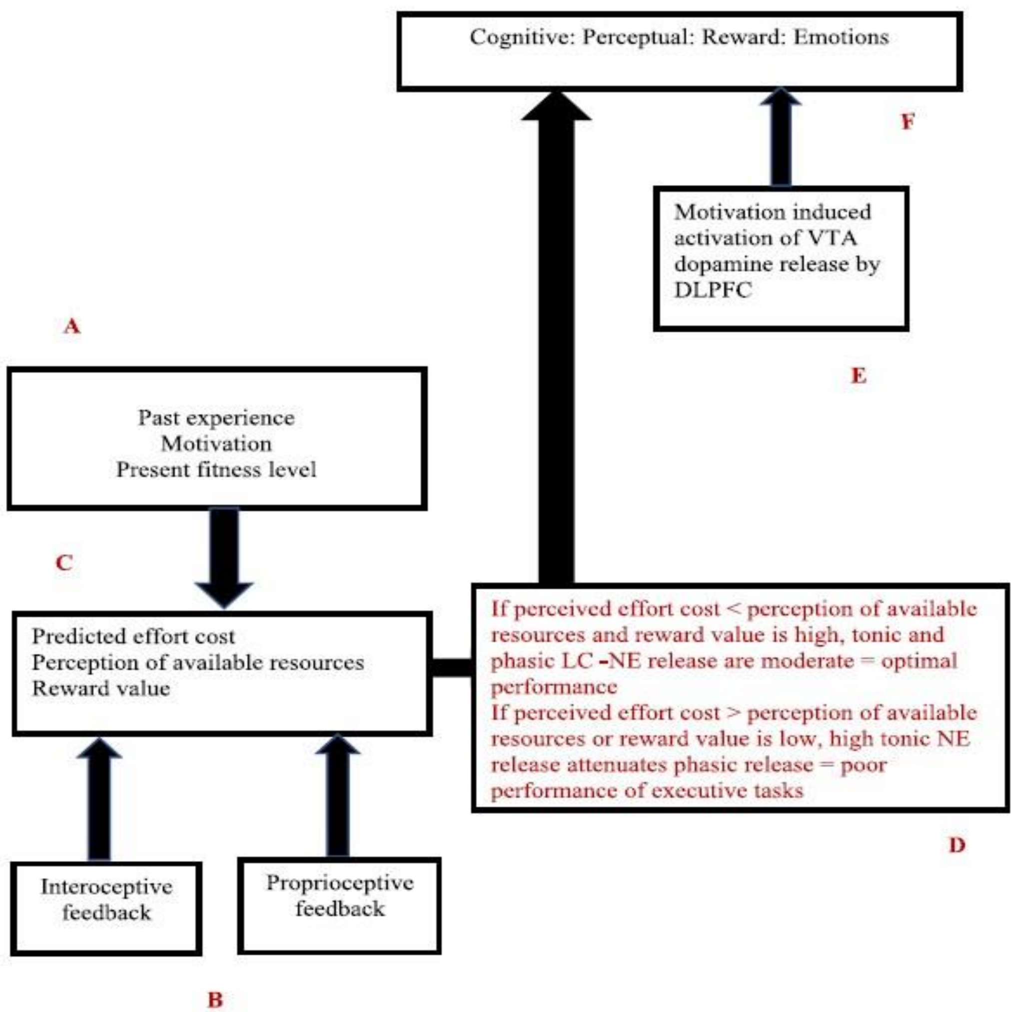


Figure 4. Overview of the interoception model (T. McMorris, 2021).“A. Psychological factors affecting prediction of effort costs, perception of available resources and reward value.B. Information from small diameter primary afferents, large diameter sensory fibers in skin, muscles and joints, and chemoreceptors and mechanoreceptors in vagal and glossopharyngeal nerves.C. Information from A is evaluated by DLPFC and predicted effort cost is forwarded to the AIC and ACC. Information from B, held in the AIC, ACC and OFC, is compared to the predictions from A, and fed back to the DLPFC for a decision on what action to take.

D. The decision depends on comparison of perceived effort costs and expected value of the reward. If available resources are perceived to be sufficient to meet predicted effort costs and the reward is high, the OFC and ACC initiate moderate tonic and phasic release of LC-NE. This is optimal for tasks requiring activation of top-down and/or bottom-up salient stimuli. If the perceived resources are thought to be insufficient to meet the costs or the reward is poor, high tonic release is initiated, which attenuates phasic release. This has an inhibitory effect on tasks requiring activation by salient stimuli but aids tasks requiring switching to alternative S-R pairings or alternative courses of action.E. At rest or during low intensity exercise, in motivated individuals, the DLPFC may trigger increased tonic release of dopamine from the VTA, which can result in optimal cognitive performance by inducing moderate tonic and phasic LC-NE release.
F. It should be noted that cognition involves interactions with perception, motivation and emotions ACC anterior cingulate cortex; AIC anterior insula cortex; DLPFC dorsolateral prefrontal cortex; LC-NE locus coeruleus-norepinephrine; OFC orbitofrontal cortex; S-R stimulus-response; VTA ventral tegmental area." (T. McMorris, 2021)

2.6 Remaining Gaps in the Literature

While previous research provided important insights into the effect of exercise on cognition, some crucial remaining questions remain to be answered. First, there are many inconsistencies over what is considered to be an 'immediate' exercise effect. More precise quantifications and standardized definitions of terminology for the time after exercise are needed. Secondly, the time course to retrieve a stable state of executive function similar to baseline level after a change in cognition (improvement or impairment) immediately after exercise is still unclear. In order to understand precisely the effects of exercise on cognition, continuous measurement of the cognitive task is needed to establish the time course of potential changes. The very critical moments, from a few seconds to a few minutes, that follow the end of the participant's effort deserve greater consideration and precision.

Thus, the present investigation aimed to determine the extent to which executive function is affected right after failure at HI exercise. It also aimed to observe how these changes in executive function (compared to baseline) evolve over time after termination of exercise. HI was compared to MI in order to observe the effect size of intensity per se. Both intensities were compared to baseline tests to observe the effect size of exercise. Since most of the studies in this domain used cycle ergometers to control exercise intensity (Myungjin Jung et al., 2023; Sudo et al., 2022; P. D. Tomporowski, 2003), and since we expected the computational cost of running to be higher than cycling, exercise in the present investigation was completed on treadmill.

The present study used the Eriksen flanker task (Eriksen & Eriksen, 1974) as a measure of executive control. The flanker task (described in section 3.6) is believed to assess one's capability to respond appropriately to relevant stimuli while inhibiting response to irrelevant flanking stimuli (Eriksen & Eriksen, 1974). Inhibitory function can arguably be required during or immediately after a strenuous bout of aerobic exercise. Also, the flanker task has been reported to be influenced by such type of exercise (M. Jung et al., 2022; T. McMorris & Hale, 2012; Sudo et al., 2022). Similarly to the general field of acute exercise influence on cognitive function, outcomes in flanker task performance have indicated debilitating, enhancing, and no effects of acute exercise depending on the influencing variables identified above (Section 2.3). Those trends are discussed and compared to the present study results into the discussion section (5.1).

Several factors prompted us to enroll endurance-trained individuals. Firstly, no study using highly aerobically trained individuals while investigating exercise-induced changes in executive function, from failure until full recovery, had been completed.

Secondly, we expected the capability of such individuals to try their very best during physical exercise to be greater than average (more pain tolerance and ease with dealing with their body limits). We also believed that such individuals would show more difference between the respective psychophysiological states experienced during moderate and strenuous exercise bouts. Additionally, it was believed that these psychophysiological states at both intensities would tend to be more stable and easier to manage compared to lower-fit individuals. Indeed, endurance-trained individuals had gone very often to different intensity levels in their near athletic background.

3 Methods

3.1 Participants

High-fit adult individuals from the Michigan Technological University Nordic ski team were recruited for this study. Participants were between 18 and 25 yrs of age. In a conservative manner, 2 additional high-fit older individuals that are not part of the Michigan Technological University ski team athletes' roster were added to the study. The complete cohort (n = 14, 5 female, 9 male) included only endurance-trained adults (Table 3. More complete data are available in appendix A). Participants were tested during the pre-season phase of their yearly training (~450-700 hours), which typically consists of a weekly volume of ~10-15 hours (80% aerobic, 20% strength training). Participants were informed of the purpose and risks of this study and were given informed written consent before participating. Participants were excluded from the study if they used any product containing tobacco, presented diabetes, or had any type of cardiopulmonary disorders, including but not limited to hypertension, implanted devices such as, but not limited to a pacemaker or pain pump, skin or dermatological disorders, neurological disorders, recent injuries that would limit or prevent exercise, and if they presented any contraindication to running. The participant had to satisfy the inclusion criteria addressed by the Physiology laboratory of the Kinesiology department from the Michigan Technological University, as presented during the health background screening prior to the first study visit. Participants provided informed written consent before any anthropometrical and data collection were collected. The experimental protocol and procedures were approved by the Michigan Technological University Institutional Review Board.

Table 3. Summary of anthropometric characteristics.

	Total (n=14)		female (n=5)		male (n=9)	
	mean	(sd)	mean	(sd)	mean	(sd)
Age	22.6	(5.2)	22.8	(6.9)	22.6	(4.5)
College years	2.9	(1.7)	2.6	(2.1)	3.0	(1.5)
Body mass (kg)	70.9	(8.8)	63.0	(5.1)	75.3	(7.2)
Body fat (%)	12.5	(5.5)	18.8	(3.3)	9.1	(2.5)
VO_{2max} (ml/min/kg)	64.6	(6.7)	58.0	(3.7)	68.2	(4.8)
HR at rest (beats/min)	54	(9)	50	(8)	57	(9)
Max HR (beats/min)	192	(14)	186	(16)	195	(12)
Training volume of past year (h)	489	(91)	436	(58)	519	(95)

3.2 Study Overview

For this investigation, we used a repeated measures design to determine the effect of exercise intensity on executive function. Participants reported to the laboratory on 4 separate occasions: 2 preliminary and 2 experimental visits. During the first preliminary visit (Visit 1), participants performed an executive function test practice as well as a submaximal running protocol. In addition, demographic, anthropometric, and training characteristics were recorded. During the second preliminary visit (Visit 2), participants performed the same executive function test practice followed by a VO_{2max} running test. These preliminary visits helped to minimize the learning effect of cognitive task and to establish a linear relationship between each individual's oxygen consumption and corresponding treadmill speed. The 2 experimental visits assessed executive function performance before and right after moderate- and high-intensity exercise. For the first experimental visit (Visit 3), participants ran on the treadmill at a speed corresponding to 90% of VO_{2max} (HI) until the limit of exercise tolerance (T_{lim}90%). For the second experimental visit (Visit 4), participants ran at 60% of VO_{2max} (MI) (Figure 5 illustrates the overview of each experimental day). All laboratory visits were performed at the same time of day in a thermoneutral environment. Participants were asked to refrain from high-intensity training and to avoid caffeine and alcohol consumption 12 h prior to testing. They were also asked not to eat at least 2 h before the visits.

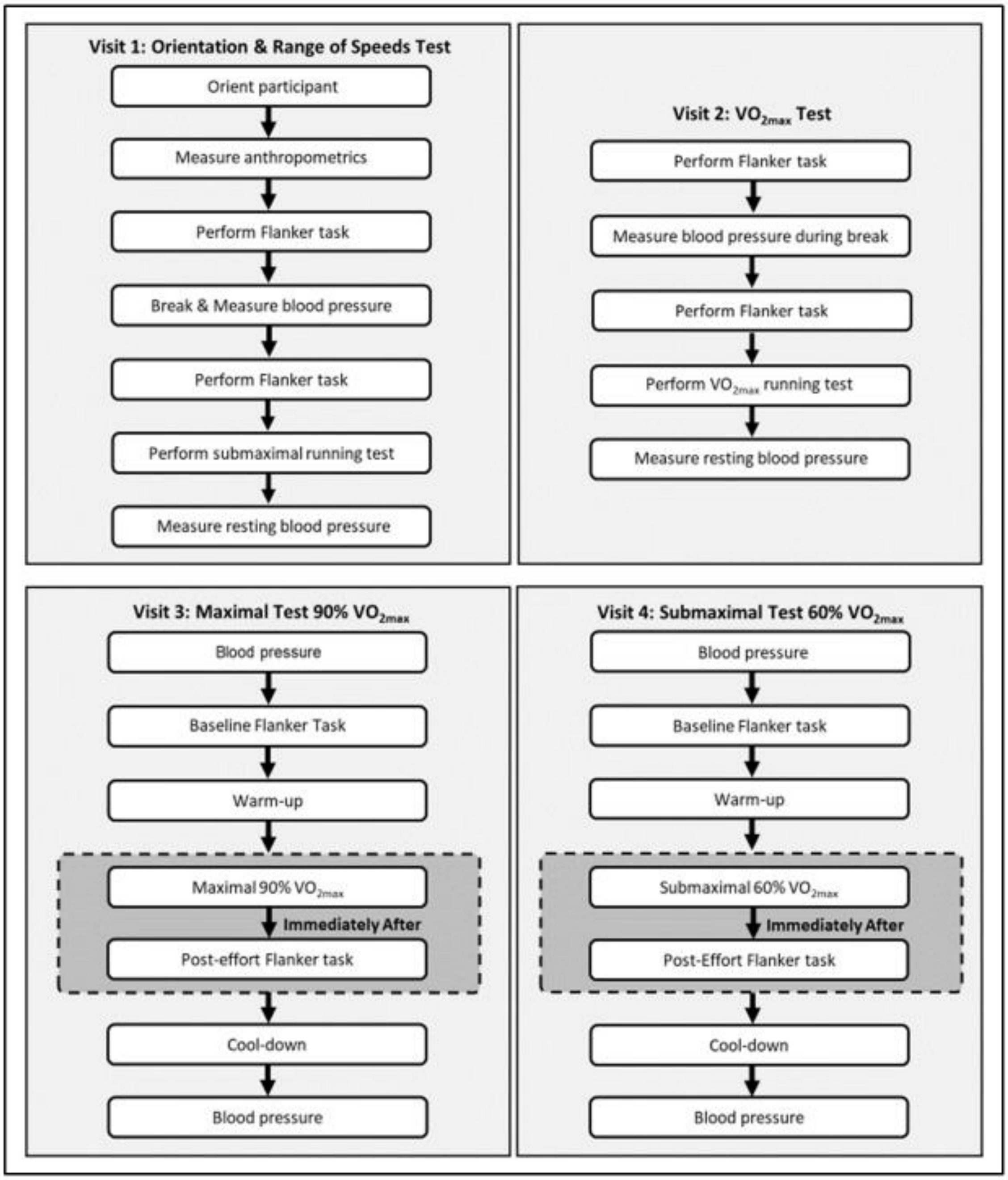


Figure 5. Overview of the four study visits

3.3 Demographic, Anthropometric, and Training Characteristics

Sex, age, academic year, height (m), body mass (kg), blood pressure (mmHg), and body fat (%) of participants were recorded. Their annual and weekly aerobic and strength training hours were collected, as well as their USSA points (giving a rough national/international level of competition performance from the last season).

After resting quietly in a seated position for 10 min, brachial systolic and diastolic blood pressure were obtained in the right arm using an automatic blood pressure cuff (OMRON, Model HEM-907XL, Kyoto, Japan). All blood pressure measures were obtained with the participant in a seated position. A minimum of two measurements were taken with a 1 min rest between measures. If systolic or diastolic blood pressure vary by more than 5 mmHg, measurements were repeated until values are within 5 mmHg of each other. The two sequential values within 5 mmHg were averaged and used for analysis.

Subcutaneous fat measurements were recorded at 7 different sites – triceps, chest, subscapular, midaxillary, suprailiac, abdominal, and thigh – on the same body side to estimate overall body fat. A Skinfold caliper (Beta Technology Incorporated, Lange Skinfold Caliper, Santa Cruz, CA, USA) was used perpendicularly to the analyzed site and the measure was taken at the middle of the pinched skin. The investigator read each measure 2 s after releasing the caliper and recorded it to the closest 0.5 mm. Measurements were executed twice to obtain more accurate results. The 7-site skinfold Jackson-Pollock formula (Jackson & Pollock, 1978; Jackson, Pollock, & Ward, 1980) was used to estimate overall body fat from skinfold measurements.

3.4 Submaximal Running and VO_{2max}

To establish the linear relationship between steady-state VO_2 and running speed, participants completed a submaximal running protocol on a treadmill (Trackmaster TMX428CP, Full Vision Inc., Newton, KS, USA). Specifically, participants completed 4 to 5 different stages each corresponding to a pre-estimated speed. Each stage was at least 5 minutes long and could be cautiously adapted during the test (e.g., if it did not elicit enough cardiorespiratory stress) (Table 3). Gas exchange data was measured continuously using open-circuit spirometry (True Max 2400, Parvo Medics, Sandy, UT, United States). The metabolic measurement system was calibrated with a 3 L calibration syringe and medical gasses of known concentrations (16.00% O_2, 4.00% CO_2, and balanced N_2). Heart rate was measured continuously using a Polar transmitter (Polar Electro OY, Kempele, Finland). Gas exchange ratio and heart data were averaged every 15 s throughout the test. Whole body rating and legs rating of perceived exertion (RPE) using a Borg 6-20 scale (Borg, 1982) were recorded at baseline, during the last 30 s of the warm-up, and during the last 30 s of minute 3 and minute 5 of each stage. Blood lactates (mmol/L) using a lactate meter device (Lactate Plus, Nova Biomedical, Waltham, MA, USA) were collected at the end of each stage.

Table 4. Submaximal test protocol

STAGE	SPEED	TIME
baseline	x	0-3
warm-up	3	3-5
1	5	5-10
2	6	10-15
3	7	15-20
4	8	20-25

* Arbitrary changes can be applied if needed: an additional stage can be applied; the speed can be adapted in early stage; the stages can be lengthened if respiratory plateau is not reached
* The grade remains at 0% over the entire test

To determine maximal oxygen consumption, participants performed a graded exercise test until task failure using the protocol yearly employed by the Nordic ski team coaching staff. For men, the protocol began at a walking self-selected speed and 0% grade for 2 minutes to warm-up. The treadmill was then set at 3 mph and 6% grade for 3 min. Speed then increased by 1 mph every 3 min all along the test except when slope was increased. The treadmill slope was 6% until stage 4 included, and increased by 2% at stage 5 and 6, and starting stage 8 until failure (Table 4). For women, the protocol began at a walking self-selected speed and 0% grade for 2 minutes to warm-up. The treadmill was then set at 3 mph and 4% grade for 3 minutes. Speed then increased by 1 mph every 3 min all along the test except when slope was increased. The treadmill slope was 4% until stage 4 included, and increased by 2% at stage 5, 6, 7 and starting stage 9 until failure (Table 5). The test was terminated voluntarily by the participant, or by an investigator if the participant could not keep up the pace and the running speed was considered as unsafe to be maintained despite standardized verbal encouragement. The highest 30 s average of VO_2 and heart rate achieved during the test were identified.

Achievement of VO_{2max} test was considered as satisfying if a minimum of two of the three following criteria were attained by participants: (1) respiratory exchange ratio (RER) of 1.05; (2) RPE above or equal to 17; and (3) VO_2 plateau. Rating of perceived exertion was collected at rest before launching the test, within the last 30 s of warm-up, and within the last 30 s of each stage. Blood lactates (mmol/L) were collected using a lactate meter device (Lactate Plus, Nova Biomedical, Waltham, MA, USA) at the end of the test. Running speeds that elicited 60 and 90% of VO_{2max} were estimated by interpolating the linear relationship between VO_2 and running speed.

Table 5. VO2peak test protocol - men

STAGE	SPEED	GRADE	TIME
baseline	x	x	0-3
warm-up	self-selected	0	3-5
1	3	6	5-8
2	4	6	8-11
3	5	6	11-14
4	6	6	14-17
5	6	8	17-20
6	6	10	20-23
7	7	10	23-26
8	7	12	26-29
9	7	14	29-32
10	7	16	32-35
11	7	18	35-38

Table 6. VO2max test protocol - women

STAGE	SPEED	GRADE	TIME
baseline	x	x	0-3
warm-up	self-selected	0	3-5
1	3	4	5-8
2	4	4	8-11
3	5	4	11-14
4	6	4	14-17
5	6	6	17-20
6	6	8	20-23
7	6	10	23-26
8	7	10	26-29
9	7	12	29-32
10	7	14	32-35

3.5 Exercise Trials

On separate days, participants performed a treadmill run to the limit of exercise tolerance at 90% VO_{2max} (T_{lim}90%), and a treadmill run at 60% of VO_{2max} based on each own T_{lim}90% duration. Before each running trial, baseline physiological responses were recorded in a standing position for 5 min. Subsequently, participants performed 10-min self-paced warm-up that did not overgo their 60% of VO_{2max} calculated speed. During Visit 3, at the very end of the warm-up, participants ran 10 s at their 90% VO_{2max} calculated speed in order to familiarize with it. The end of warm-up was used to practice the transition between the termination of exercise and the start of the executive function task (i.e. to stop the treadmill, safely walk to the standing desk located next to the treadmill where participants completed the executive function task, and start it as soon as possible). For the T_{lim}90% protocol, participants were given 30 sec to reach the 90% VO_{2max} speed and then maintained this pace until volitional exhaustion. For the 60% trial, participants were given 30 sec to reach the 60% VO_{2max} speed and then ran at 60% of their measured VO_{2max} for the same duration as they did in Visit 3. The isochronal condition between 90% and 60% was set in order to isolate exercise intensity and cancel out the duration effect in the executive performance responses. For both experimental running trials, heart rate was measured every 15 sec using a Polar transmitter (Polar Electro OY, Kempele, Finland). Whole body RPE was assessed using Borg's scale during the last 30 s of warm-up, at rest before the running trial, and every 2 min of the running trial. RPE at the moment of failure was also collected afterward (after the cognitive task). (See Figure 6 for an overview of the study visits). It is important to note that HI was selected such that: 1) it was above the 2nd ventilatory threshold, which has been suggested to impair executive function (Michel Audiffren, 2016; Myungjin Jung et al., 2023); and 2) participants could run long enough to provoke the mechanisms underlying this deterioration (Browne et al., 2017). MI was selected such that executive function would be improved as it has been reported to be above the walk-run transition for trained individuals (Michel Audiffren, 2016; Myungjin Jung et al., 2023).

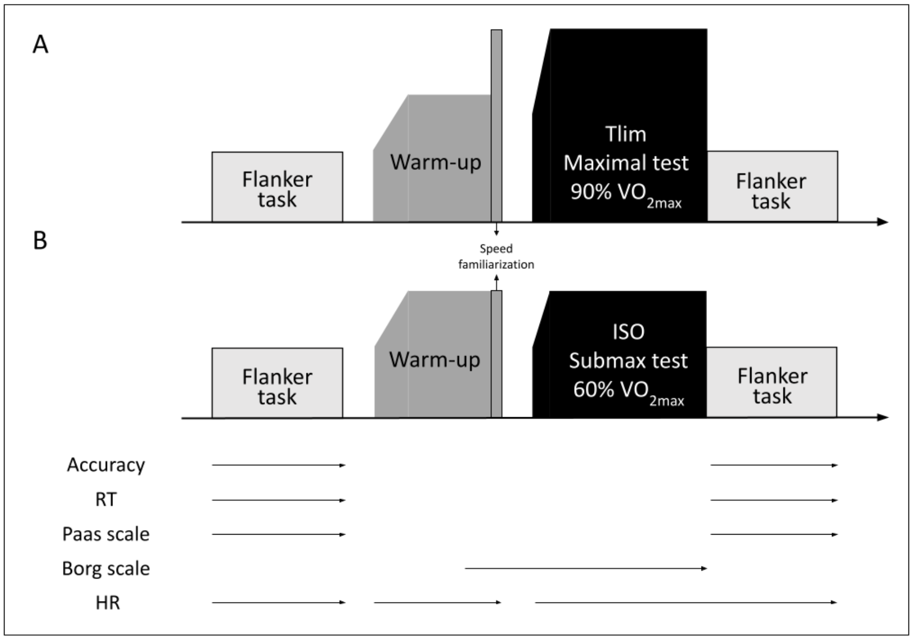


Figure 6. Overview of experimental visits (3 & 4). A) The time course of visit 3 (running Time to failure at 90% of VO_{2max}). B) The time course of Visit 4 (isochronal running test at 60% of VO_{2max}). ACC (%), RT - RT (ms), Paas scale of perceived mental effort (1-9), Borg scale of perceived physical exertion (6-20), and HR - Heart Rate (bpm).

3.6 Cognitive Assessment

During the preliminary visits (Visit 1 and 2), participants performed the executive function task two times separated by 20 min to simulate the time allocated to the running trials of Visit 3 and 4. Completing the flanker task during the preliminary visits also served as a practice to minimize learning effect. During the experimental visits (Visit 3 and 4), executive function was assessed before and immediately after cessation of exercise. The time separating the physical exercise and beginning of the cognitive task was on average 10 sec (SD = 2) after HI, and 11 sec (SD = 3) after MI (see appendix B). Specifically, participants performed an Eriksen flanker task (Eriksen & Eriksen, 1974) to assess changes in their inhibitory control performance before and after exercise. The flanker task was programmed by using the Psychology Experiment Building Language (PEBL) open-source software (Mueller & Piper, 2014). The three main reasons for selecting this cognitive task included: 1) it is believed to assess one's capability to respond appropriately to relevant stimuli while inhibiting response to irrelevant flanking stimuli (Eriksen & Eriksen, 1974), which can arguably be required during or immediately after a strenuous bout of aerobic exercise; 2) it has been reported to be influenced by such type of exercise (M. Jung et al., 2022; T. McMorris & Hale, 2012; Sudo et al., 2022); 3) it offered ease of implementation in the context of the present study that required to quickly collect cognitive data after exercise failure. This task was achieved by facing a computer screen (23 in) and using a computer pad with left and right shift keys of equal size. In order to standardize postural conditions, the flanker task was performed in standing position, with the help of a standing desk set beforehand at the participant's self-selected height. For any flanker task, the mere instruction *'to be as accurate as possible, as fast as possible'* remained systematically provided throughout the entire study.

During the test, participants had to hit either the right or left shift key as indicated by the direction of an arrow appearing in the screen center. One trial ran as follows: 1) A little cross appeared in the middle of the screen (target) for 500 ms before a central arrow immediately replaced it. 2) Participants hit one of the two shift keys (left or right) as fast as possible within the allotted time of 1200 ms (which was, except in the case of extreme outliers, more than enough to enable participants to respond). 3) After the key hit occurred – or above 1200 ms – the screen remained empty (fully black) for 800 ms before the same sequence started again. One session of the flanker task was composed of 234 trials divided into three equal sections of 78 trials. No break separated the three sections (Table 6). The trials could have 3 different designs: congruent, incongruent, and neutral. Each design consisted of a line containing 5 characters as shown in Figure 2.

All three sections were made of the same random series of these three designs. The appearance of each design in both left and right directions was equiprobable within one section (and thus for the entire task); each possible combination CON/NEU/INC x LEFT/RIGHT therefore appeared 13 times per section (Table 6). No penalty corresponding to error number or overall score was credited; RTs (RT) and number of errors was observed separately in order to analyze any potential change in trade-off strategy between speed and errors. This helped drawing an idea of the risks taken by the participants depending on the potential impact of exercise on their executive function performance. The pace at which participants went through the test – which was RT-dependent – was voluntarily left at their discretion. However, as shown by pilot testing, total completion of the flanker task took about 7 min, depending on the participants' RT; the test could therefore be considered as self-paced. The Paas scale was employed to obtain overall and per-section self-reported ratings of mental effort (SRRME) to estimate participants perceived cognitive load. The Paas scale uses a rating ordinated from 1 to 9, 1 representing “very light effort” and 9 “very heavy effort”. This helped to draw a global idea of the effort engaged in the flanker task before and after exercising (risk taken with respect to the speed-accuracy tradeoff).

Table 7. Basic flanker task settings used for the study, from the Pebl software settings menu (Mueller & Piper, 2014)

Variable	Setting	Description
numreps	13	Number of repeats of 2x3 design default
practicereps	0	Number of repetitions of design in practice
includedashtrials	1	Whether [-->--] and [--<--] trials should be included
includeemptytrials	0	Whether [>] and [<] trials should be used
arrowsize	40	Pixel length of arrow (not head, entire arrow)
gap	4	Pixel gap between arrows
fixationtime	500	Time prior to trial that fixation appears, in ms
timeout	1200	Time allotted to make response, in ms
iti	800	Inter-trial interval, time between response and new trial starting, in ms

Table 8. Average task duration during study visits.

	Pre-HI	Post-HI	Pre-MI	Post-MI
Mean (sec)	408	403	406	403
Mean (min:sec)	06:48	06:43	06:46	06:43

3.7 Data Analysis

RT and ACC (right; wrong; timeout of 1200 ms) were recorded for each trial. RT included information processing and motor response, (i.e. from the moment the information was revealed to the subject to the moment the response was entered by the participant). SRRME put into the cognitive task was asked afterwards to the participants for each overall test, as well as for each section of the test (1 section = 1 third of the overall task).

RT (ms) and ACC (% of success) were compared overall and the results were divided into 6 subsections, called *epochs* for the remainder of the study (epoch 1 ranging from trial 1 to trial 39; epoch 2 from trial 40 to & 78; epoch 3 from 79 to 117; epoch 4 ranging from trial 118 to trial 156; epoch 5 from trial 157 to & 195; and epoch 6 from 196 to 234). The purpose of analyzing the task overall and through epochs was to compare potential changes captured by the whole task to the time course of changes occurring within the task. Mean per epoch was used to give an insight into the RT and ACC trendline in post-exercise recovery (whether in the sense of improvement or impairment) vs pre-exercise condition. This also gave an estimation of which time length after cessation of exercise showed changes, and at what extent.

3.8 Statistical Analysis

3.8.1 Sample Size calculation

Based on published literature, a power of 0.80 (ß = 0.20), a significance level (α) of 0.05, and an assumed large effect size of 0.8 indicated that 12 participants would be needed to detect an effect of exercise when using a one-tailed t-test for two dependent means, and 10 participants when using a repeated measures ANOVA within-subjects. Furthermore, previous research with similar statistical designs reported significant results with 10 to 30 participants. This range of participants fell into the Michigan Technological University Nordic Ski Team roster size.

3.8.2 Statistical Analysis

The 2 flanker tasks of each preliminary visit (visits 1 & 2) were used as familiarization tasks to smoothen potential slight learning effects still occurring after the first task. Pearson's correlation matrices demonstrated that the correlation between means and variances across all tests at rest condition (except the very first one) was moderate amongst congruent and strong amongst incongruent trials. We assumed that test-retest reliability was good enough at rest to allow the direct comparison between the post-exercise tests and their respective pre-exercise tests. (Pearson's correlation matrices are available in appendix D). Thus, the pre-exercise flanker tasks from the study visits were used as baseline (resting condition) to be compared against their respective post-exercise test (post-HI vs pre-HI, and post-MI vs pre-MI) for RT, ACC, and SSRME.

The flanker tasks were first compared as a whole (e.g. whole task pre-HI vs whole task post-HI). Incongruent and congruent trials were analyzed (e.g. whole task pre-HI incongruent vs whole task post-HI incongruent). A 2 (intensity) by 2 (congruency) repeated measures ANOVA was used to assess changes in RT and compare the overall tasks for both congruent and incongruent trials. Prior to performing the repeated measure ANOVA, a Mauchly's test was used to assess sphericity of the dependent variables. A Greenhouse-Geisser correction was performed in case of violation of sphericity.

Since incongruent trials are meant to reflect executive control (congruent are used to contrast) our focus was put on them for the across-time analysis. As an a priori selection, each incongruent epoch was compared to its equivalent (i.e. epoch 1 pre-HI vs epoch 1 post-HI, 2 vs 2, 3 vs 3, 4 vs 4, 5 vs 5, 6 vs 6). A paired sample t-test was used to compare each epoch pre-exercise to its equivalent post-exercise in RT and ACC. The direction of the differences being known, the p-values are given as one-tailed.

SRRME was divided in 3 sections (i.e. “early”, “mid”, and “late” task). Participants’ rating for each section was asked in addition of an overall rating for the whole task. a paired sample t-test was used to compare the overall test performance in each baseline condition (HI vs MI). A 2 (intensity) by 3 (section) repeated measures ANOVA was used to compare the post-HI cognitive task sections to their post-MI equivalent. Prior to performing the repeated measure ANOVA, a Shapiro-Wilk test was used to assess normality assumption of the dependent variables (exercise intensity vs section) within each combination of levels of the independent variables. A Mauchly’s test was used to assess their sphericity. A Greenhouse-Geisser correction was performed in case of violation of sphericity. A significance level (α) of 0.05 was used for all tests. All analyses were conducted using the software SPSS Statistics for Windows (SPSS Inc., IBM Corps, Armonk, NY, USA).

4 Results

4.1 Accuracy in overall pre- and post-exercise tests

No significant change in ACC was observed after HI and MI exercise regarding the incongruent trials (Figure 7 & 8). Complete results are presented in (appendix C, section 1). A main effect of pre-post HI failed to reach significance, $F(1,13) = 4.314$, $p = .058$, supported by the very small difference in accuracy between overall Pre-HI and Post-HI in ACC, mean diff = 0.1 %. Overall, congruent trials were more accurate than incongruent trials, mean diff = 0.5 %, $p = <.001$. The main effect of congruency was large, $F(1,13) = 35.298$, $\eta^2_p = 0.731$. If the overall congruency*pre-post interaction was not significant, $F(1,13) = 1.557$, $p = .234$, the pairwise comparison showed that post-HI congruent trials were less accurate than pre-HI congruent trials, mean diff = 0.5 %, $p = .019$, $\eta^2_p = 0.357$ (large). Post-HI incongruent trials were not significantly different from pre-HI despite a greater mean difference, mean diff = 2.0 %, $p = .119$. It is possible that the study was slightly underpowered to statistically detect this specific change in incongruent trials post-exercise accuracy. As for the pre-post HI analysis, there was no significant main effect of pre-post MI, $F(1,13) = 0.285$, $p = .602$, as suggested by the weak difference in overall pre-post ACC, mean diff = 0.3 %. A large main effect of congruency was still observable, $F(1,13) = 33.514$, $p = <.001$, $\eta^2_p = 0.721$. Overall incongruent trials were less accurate than the congruent ones, mean diff = 4.9 %, $p = <.001$. Similarly to the overall HI analysis, post-MI congruent trials were less accurate than during pre-MI, mean diff = 0.8 %, $p = .045$, $\eta^2_p = 0.276$ (large), while incongruent trials did not show any change between post- and pre-MI exercise, mean diff = 0.2 %, p = .863. There was no overall interaction congruency*pre-post, F(1,13) = 1.018, p = .331.

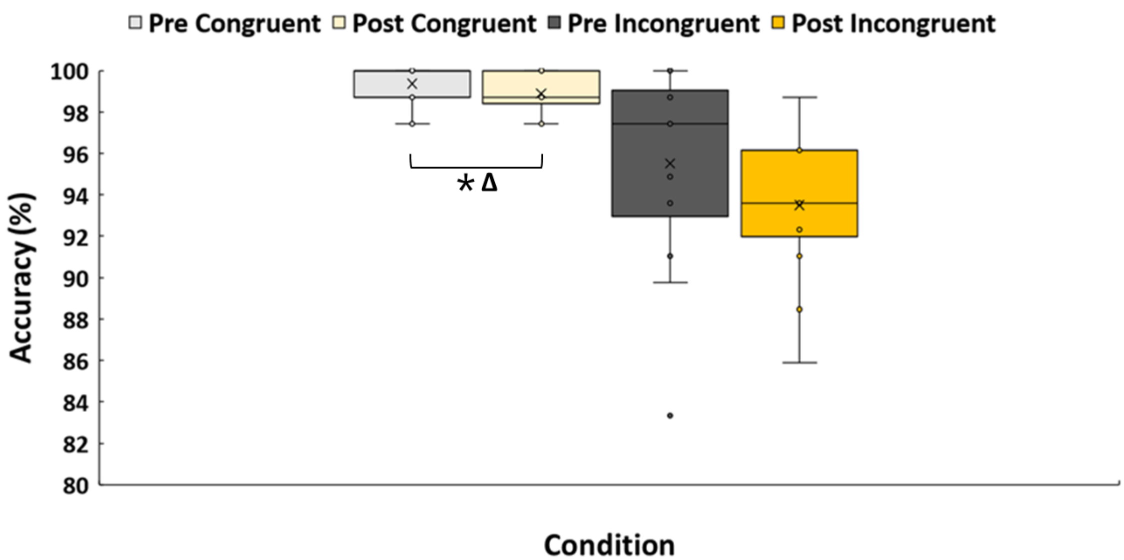


Figure 7. Comparison of flanker congruent and incongruent test accuracy before and after high intensity exercise. * = $p < .05$; $\Delta = \eta^2_p > 0.14$

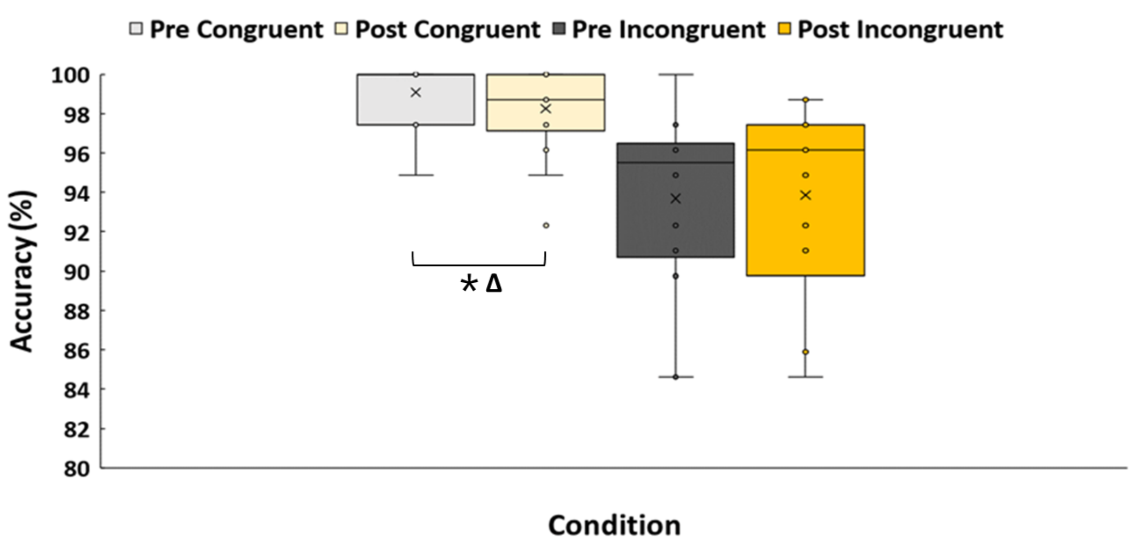


Figure 8. Comparison of flanker congruent and incongruent test accuracy before and after moderate intensity exercise. * = $p < .05$; $\Delta = \eta^2_p > 0.14$

4.2 Reaction time in overall pre- and post-exercise tests

Participants demonstrated faster responses following both HI and MI exercise (Figure 9 & 10). This improvement in RT was significantly greater following HI. Overall post-HI was faster than pre-HI, mean difference = 23 ms, p = .022, with a significant main effect of pre-post HI, $F(1,13) = 6.776$, $p = .022$, $\eta^2_p = 0.343$ (large). A main effect of congruency was also found, $F(1,13) = 290.403$, $p = <.001$, $\eta^2_p = 0.957$ (large). Overall congruent trials were faster than incongruent trials, mean difference = 44 ms, p = <.001. The interaction pre-post*congruency was significant, $F(1,13) = 9.752$, $p = .008$, $\eta^2_p = 0.429$ (large). Post-HI congruent flanker trials were not significantly faster than the pre-HI congruent ones, mean difference = 18 ms, p = .071. The post-HI incongruent trials were faster than the pre-HI incongruent ones, mean diff = 28 ms, p = .008. Regarding MI, there was a statistically significant main effect of pre-post, $F(1,13) = 12.382$, $p = .004$, $\eta^2_p = 0.488$ (large). The follow-up test showed that overall post-MI was faster than pre-MI, mean difference = 15 ms, p = .004. A main effect of congruency was also found, $F(1,13) = 185.555$, $p = <.001$, $\eta^2_p = 0.935$ (large). Overall congruent trials were faster than incongruent, mean difference = 47 ms, p = <.001. The interaction pre-post*congruency was significant, $F(1,13) = 5.713$, $p = .033$, $\eta^2_p = 0.305$ (large). Post-MI congruent trials were faster than the pre-MI congruent ones, mean difference = 11 ms, p = .012. The post-MI incongruent trials were faster than the pre-MI incongruent ones, mean diff = 18 ms, p = .003. (Means and standard errors for RT are presented in Table appendix C, section 2).

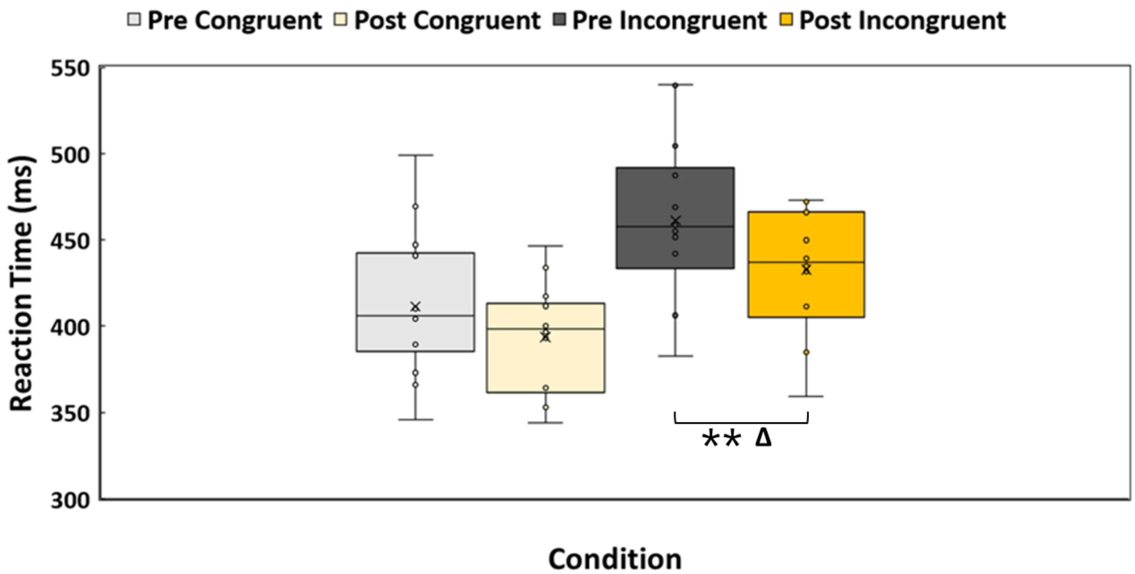


Figure 9. Comparison of flanker congruent and incongruent test reaction time before and after high-intensity exercise. ** = $p < .01$; Δ = $\eta^2_p > 0.14$

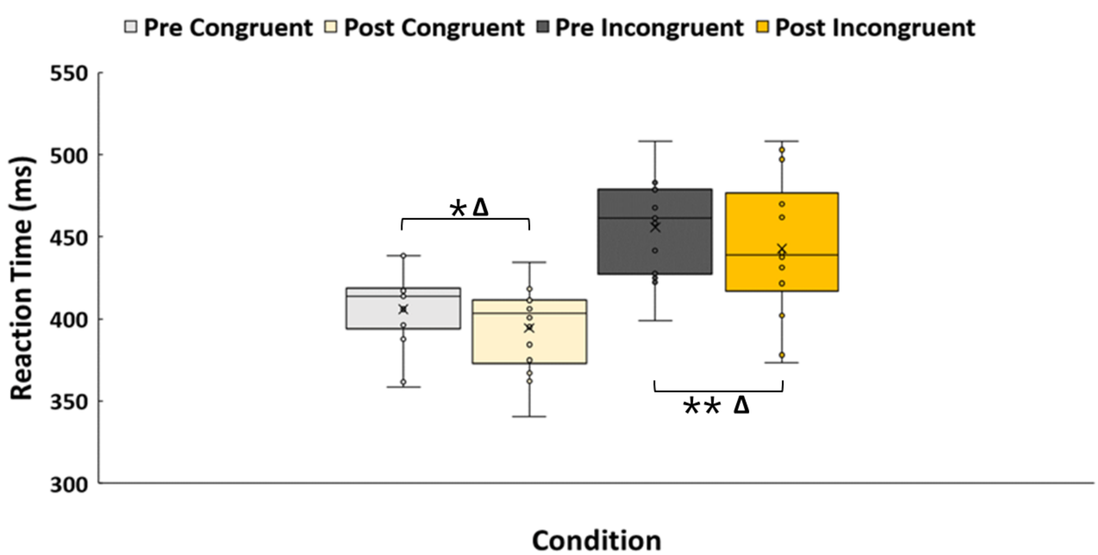


Figure 10. Comparison of flanker congruent and incongruent test reaction time before and after moderate-intensity exercise. * = $p < .05$; ** = $p < .01$; Δ = $\eta^2_p > 0.14$

4.3 Incongruent accuracy & reaction time across flanker tasks in pre- and post-exercise tests

The overall comparison in ACC pre- to post-exercise hid an impairment that occurred in early task (within 2 min). The lack of difference pre-post-HI was effective starting the third epoch comparison (Figure 11). Post-HI epoch 1 and 2 were less accurate than their equivalent pre-HI: mean diff (epoch 1) = 6.1 %, SD = 11.4, $t(13) = 2.001$, $p = .033$, Cohen's d = 0.535 (moderate); mean diff (epoch 2) = 4.4 %, SD = 7.9, $t(13) = 2.077$, $p = .029$, Cohen's d = 0.555 (moderate). Post-HI epochs 3 (Cohen's d = 0.194), 4 (Cohen's d = 0.041), 5 (Cohen's d = -0.124), and 6 (Cohen's d = -0.202) were not different from their respective pre-HI equivalents. No change was observed within the time course of executive function performance regarding MI (Figure 12). The lack of tangible trend and statistically different epoch comparison following MI aligns with the small effect sizes observed for each of them, Cohen's d (epoch 1) = -0.345, Cohen's d (epoch 2) = -0.356, Cohen's d (epoch 3) = 0.082, Cohen's d (epoch 4) = 0.401, Cohen's d (epoch 5) = -0.211, Cohen's d (epoch 6) = 0.341.

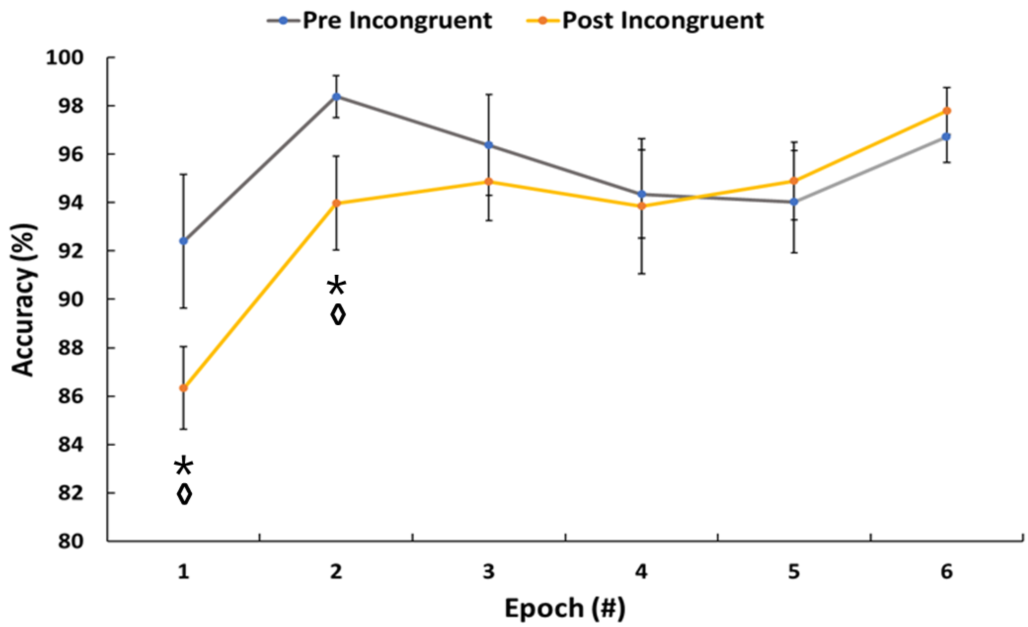


Figure 11. Comparison of time course changes in accuracy before and after high-intensity exercise for incongruent trials (bars represent standard error).
* = p < .05; ◊ = Cohen's d > 0.5

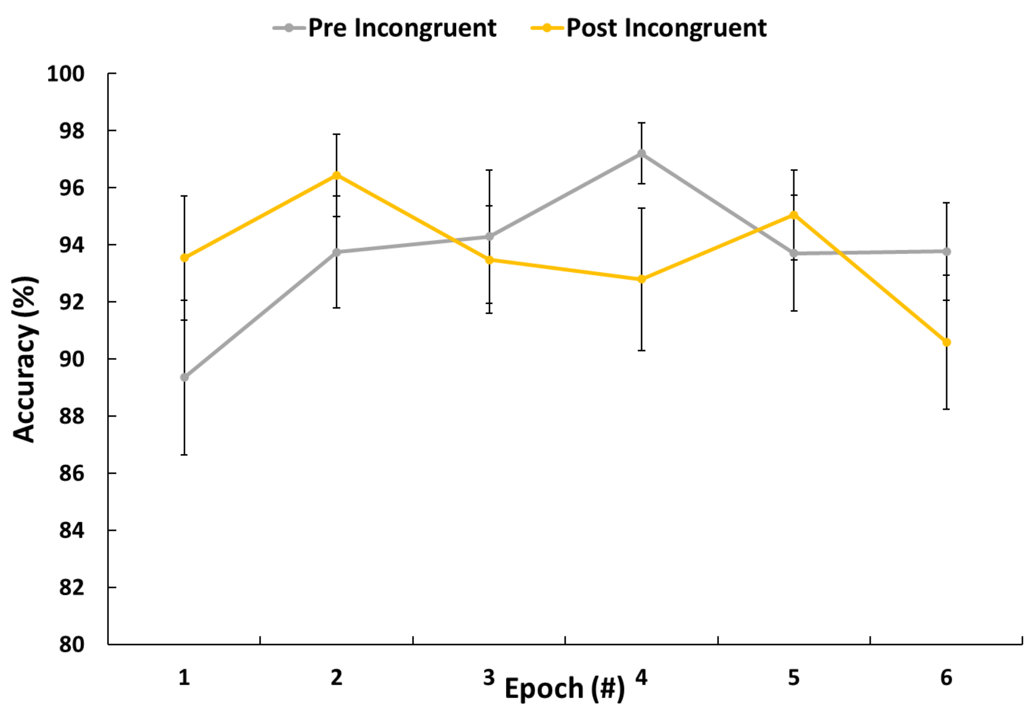


Figure 12. Comparison of time course changes in accuracy before and after moderate-intensity exercise for incongruent trials (bars represent standard error).

Participant's improvement in RT following HI was more pronounced in early-task but remained effective all along the task (Figure 13). Post hoc analyses indicated that post-HI epochs 1, 2, 3, 5, and 6 were faster than their pre-HI equivalents. Respectively, mean difference (epoch 1) = 49 ms, SD = 59, $t(13) = 3.067$, $p = .005$, Cohen's $d = 0.820$ (large); mean difference (epoch 2) = 38 ms, SD = 42, $t(13) = 3.420$, $p = .002$, Cohen's $d = 0.914$ (large); mean difference (epoch 3) = 23 ms, SD = 34, $t(13) = 2.578$, $p = .011$, Cohen's $d = 0.689$ (moderate); mean difference (epoch 5) = 21 ms, SD = 40, $t(13) = 1.990$, $p = .034$, Cohen's $d = 0.532$ (moderate); mean difference (epoch 6) = 26 ms, SD = 50, $t(13) = 1.938$, $p = .037$, Cohen's $d = 0.518$ (moderate). Only the 4th epoch was unsignificantly different (Cohen's $d = 0.309$). Improvements in RT regarding post-MI were significant only after a few moments in the flanker task (Figure 14). Surprisingly, the t-test showed no significant difference within the 1st epoch (Cohen's $d = 0.136$) and the 2nd epoch (Cohen's $d = 0.183$). However, post-MI epochs 3, 4, 5, and 6 were faster than their pre-HI equivalents. Respectively, mean difference (epoch 3) = 21 ms, SD = 29, $t(13) = 2.768$, $p = .008$, Cohen's $d = 0.740$ (moderate); mean difference (epoch 4) = 31 ms, SD = 22, $t(13) = 5.327$, $p = <.001$, Cohen's $d = 1.424$ (large); mean difference (epoch 5) = 19 ms, SD = 37, $t(13) = 1.882$, $p = .041$, Cohen's $d = 0.503$ (moderate); mean difference (epoch 6) = 34 ms, SD = 38, $t(13) = 3.359$, $p = .003$, Cohen's $d = 0.898$ (large). Complete results are presented in (appendix C, section 4).

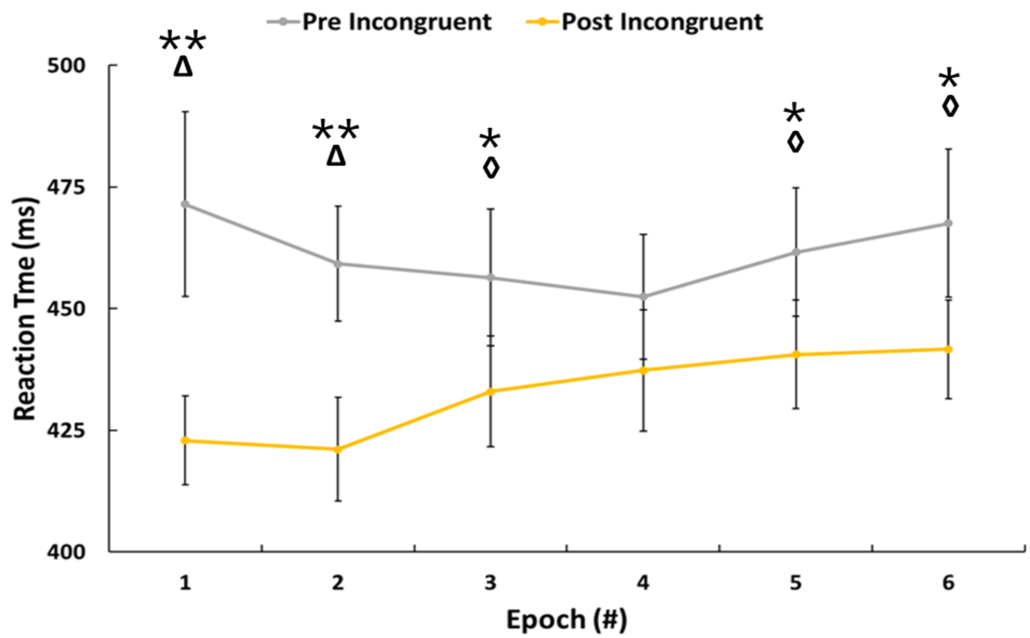


Figure 13. Comparison of time course changes in reaction time before and after high-intensity exercise for incongruent trials (bars represent standard error).
* = p < .05; ** = p < .01; ◊ = Cohen's d > 0.5; Δ = Cohen's d > 0.8

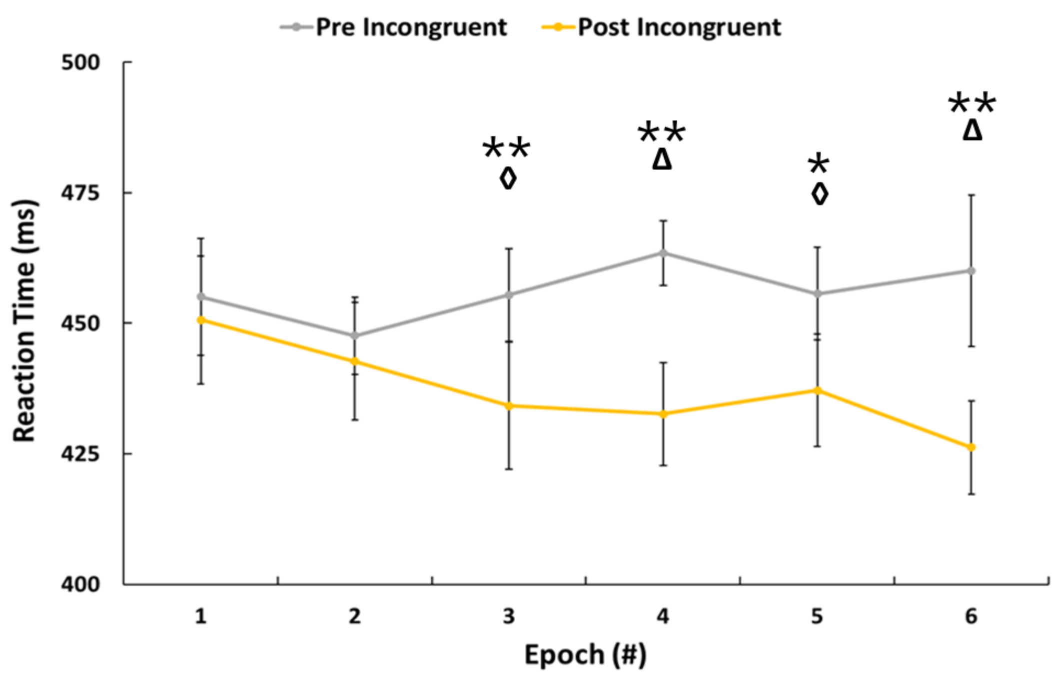


Figure 14. Comparison of time course changes in reaction time before and after moderate-intensity exercise for incongruent trials (bars represent standard error).
* = p < .05; ** = p < .01; ◊ = Cohen's d > 0.5; Δ = Cohen's d > 0.8

4.4 Self-reported mental effort across time in post-exercise tests

Participants self-reported the task as more mentally effortful after the HI run. This change in felt effort was greater in the first moments than later in the flanker task. MI did not provoke any change compared to baseline (Figure 15). There was a statistically significant interaction between section*intensity -> $F(2,26) = 15.364$, $p = <.001$, $\eta^2_p = 0.542$ (large). A statistically significant main effect of section following a Greenhouse-Geisser correction after violating sphericity assumption, $F(1.358,17.656) = 14.519$, $p = <.001$, $\eta^2_p = 0.528$ (large). A statistically significant main effect of intensity was also found, $F(1,13) = 31.178$, $p = <.001$, $\eta^2_p = 0.706$ (large). Post-HI in early-task was self-reported as more effortful than post-MI, mean diff = 2.7 (scale 1 to 9), $p = <.001$, $\eta^2_p = 0.737$ (large). Post-HI mid-task was also greater than post-MI, mean diff = 1.5 (scale 1 to 9), $p = <.001$, $\eta^2_p = 0.594$ (large). Post-HI late-task was again greater than post-MI, mean diff = 0.6 (scale 1 to 9), $p = .033$, $\eta^2_p = 0.305$ (large) (Figure 15). Post-HI early-task was self-reported as “more effortful” by the participants than post-HI mid-task, mean diff = 1.5 (scale 1 to 9), $p = <.001$. Post-HI early-task was self-reported as more mentally effortful than post-HI late-task, mean diff = 2.3 (scale 1 to 9), $p = <.001$. Post-HI mid-task was also significantly greater than post-HI late-task, mean diff = 0.8 (scale 1 to 9), $p = .045$. The effect of HI was large, $\eta^2_p = 0.733$. None of the post-MI sections were different from each other (Figure 15). Respectively, mean diff (early-task vs mid-task) = 0.3 (scale 1 to 9), $p = .653$; mean diff (early-task vs late-task) = 0.2 (scale 1 to 9), p =

1.000; mean diff (mid-task vs late-task) = -0.1 (scale 1 to 9), p = 1.000. The effect size of MI was moderate, $\eta^2_p = 0.117$. When comparing the overall flanker tasks between post-HI and post-MI, post-HI was self-reported as more effortful than post-MI, mean diff = 2.1, SD = 0.9, t(13) = 8.453, p = <.001, Cohen's d = 2.259 (large). Complete results are presented in (appendix C, section 5).

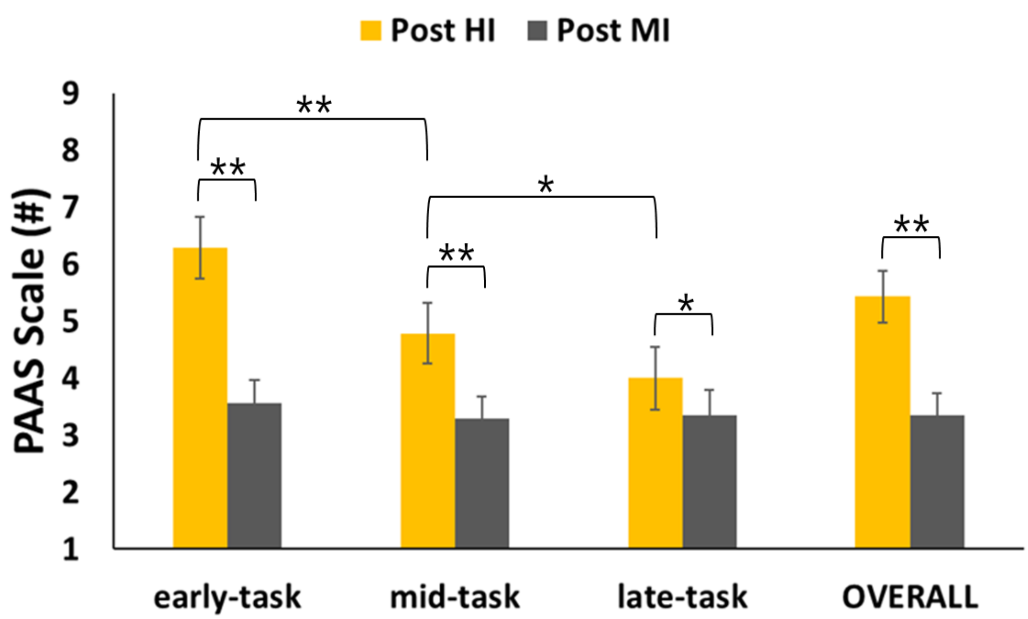


Figure 15. Changes in self-reported rating of mental effort (1 = "very light", 9 = "very heavy") after high- and moderate-intensity exercise, by task section and overall task (bars represent standard error).
* = p < .05;   ** = p < .01.   All effect sizes of significant differences were large.

5 Discussion

5.1 Results interpretation

The present study aimed to compare the time course of recovery following HI with the time course of recovery following MI. Our findings suggest that the strongest effects occur immediately after exercise for ACC, RT, and SRRME. This trend indicates an ability to recover quickly among well-trained individuals. It also suggests that different studies reporting limited changes following exercise may overlook potentially greater effects occurring during the first moments after the termination of exercise when analyzing the cognitive task. These results further our foundational understanding of the effects of exercise on executive function by exploring the time course of cognitive recovery immediately following exercise.

Reaction time of incongruent trials was significantly faster after HI exercise ($p = .008$), but not congruent trials ($p = .071$). An improved RT in executive functioning echoes the ones made by Chang et al. (H. Chang, Kim, Jung, & Kato, 2017) and Finkenzeller et al. (Finkenzeller, Doppelmayr, Wurth, & Amesberger, 2018) who respectively reported an improvement in RT shortly following a HI bout in a Stroop and flanker task. Schmit et al. (Schmit et al., 2015) and Tempest et al. (Tempest et al., 2017) also reported improvement in RT using a flanker task during cycle exercise at HI. While the theory of over-arousal predicts a transient decrement in cognitive functions, arousal has been reported as the main theory to explain improvement in RT via the release of catecholamines into the bloodstream and central nervous system (Audiffren, 2016). This finding is contrary to previous research (Coco et al., 2020; Hill et al., 2019; McMorris, 2009) which found impairment in RT either during or immediately following HI exercise.

Assessment of the time course of RT changes following HI exercise revealed that all post-HI epochs except epoch 4 were faster than their pre-HI equivalents. RT also improved following MI exercise although not as much as during HI. This trend of an improvement in RT immediately following MI without being as large as the improvement in RT following HI would align with our second hypothesis. Improvement in RT following MI exercise was found in studies assessing it either shortly after or during exercise (Kamijo et al., 2007; Kamijo et al., 2009; Davranche, Hall, et McMorris, 2009; Ando et al., 2011). These differences across the flanker task suggest that post-HI remained faster than pre-HI RT all along the task with greater differences among the 2 first epochs (about 2 min 15 sec in the task). This trend aligns with our third hypothesis suggesting that greater differences would appear early rather than later in the task. The rationale behind this is that the higher the exercise-induced stress, the greater the changes. In a similar study whose aim was to assess the time course of executive function recovery following HI cycling exercise, Finkezeller et al. (Finkenzeller, Doppelmayr, Wurth, & Amesberger, 2018) found improvement in RT when assessed over 3 different flanker tasks, respectively immediately, 5 min, and 15 min after exercise. Unlike the present study, improvement in RT remained stable for all 3 tasks and was not greater for any task closer to the exercise end. Perhaps the authors did not consider that a greater improvement of RT (if any) might have occurred in the very first moments after the effort stopped, but that this trend might have been diluted in the first of their three tasks. Still, their findings suggest that improvement in RT, even if smaller than after the improvement occurring within the first 2 minutes, may remain persistent for a period significantly longer than the duration of the flanker task of the present study.

Interestingly, RT changes following MI exercise drew a different trend during the analysis of the time course. When comparing each post-MI epoch to their pre-MI equivalent no difference was detected between the first 2 epochs. They only split later in the task, starting epoch 3 throughout the end. This trend goes against our third hypothesis that expected an improvement to occur in early task before merging to baseline values. This counterintuitive trend drawing no difference in early task is to take carefully, even though supported by 2 studies that did not find any change in RT during a MI cycle effort (Labelle et al., 2013; Pontifex et Hillman, 2007). Though, the trend of a stable difference in improved RT after a couple of minutes in the task is consistent with the trend observed after HI exercise and with Finkenzeller et al. (Finkenzeller, Doppelmayr, Wurth, & Amesberger, 2018). The present findings as well as similar ones in the literature suggest that improvement in RT, when occurring post-exercise, is maintained over multiple minutes (H. Chang, Kim, Jung, & Kato, 2017; Finkenzeller, Doppelmayr, Wurth, & Amesberger, 2018; O'Leary, Pontifex, Scudder, Brown, & Hillman, 2011).

We would like to acknowledge that HI exercise statistically failed to affect overall ACC of the incongruent trials ($p = .119$). Therefore, our analysis failed to confirm our first hypothesis that expected a decrease in executive control ACC following HI exercise. However, the time course analysis following HI intervention is consistent with our third hypothesis that predicted an ACC impairment in the first moments in the flanker task. Indeed, the decrement in ACC post-exercise among the 2 first epochs suggested that the analysis of the overall task diluted an impairment occurring in early task (within 2-to-3 min in the task). Post-HI epochs 3, 4, 5, and 6 are not different from their pre-HI equivalent. The trend of an impairment in early task that merges with baseline level for the rest of the flanker task also aligns with our third hypothesis. A decrement in ACC for overall post-HI is consistent with previous research that found decreases in ACC immediately following a cycle ergometer ride to exhaustion (Coco et al., 2020). A decreased ACC fits as well previous studies that investigated changes in executive function during exercise at HI (Labelle et al., 2013; McMorris et al., 2009; Schmit et al., 2015). Although in the study performed by Pontifex & Hillman (Pontifex et Hillman, 2007) participants cycled at MI, it is probably because they completed a flanker task *during* this effort that their accuracy decreased when compared to control condition (no change in RT). Because of the inertia in the psychophysiological state following HI exercise, similar trends to what occurs during exercise are expected in the first moments after its termination, before quickly returning to baseline level. Short-term transient impairment of ACC, which in the case of the flanker task represents the ability to complete it properly (Eriksen & Eriksen, 1974), is supported by the hierarchical downregulation of the brain areas that are the least necessary to maintain the movement at HI (Dietrich et Audiffren, 2011; Sudo et al., 2022). Hence, the executive control tasks leveraging greater mental workload and attention would be first limited to prioritizing an allocation of resources towards the supplementary motor cortex rather than the PFC (Jung et al., 2023).

HI exercise-induced over-arousal may have also played a factor. An excessive release of dopamine and norepinephrine neurotransmitters would cause a hyperpolarization of the neural membranes, disturbing the activity of K+ and Na+

channels via an excessive adenosine monophosphate (cAMP) activation. This process would inhibit the neuronal activity in the PFC (Jung et al., 2023). Various authors found no significant changes following an acute aerobic HI effort (H. Chang, Kim, Jung, & Kato, 2017; Finkenzeller, Doppelmayr, Wurth, & Amesberger, 2018; Hill et al., 2019; Tempest et al., 2017). Another explanation could come from an inherent inability of the flanker task to allow a better score than 100% ACC. It is possible, then, that potential slight decrement could be hard to detect, not because of the difficulty of letting the post-exercise perform poorly, but because of the impossibility of allowing some participants to perform better in resting condition (ceiling effect).

While there were significant overall post-MI congruent trials that showed less ACC than their pre-MI equivalents, the pre-post comparison of overall MI incongruent trials indicated no difference ($p = .863$). The mean difference in ACC between pre-MI and post-MI incongruent was moreover very small (= 0.2 %) compared to the mean difference between pre-HI and post-HI incongruent (= 2.0 %). This was accompanied by insignificant differences among incongruent trials between each pre-MI and post-MI respective epoch pair. This goes against our first hypothesis, which expected an overall increase in accuracy following MI intervention. De facto, this contradicts our third hypothesis which also predicted changes in ACC in early task. Similar findings were found in multiple studies assessing the effect of MI soon after termination of exercise or during exercise (Ando et al., 2011; Davranche, Hall et McMorris, 2009; Hill et al., 2019; Kamijo et al., 2007; Kamijo et al., 2009; O'Leary, Pontifex, Scudder, Brown, & Hillman, 2011; Stroth et al., 2009). The present results seem to draw the trend of a null difference between pre- and post-exercise at moderate and lower intensities. One possible explanation for these things may be that the running intensity was too low to provoke any significant change. These findings would be consistent with previous research that found no difference after MI even when cognitive function was assessed very closely after the effort stopped (Sudo et al., 2022; Jung et al., 2022). The very high fitness of the participants may also have played a role in the lack of significant difference following MI at such intensity (presently 60% VO_{2max}). Endurance athletes are indeed able to recover faster after lower-intensities efforts (Seiler et al., 2007). Such individuals might also need higher intensities to trigger any exercise-induced change in ACC (Stroth et al., 2009; Labelle et al., 2013).

The present results seemed to indicate a RT-ACC trade-off following the HI exercise. In this context, reaction time was improved while accuracy was transitorily impaired. No RT-ACC trade-off was identifiable following MI, suggesting an overall improvement in flanker task performance (faster responses for no differences in answer quality). The RAH model was proposed by Dietrich et Audiffren (Dietrich et Audiffren, 2011) in their holistic framework. This model manages to explain the emergence of such a trade-off, which takes shape as the exercise intensity increases. In the context of exercise-induced arousal, RT would be improved as the hypofrontality process would impair one's ability to respond properly to stimuli as often as in resting condition. Then, the natural response to the exercise stress (or any form of stress) would be to take more risks in order to respond quicker, thus increasing the rate of responses that are both fast and accurate, even if this implies lowering the overall accuracy (Audiffren, 2016). On the other hand, the seeming lack of trade-off following MI can simply be explained by the nature of the flanker task itself, which may be still too simple to reveal any potential impairment in ACC. Overall, ACC seemed to be more volatile and less reliable than the RT results. Again, this can be due to the nature of the task itself, in which each outcome is either right or wrong, without continuous degrees of falseness that would bring more precision to the extent of right or wrong responses.

Older systematic reviews and meta-analyses tended to consider acute MI exercise as having a moderate, rather beneficial, and greater impact on cognitive function than other intensities (Tomporowski, 2003; McMorris et Hale, 2012; Chang et al., 2012). More recent studies oriented their focus on the consequences of HI exercise either during or immediately after the effort (H. Chang, Kim, Jung, & Kato, 2017; Coco et al., 2020; Du Rietz et al., 2019; Finkenzeller, Doppelmayr, Wurth, & Amesberger, 2018; Hill et al., 2019; Komiyama et al., 2020; Samuel et al., 2017; Stone et al., 2020; Sudo et al., 2017; Tempest et al., 2017; Zimmer et al., 2017). Later systematic reviews operated a switch in the direction of a stronger and detrimental effect of HI exercise on cognitive functions (Dietrich et Audiffren, 2011; Jung et al., 2023; McMorris et al., 2015; Sudo et al., 2022). Overall, the present study tends to show that HI exercise has a greater effect on executive function than MI. More specifically, this effect goes in the direction of RT improvement and ACC slight impairment when performing an Eriksen flanker task. The time course analysis of the present study suggests that a seemingly greater MI impact on cognitive performance may be due to an underestimation of the HI. The reason behind this misunderstanding may be the very transient and greater impact of HI exercise. These effects would quickly fade during recovery, before leaving room for longer-term and beneficial impact of exercise after complete recovery (starting minutes-to-tens-of-minutes following exercise).

Post-HI was self-reported as more mentally effortful than post-MI throughout the entire task. Post-HI early-task was also significantly greater than post-HI mid-task, which was in turn significantly greater than post-HI late-task. However, the post-MI SRRME was consistently low for the entirety of the flanker task. These findings are in accordance with our fourth hypothesis. It is not surprising that performing a cognitive task immediately after exercise was reported as more effortful than at rest. In such a psychophysiological state, a theoretical lack of resources (Dietrich et Audiffren, 2011; Jung et al., 2023; McMorris et al., 2021; Sudo et al., 2022) can require a higher focus to complete tasks involving higher-order processes (Audiffren et Andre, 2015). One study (M. Audiffren, Tomporowski, & Zagrodnik, 2009) did not report any change in executive function during a cycling exercise at HI. Interestingly, the authors identified instead a shift to a less effortful strategy allowing participants to maintain their executive performance despite the effort. To our knowledge, the use of a self-reported measure of mental effort was not used before the present study.

5.2 Contributions and future implications

As with previous research, the present study reported the trends drawn by flanker tasks analyzed in their entirety before, and following HI and MI. To our knowledge, the present study was nevertheless the first one to also report an analysis of the time course of executive function changes accross the flanker tasks. The results reported the trends drawn by the time course analyses as being more nuanced and complex than the mere reading of the flanker tasks analyzed overall. As exepected, the effects of HI and MI exercise were not consistent all the way through (e.g. greater differences observed in early task following HI). The present study suggests that greater attention should be paid to the time scales used to analyze the immediate effects of exercise on cognitive functions. Analyzing a task in its entirety runs the risk of overlooking potentially strong effects taking place in the early stages of the task. This would be tantamount to neglecting the changing psychophysiological state of individuals recovering from exercise.

The results of this research have potentially larger implications for our foundational understanding of the relationship between exercise and cognition. Knowledge gained from these results provides valuable insights into activities that couple high physiological and cognitive demands (e.g., sports, military, firefighting). Situations involving physical stress are often situations that put the people involved in a time crisis. When physical stress and cognitive demands do not occur simultaneously, this time crisis allows little or no recovery time to project oneself into a cognitive action that follows the cessation of physical constraint. Implications of this work might be extended to any context in which acute physiological arousal interferes with higher-order cognitive processes. Ultimately, the theme of the present study falls into the dual-task paradigm, involving competition in the allocation of resources (e.g., attention, oxygen, glucose).

5.3 Limitations

We acknowledge several limitations of this study. Firstly, the flanker task may be of insufficient utility to answer our research question. While it is a well-documented method to measure executive control, it is possible that the task is still too simple to reveal a stronger exercise effect on ACC. This simplicity leads to potentially a ceiling effect, that limits the ability to detect exercise-induced changes in executive function. Alternatively, if the arousal theory can explain HI-induced changes in RT at the expense of ACC, a smaller potential trade-off could be assessed with the use of a more complex task. Future studies should consider more challenging but test-retest reliable tasks to assess higher-order processing during or following exercise.

Secondly, limitations regarding the feasibility of collecting some of the measures and the nature of these measures may have affected our findings. The SRRME had to be reported afterward since it was naturally impossible for the participants to report it while performing the task, potentially bringing memory bias. Interestingly, it was also noticed by the experimenter that participants tended to report a rating of the overall task that was closer to the greatest-rated section than the real average. Moreover, the simple fact of experiencing the moments following a strenuous HI run can already be perceived as taxing. This feeling cannot be separated from the actual additional effort that participants have to put into the task to perform: “hard to perform” vs “hard to be”. More complete types of SRRME should be considered in future research, as well as any technique allowing the measurement of the effort, or energy cost put into the cognitive task.

We also acknowledge the small sample size of this exploratory study. While attempts were made to collect a larger sample, the availability of individuals who met the stringent inclusion criteria affected our recruitment ability and resultant sample size. Therefore, a main effect of condition may have been sometimes underpowered, notably regarding the more variable ACC. As mentioned above, the use of a task more sensitive to the quality of the response rather than the speed at which it is given could alleviate the need for a large number of participants to reveal potential changes.

The present study is designed in such a manner that the MI visit had to follow the HI visit. As a reminder, this is because the HI run duration determined the MI run duration. This was a deliberate choice to cancel out duration effect and isolate intensity in the exercise-induced changes. The downside is that it turns out impossible to randomly cross the order HI-MI / MI-HI to eliminate potential visit-order bias. The present study was also performed on varsity endurance athletes. Such high-fit individuals present characteristics that might influence the strength of the exercise-induced effects, as well as the time course of cognitive recovery. Similar studies assessing the time course of cognitive changes following acute exercise are needed with lower-fit individuals. As anticipated, the delay separating the end of the runs and the flanker tasks was impossible to reduce to 0, and presented some variability (appendix A), as participants were instructed to transit as fast as possible from the treadmill to the standing desk. "Immediate" post-exercise assessment being in practice hardly possible, future research is encouraged to report the delay separating the end of exercise and the beginning of the cognitive task. The design requiring a total of 4 visits made the scheduling hard to control, depending on each student-athlete's availability. Moreover, physical and mental shape of the participants were subject to changing across multiple weeks of participation (4 to 5), depending on training and school load fluctuations.

Lastly, the preliminary running protocols showed some limitations. Submaximal and maximal tests may not have matched the runner profile of all participants. Performance during the submaximal test was only determined by treadmill speed (flat grade), while performance during the VO2max test was determined by 2 “failure” factors, those of treadmill slope and speed. The running tasks of study visits being performed on flat only, the actual intensities at which ran the participants could potentially not match with high precision the targeted intensities (respectively 90% and 60% of VO2max). For instance, a very technically efficient flat runner could run at relatively high speed without using a great amount of aerobic capacity, the effort becoming very hard to maintain within a very thin higher extent above their anaerobic threshold. Inversely, very fit athletes having a less efficient running technique could lack the muscle coordination necessary to run at high speed. Since less concern was addressed about the potential of the VO2max test to reflect the true maximum aerobic capacity of the participants, very fit athletes who did not have a truly efficient flat running coordination potentially failed earlier in the Tlim 90% than average, not because they reached aerobic failure but because they mechanically could not maintain such a speed with good muscle smoothness (i.e. “too fit for their own legs”). Less fit but technically efficient flat runner could, on the other hand, run at a more comfortable speed, actually relative to a lower aerobic intensity than targeted, the targeted flat running speed being underrated in this case. This is why the moment at which participants failed was called “exercise failure” instead of “exhaustion”.

6 Conclusion

The results of this study indicate a strong beneficial effect of a HI run on RT in a flanker task performed immediately after exercise. They also suggest that more effort was put into completing the task after HI. Changes in all three variables (RT, ACC, SRRME) were the strongest within the first 2 min following HI. The results also indicate a greater effect of HI than MI on executive control. Globally, the present study concludes that assessing the task only as a whole during the recovery of participants may dilute potential stronger effects happening in early task. In the hypothesis of very transient strong effects occurring during the first moments following exercise, future research is invited to consider the time course of cognitive recovery. For this purpose, it is also advised to report with precision the time separating the end of the exercise from the beginning of the cognitive task, even if very small.

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A Anthropometric characteristics

Table A.1. Anthropometric characteristics

	Total (n=14)		female (n=5)		male (n=9)	
	mean	(sd)	mean	(sd)	mean	(sd)
Age	22.6	(5.2)	22.8	(6.8)	22.6	(4.5)
College years	2.9	(1.7)	2.6	(2.1)	3.0	(1.5)
Body height (cm)	175.4	(6.7)	169.6	(4.6)	178.6	(5.4)
Body mass (kg)	70.9	(8.8)	63.0	(5.1)	75.3	(7.2)
Body fat (%)	12.5	(5.5)	18.8	(3.3)	9.1	(2.5)
BMI (kg/m2)	23.0	(1.7)	21.9	(0.8)	23.6	(1.7)
Peak VO_2 (ml/min/kg)	64.6	(6.7)	58.0	(3.7)	68.2	(4.8)
Peak VO_2 (l/min)	4.61	(0.89)	3.65	(0.31)	5.14	(0.59)
VO_2/speed (ml/min/kg/mph)	5.92	(0.53)	5.66	(0.69)	6.06	(0.39)
Seated Resting HR (beats/min)	54	(9)	50	(8)	57	(9)
Max HR (beats/min)	192	(14)	186	(16)	195	(12)
Systolic Blood Pressure (mmHg)	115	(10)	108	(6)	120	(10)
Diastolic Blood Pressure (mmHg)	69	(8)	68	(9)	69	(8)
Training volume of past year (h)	489	(91)	436	(58)	519	(95)
USSA points	109.39	(35.64)	131.46	(37.23)	94.67	(28.36)

B Exercise characteristics

Table B.1. VO_{2max} test results

Measure	Total (n=14)		female (n=5)		male (n=9)	
	Mean	(sd)	Mean	(sd)	Mean	(sd)
Peak VO_2 (ml/min/kg)	64.6	(6.7)	58.0	(3.7)	68.2	(4.8)
Peak VO_2 (l/min)	4.61	(0.89)	3.65	(0.31)	5.14	(0.59)
Max HR (beats/min)	192	(14)	186	(16)	195	(12)
Peak RER before failure (VCO_2/VO_2)	1.06	(0.03)	1.05	(0.04)	1.07	(0.03)
RPE at failure (Borg scale)	19.4	(0.9)	19.0	(1.4)	19.7	(0.5)
Effort duration (min:sec)	24.6	(2.4)	24.2	(1.1)	24.8	(2.9)

Table B.2. Tlim 90% VO_{2max} treadmill run outcome variables

Measure	Total (n=14)		female (n=5)		male (n=9)	
	Mean	(sd)	Mean	(sd)	Mean	(sd)
Tlim (min:sec)	10:49	(04:35)	12:11	(05:59)	09:52	(04:02)
Speed (mph)	10.6	(1.1)	9.8	(0.8)	11.1	(0.9)
RPE at failure (Borg scale)	19.4	(0.6)	19.2	(0.8)	19.4	(0.5)
Peak HR (beats/min)	188	(13)	183	(15)	191	(11)
Peak HR (% HRmax)	97.9	(6.8)	98.4	(8.1)	97.9	(5.6)
Mean HR (beats/min)	181	(14)	176	(14)	184	(15)
Mean HR (% HRmax)	92.3	(7.3)	94.6	(7.5)	94.4	(7.7)
Mean RPE (Borg scale)	17.0	(1.2)	16.8	(1.3)	17.0	(1.3)
Transition time (sec)	10.1	(1.5)	10.2	(2.2)	10.0	(1.2)

Table B.3. isochronal 60% VO_{2max} treadmill run outcome variables

Measure	Total (n=14)		female (n=5)		male (n=9)	
	Mean	(sd)	Mean	(sd)	Mean	(sd)
Run duration (min:sec)	10:49	(04:35)	12:11	(05:59)	09:52	(04:02)
Speed (mph)	7.4	(0.8)	6.7	(0.4)	7.8	(0.7)
RPE at termination (Borg scale)	10.9	(1.2)	10.6	(0.5)	11.0	(1.5)
Peak HR (beats/min)	146	(11)	140	(9)	149	(11)
Peak HR (% HRmax)	76.0	(5.7)	75.3	(4.8)	76.4	(5.6)
Mean HR (beats/min)	140	(10)	135	(8)	143	(10)
Mean HR (% HRmax)	72.9	(5.2)	72.6	(4.3)	73.3	(5.1)
Mean RPE (Borg scale)	10.5	(1.4)	10.1	(0.5)	10.7	(1.7)
Transition time (sec)	10.5	(3.3)	11.2	(5.1)	10.1	(2.0)

C Dependent variables averages and statistical tables

C.1 Overall accuracy

Table C.1.1. Overall high- and moderate-intensity accuracy (%) – descriptive statistics

Test	Mean	(std. dev)
Pre-HI congruent	99.4	(1.0)
Post-HI congruent	98.9	(1.0)
Pre-MI congruent	99.1	(1.6)
Post-MI congruent	98.3	(2.3)
Pre-HI incongruent	95.5	(4.8)
Post-HI incongruent	93.5	(3.4)
Pre-MI incongruent	93.7	(4.7)
Post-MI incongruent	93.9	(5.1)

Table C.1.2. Overall high-intensity accuracy (%) – effect of variables

Variable	F	Sig.	Partial Eta Squared	Observed Power[a]
prepost	4.314	.058	0.249	0.485
congruency	35.298	<.001	0.731	1
prepost*congruency	1.557	.234	0.107	0.212

alpha = .05

Table C.1.3. Overall high-intensity accuracy (%) - pairwise comparisons congruency by pre/post

Congruency	Pre/Post	Mean Diff Pre – Post	(std. error)	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
congruent	Pre - Post	0.5*	(0.2)	.019	0.1	0.8
incongruent	Pre - Post	2.0	(1.2)	.119	-0.6	4.6

* Mean diff significant at alpha = .05
b -> Bonferroni adjustment applied

Table C.1.4. Overall moderate-intensity accuracy (%) – effect of variables

Variable	F	Sig.	Partial Eta Squared	Observed Power[a]
prepost	0.285	.602	0.021	0.079
congruency	33.514	<.001	0.721	1
prepost*congruency	1.018	.331	0.073	0.155

alpha = .05

Table C.1.5. Overall moderate-intensity accuracy (%) - pairwise comparisons congruency by pre/post

Congruency	Pre/Post	Mean Diff Pre – Post	(std. error)	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
congruent	Pre - Post	0.8*	(0.4)	.045	0.0	1.6
incongruent	Pre - Post	0.2	(1.0)	.863	-2.4	2.1

* Mean diff significant at alpha = .05
b -> Bonferroni adjustment applied

C.2 Overall reaction time

Table C.2.1. Overall high- and moderate-intensity reaction time (ms) – descriptive statistics

Test	Mean	(std. dev)
Pre-HI congruent	411	(41)
Post-HI congruent	394	(30)
Pre-MI congruent	406	(24)
Post-MI congruent	394	(26)
Pre-HI incongruent	461	(46)
Post-HI incongruent	433	(35)
Pre-MI incongruent	456	(29)
Post-MI incongruent	438	(35)

Table C.2.2. Overall high-intensity reaction time (ms) – effect of variables

Variable	F	Sig.	Partial Eta Squared	Observed Power[a]
prepost	6.776	.022	0.343	0.673
congruency	290.403	<.001	0.957	1
prepost*congruency	9.752	.008	0.429	0.823

alpha = .05

Table C.2.3. Overall high-intensity reaction time (ms) - pairwise comparisons congruency by pre/post

Congruency	Pre/Post	Mean Diff Pre – Post	(std. error)	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
congruent	Pre - Post	18	(9)	.071	-2	37
incongruent	Pre - Post	28*	(9)	.008	9	48

* Mean diff significant at alpha = .05
b -> Bonferroni adjustment applied

Table C.2.4. Overall moderate-intensity reaction time (ms) – effect of variables

Variable	F	Sig.	Partial Eta Squared	Observed Power[a]
prepost	12.382	.004	0.488	0.901
congruency	185.555	<.001	0.935	1
prepost*congruency	5.713	.033	0.305	0.599

alpha = .05

Table C.2.5. Overall moderate-intensity reaction time (ms) - pairwise comparisons congruency by pre/post

Congruency	Pre/Post	Mean Diff Pre – Post	(std. error)	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
congruent	Pre - Post	11*	(4)	.012	3	20
incongruent	Pre - Post	18*	(5)	.003	8	29

* Mean diff significant at alpha = .05
b -> Bonferroni adjustment applied

C.3 Accuracy by incongruent epochs

Table C.3.1. Accuracy (%) paired incongruent epochs Pre/Post high-intensity – descriptive statistics

	Epoch	Mean	(std. dev)	(std. error)
Pair 1	Pre-Epoch1	92.4	(10.3)	(2.8)
	Post-Epoch1	86.3	(6.3)	(1.7)
Pair 2	Pre-Epoch2	98.4	(3.3)	(0.9)
	Post-Epoch2	94.0	(7.3)	(1.9)
Pair 3	Pre-Epoch3	96.4	(7.8)	(2.1)
	Post-Epoch3	94.9	(6.0)	(1.6)
Pair 4	Pre-Epoch4	94.4	(6.8)	(1.8)
	Post-Epoch4	93.9	(10.4)	(2.8)
Pair 5	Pre-Epoch5	94.0	(7.9)	(2.1)
	Post-Epoch5	94.9	(6.0)	(1.6)
Pair 6	Pre-Epoch6	96.7	(4.0)	(1.1)
	Post-Epoch6	97.8	(3.6)	(1.0)

Table C.3.2. Accuracy (%) paired incongruent epochs Pre/Post high-intensity – paired differences

Epoch		Paired Differences				
		Mean diff	(std. dev)	(std. error)	95% CI of diff	
					Lower	Upper
Pair 1	Pre-Epoch1 - Post-Epoch1	6.1	(11.4)	(3.0)	-0.5	12.6
Pair 2	Pre-Epoch2 - Post-Epoch2	4.4	(7.9)	(2.1)	-0.2	9.0
Pair 3	Pre-Epoch3 - Post-Epoch3	1.5	(7.8)	(2.1)	-3.0	6.0
Pair 4	Pre-Epoch4 - Post-Epoch4	0.5	(12.1)	(3.2)	-6.5	7.5
Pair 5	Pre-Epoch5 - Post-Epoch5	-0.9	(6.9)	(1.8)	-4.9	3.1
Pair 6	Pre-Epoch6 - Post-Epoch6	-1.1	(5.3)	(1.4)	-4.1	2.0

Table C.3.3. Accuracy (%) paired incongruent epochs Pre/Post high-intensity – test statistics

Epoch		t	Significance One-Sided p	Cohen's d
Pair 1	Pre-Epoch1 - Post-Epoch1	2.001	.033	0.535
Pair 2	Pre-Epoch2 - Post-Epoch2	2.077	.029	0.555
Pair 3	Pre-Epoch3 - Post-Epoch3	0.127	.240	0.194
Pair 4	Pre-Epoch4 - Post-Epoch4	0.155	.440	0.041
Pair 5	Pre-Epoch5 - Post-Epoch5	-0.465	.325	-0.124
Pair 6	Pre-Epoch6 - Post-Epoch6	-0.757	.231	-0.202

Table C.3.4. Accuracy (%) paired incongruent epochs Pre/Post moderate-intensity – descriptive statistics

	Epoch	Mean	(std. dev)	(std. error)
Pair 1	Pre-Epoch1	89.4	(10.1)	(2.7)
	Post-Epoch1	93.5	(8.2)	(2.2)
Pair 2	Pre-Epoch2	93.7	(7.3)	(2.0)
	Post-Epoch2	96.4	(5.3)	(1.4)
Pair 3	Pre-Epoch3	94.3	(8.8)	(2.3)
	Post-Epoch3	93.5	(7.1)	(1.9)
Pair 4	Pre-Epoch4	97.2	(4.0)	(1.1)
	Post-Epoch4	92.8	(9.3)	(2.5)
Pair 5	Pre-Epoch5	93.7	(7.6)	(2.0)
	Post-Epoch5	95.1	(5.9)	(1.6)
Pair 6	Pre-Epoch6	93.8	(6.4)	(1.7)
	Post-Epoch6	90.6	(8.8)	(2.4)

Table C.3.5. Accuracy (%) paired incongruent epochs Pre/Post moderate-intensity – paired differences

Epoch		Paired Differences				
		Mean diff	(std. dev)	(std. error)	95% CI of diff	
					Lower	Upper
Pair 1	Pre-Epoch1 - Post-Epoch1	-4.2	(12.1)	(3.2)	-11.2	2.8
Pair 2	Pre-Epoch2 - Post-Epoch2	-2.7	(7.6)	(2.0)	-7.1	1.7
Pair 3	Pre-Epoch3 - Post-Epoch3	0.8	(9.8)	(2.6)	-4.9	6.5
Pair 4	Pre-Epoch4 - Post-Epoch4	4.4	(11.0)	(2.9)	-1.9	10.7
Pair 5	Pre-Epoch5 - Post-Epoch5	-1.3	(6.4)	(1.7)	-5.0	2.3
Pair 6	Pre-Epoch6 - Post-Epoch6	-3.2	(9.3)	(2.5)	-2.2	8.6

Table C.3.6. Accuracy (%) paired incongruent epochs Pre/Post moderate-intensity – test statistics

Epoch		t	Significance Two-Sided p	Cohen's d
Pair 1	Pre-Epoch1 - Post-Epoch1	-1.291	.219	-0.345
Pair 2	Pre-Epoch2 - Post-Epoch2	-1.334	.205	-0.356
Pair 3	Pre-Epoch3 - Post-Epoch3	0.308	.763	0.082
Pair 4	Pre-Epoch4 - Post-Epoch4	1.501	.157	0.401
Pair 5	Pre-Epoch5 - Post-Epoch5	-0.789	.444	-0.211
Pair 6	Pre-Epoch6 - Post-Epoch6	-1.276	.224	0.341

C.4 Reaction time by incongruent epochs

Table C.4.1. Reaction time (ms) paired incongruent epochs Pre/Post high-intensity – descriptive statistics

	Epoch	Mean	(std. dev)	(std. error)
Pair 1	Pre-Epoch1	471	(71)	(19)
	Post-Epoch1	423	(34)	(9)
Pair 2	Pre-Epoch2	459	(44)	(12)
	Post-Epoch2	421	(40)	(11)
Pair 3	Pre-Epoch3	456	(53)	(14)
	Post-Epoch3	433	(42)	(11)
Pair 4	Pre-Epoch4	453	(48)	(13)
	Post-Epoch4	437	(47)	(12)
Pair 5	Pre-Epoch5	462	(49)	(13)
	Post-Epoch5	441	(42)	(11)
Pair 6	Pre-Epoch6	468	(57)	(15)
	Post-Epoch6	442	(38)	(10)

Table C.4.2. Reaction time (ms) paired incongruent epochs Pre/Post high-intensity – paired differences

Epoch		Paired Differences				
		Mean diff	(std. dev)	(std. error)	95% CI of diff	
					Lower	Upper
Pair 1	Pre-Epoch1 - Post-Epoch1	49	(59)	(16)	14	83
Pair 2	Pre-Epoch2 - Post-Epoch2	38	(42)	(11)	14	62
Pair 3	Pre-Epoch3 - Post-Epoch3	23	(34)	(9)	4	43
Pair 4	Pre-Epoch4 - Post-Epoch4	15	(49)	(13)	-13	44
Pair 5	Pre-Epoch5 - Post-Epoch5	21	(40)	(11)	-2	44
Pair 6	Pre-Epoch6 - Post-Epoch6	26	(50)	(13)	-3	55

Table C.4.3. Reaction time (ms) paired incongruent epochs Pre/Post high-intensity – test statistics

Epoch		t	Significance One-Sided p	Cohen's d
Pair 1	Pre-Epoch1 - Post-Epoch1	3.067	.005	0.82
Pair 2	Pre-Epoch2 - Post-Epoch2	3.42	.002	0.914
Pair 3	Pre-Epoch3 - Post-Epoch3	2.578	.011	0.689
Pair 4	Pre-Epoch4 - Post-Epoch4	1.157	.134	0.309
Pair 5	Pre-Epoch5 - Post-Epoch5	1.99	.034	0.532
Pair 6	Pre-Epoch6 - Post-Epoch6	1.938	.037	0.518

Table C.4.4. Reaction time (ms) paired incongruent epochs Pre/Post moderate-intensity – descriptive statistics

Epoch		Mean	(std. dev)	(std. error)
Pair 1	Pre-Epoch1	455	(42)	(11)
	Post-Epoch1	451	(46)	(12)
Pair 2	Pre-Epoch2	448	(28)	(7)
	Post-Epoch2	443	(42)	(11)
Pair 3	Pre-Epoch3	455	(33)	(9)
	Post-Epoch3	434	(46)	(12)
Pair 4	Pre-Epoch4	463	(23)	(6)
	Post-Epoch4	433	(37)	(10)
Pair 5	Pre-Epoch5	456	(33)	(9)
	Post-Epoch5	437	(40)	(11)
Pair 6	Pre-Epoch6	460	(54)	(15)
	Post-Epoch6	426	(34)	(9)

Table C.4.5. Reaction time (ms) paired incongruent epochs Pre/Post moderate-intensity – paired differences

Epoch		Paired Differences				
		Mean diff	(std. dev)	(std. error)	95% CI of diff	
					Lower	Upper
Pair 1	Pre-Epoch1 - Post-Epoch1	4	(32)	(9)	-14	23
Pair 2	Pre-Epoch2 - Post-Epoch2	5	(27)	(7)	-10	20
Pair 3	Pre-Epoch3 - Post-Epoch3	21	(29)	(8)	5	38
Pair 4	Pre-Epoch4 - Post-Epoch4	31	(22)	(6)	18	43
Pair 5	Pre-Epoch5 - Post-Epoch5	19	(37)	(10)	-3	40
Pair 6	Pre-Epoch6 - Post-Epoch6	34	(38)	(10)	12	56

Table C.4.6. Reaction time (ms) paired epochs Pre/Post moderate-intensity – test statistics

Epoch		t	Significance One-Sided p	Cohen's d
Pair 1	Pre-Epoch1 - Post-Epoch1	0.509	.31	0.136
Pair 2	Pre-Epoch2 - Post-Epoch2	0.685	.253	0.183
Pair 3	Pre-Epoch3 - Post-Epoch3	2.768	.008	0.74
Pair 4	Pre-Epoch4 - Post-Epoch4	5.327	<.001	1.424
Pair 5	Pre-Epoch5 - Post-Epoch5	1.882	.041	0.503
Pair 6	Pre-Epoch6 - Post-Epoch6	3.359	.003	0.898

C.5 Self-reported rating of mental effort

Table C.5.1. Self-reported rating of mental effort (scale 1 to 9) after high- and moderate-intensity – descriptive statistics

Section	Mean	(std. dev)
Post-HI early task	(6.3)	(2.0)
Post-HI mid task	(4.8)	(2.0)
Post-HI late task	(4.0)	(2.0)
Post-MI early task	(3.6)	(1.5)
Post-MI mid task	(3.3)	(1.5)
Post-MI late task	(3.4)	(1.6)
Post-HI overall task	(5.4)	(1.7)
Post-MI overall task	(3.4)	(1.4)

Table C.5.2. Self-reported rating of mental effort (scale 1 to 9) after high- and moderate-intensity by sections – effect of variables

Variable	F	Sig.	Partial Eta Squared	Observed Power[a]
section	14.519	<.001	0.528	0.997
intensity	31.178	<.001	0.706	0.999
Section*intensity	15.364	<.001	0.542	0.998

alpha = .05

Table C.5.3. Self-reported rating of mental effort (scale 1 to 9) after high- and moderate-intensity by sections – pairwise comparisons intensity by section

Intensity	Section	Mean Diff (earlier section – later section)	(std. error)	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
Post-HI	early - mid	1.5*	0.3	<.001	0.8	2.2
	early - late	2.3*	0.5	<.001	1.1	3.5
	mid - late	0.8*	0.3	.045	0.1	1.6
Post-MI	early - mid	0.3	0.2	.653	-0.3	0.9
	early - late	0.2	0.3	1	-0.7	1.1
	mid - early	-0.1	0.2	1	-0.7	0.6

* Mean diff significant at alpha = .05
b -> Bonferroni adjustment applied

Table C.5.4. Self-reported rating of mental effort (scale 1 to 9) after high- and moderate-intensity by sections – pairwise comparisons section by intensity

Section	Intensity	Mean Diff (Post-HI - Post-MI)	(std. error)	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
early task	HI - MI	2.7*	0.5	<.001	1.7	3.7
mid task	HI - MI	1.5*	0.3	<.001	0.8	2.2
late task	HI - MI	0.6*	0.3	.033	0.1	1.2

* Mean diff significant at alpha = .05
b -> Bonferroni adjustment applied

Table C.5.5. Overall Self-reported rating of mental effort (scale 1 to 9) after high- and moderate-intensity – descriptive statistics

Test		Mean	(std. dev)	(std. error)
Pair 1	Post-HI	5.4	(1.7)	(0.5)
	Post-MI	3.4	(1.4)	(0.4)

Table C.5.6. Overall Self-reported rating of mental effort (scale 1 to 9) after high- and moderate-intensity – paired differences

Epoch		Paired Differences				
		Mean diff	(std. dev)	(std. error)	95% CI of diff	
					Lower	Upper
Pair 1	Post-HI - Post-MI	2.1	(0.9)	(0.2)	1.5	2.6

D Test-retest reliability (resting condition)

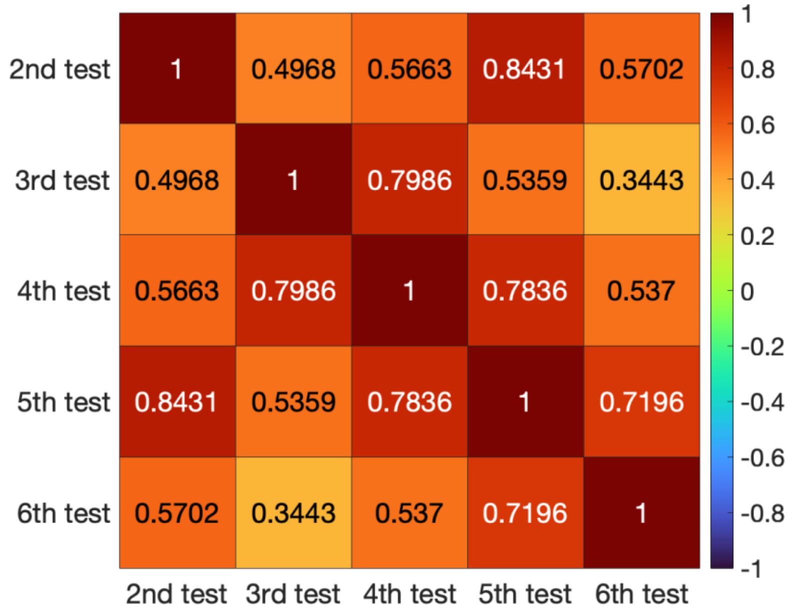

Figure D.1. Reliability of accuracy (at rest) congruent trials – Pearson's correlation matrix

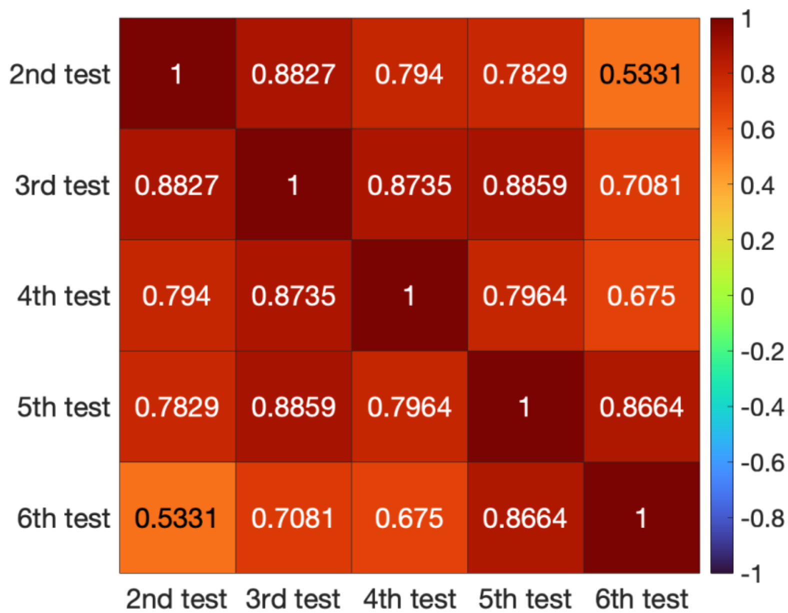

Figure D.2. Reliability of accuracy (at rest) incongruent trials – Pearson's correlation matrix

Figure D.3. Reliability of reaction time (at rest) congruent trials – Pearson's correlation matrix

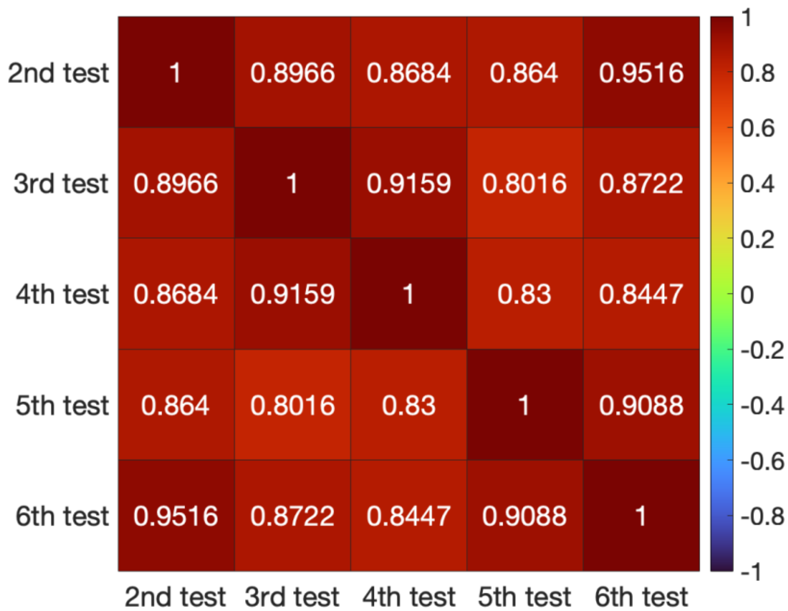

Figure D.4. Reliability of reaction time (at rest) incongruent trials – Pearson's correlation matrix