Inhibitory control during light, moderate and hard exercise intensity levels following mindfulness integrated exercise cognitive training

Noah D'Unienville[1,2], Sabrina Sghirripa[4], Alex Chatburn[3], Philip Temby[4], David Crone[4], Marissa Bond[5], Matthias Schlesewsky[3], Ina Bornkessel-Schlesewsky[3], Maarten A. Immink[1,3*]

[1]Flinders University; [2]University of Adelaide; [3]University of South Australia; [4]Department of Defence, Defence Science and Technology (DST) Group; [5]Lumination, Adelaide, Australia

[*]Correspondence
maarten.immink@flinders.edu.au
twitter: @docmaarten

Funding: This research was funded by the Defence Innovation Partnership Collaborative Research Fund, South Australian Government, and the Australian Department of Defence.

Acknowledgement: Through the project's industry partnership with Lumination, Mr Jake Mackinlay provided technical support for implementation of the cognitive task on a bicycle ergometer including stimulus presentation in augmented reality glasses and handlebar-mounted response keys.

Declarations: The authors declare no conflicts of interest and no financial gain associated with this research.

Preprint
This manuscript is a preprint. All authors reviewed and approved the final version of this manuscript.

Citation
d'Unienville, N., Sghirripa, S., Chatburn, A., Temby, P., Crone, D., Bond, M., Schlesewsky, M., Bornkessel-Schlesewsky, I. & Immink, M.A. (2023). Inhibitory control during light, moderate and hard exercise intensity levels following mindfulness integrated exercise cognitive training. *SportRxiv.*

ABSTRACT

Evidence suggests that inhibitory control during high intensity exercise is suppressed. Mindfulness and aerobic exercise forms of cognitive training have been shown to enhance inhibitory control and might serve to reduce loss of inhibitory control during high exercise intensity. However, it is unclear whether they may have synergistic effects for cognitive enhancement. Our aims were to investigate effects of exercise intensity on inhibitory control and to test if integrating mindfulness techniques into exercise training provided heightened enhancement of inhibitory control over exercise training alone. Fifty-five active, healthy young adults (30 females; 23 ± 4 years) completed a Go/NoGo task while simultaneously stationary cycling at light, moderate and hard intensities before and after completing multiple brief sessions of cognitive training based on mindfulness and exercise, or exercise alone. A third, control condition completed reading in place of exercise and mindfulness training. Go/NoGo task error rates, response latency and intraindividual variance in response latency did not differ significantly between exercise intensity conditions. Moreover, there was no significant effect of, or differences between, cognitive training conditions on Go/NoGo task performance. Inhibitory control during exercise is not influenced by exercise intensity, at least at the intensity levels induced in this experiment. Furthermore, exercise and mindfulness + exercise does not appear to lend benefits to inhibitory control in situations where inhibitory control during exercise is already high.

Introduction

Identifying effective approaches to augmenting human cognition continues to attract attention among scholars and the public. The basic premise, originally proposed over a century ago by Woodworth and Thorndike (1901), is that cognitive function is enhanced by undertaking activities that are cognitively demanding. One cognitive enhancement activity that has attracted a growing level of interest is exercise (Lambourne and Tomporowski, 2010; McMorris, 2016; Smith et al., 2010; Tomporowski, 2003). To understand the demands that exercise places on cognition, research has been dedicated to describing cognitive performance during exercise (Cantelon & Giles, 2021).

Exercise intensity has been found to be a critical factor for how exercise affects concurrent cognitive performance. Specifically, moderate exercise intensity levels are thought to enhance while low and high intensity levels suppress cognitive performance relative to resting conditions (Kamijo et al., 2004; McMorris & Graydon, 2000; Tomporowski, 2003). The second factor influencing exercise-cognition relationships is the cognitive domain under investigation. Cognitive tasks that predominantly rely on executive function are more sensitive to exercise intensity influences than lower-order cognitive tasks (Kamijo et al., 2007; Hillman, Snook & Jerome, 2003; McMorris & Graydon, 2000).

The Go/NoGo task is a popular paradigm for investigating inhibitory control dimensions of executive function (Simmonds, Pekar & Mostofsky, 2008). Smith et al. (2016) reported significantly higher Go/NoGo task error rates and longer reaction times during high treadmill running intensity as compared to moderate intensity and rest conditions. To our awareness, Smith at al. (2016) is the only study to investigate Go/NoGo task performance during exercise at varying exercise intensity levels. Other studies (Akatsuka, Mitsuzono & Yamashiro, 2023; Kamijo et al., 2004; Netz et al., 2016) have investigated acute effects of exercise intensity on Go/NoGo task performance where participants completed the task before and after a bout of exercise. In contrast to suppressed task performance during high intensity exercise reported by Smith et al. (2016), Akatsuka, Mitsuzono & Yamashiro (2023) and Kamijo et al. (2004) reported no acute effects of mild, moderate or high intensity exercise on subsequent Go/NoGo task errors or reaction time. Netz et al. (2016), however, reported increased accuracy and decreased reaction time in the Go/NoGo task immediately after moderate intensity exercise.

Since Smith et al. (2016) is the only study to investigate concurrent effects of exercise intensity on Go/NoGo task performance with findings that contrast with reported acute effects of exercise intensity on this task (Akatsuka, Mitsuzono & Yamashiro, 2023; Kamijo et al., 2004; Netz et al., 2016), our first research aim was to revisit the question of how Go/NoGo task performance is influenced by concurrent exercise at light, moderate and high intensity levels. In anticipation that high intensity exercise suppresses inhibitory control function, as reported by Smith et al. (2016), our second aim was to investigate if cognitive training, based on exercise and mindfulness techniques, could alleviate this loss of executive function under demanding exercise conditions.

Aerobic exercise as cognitive training

Aerobic exercise has been shown to contribute to cognitive enhancement (Ludyga et al., 2020; Wang, 2020). Exercise-induced cognitive enhancement has been described as arising from upregulation of neurotrophins, including brain-derived neurotrophic factor (BDNF; Vaynman et al., 2004), that contribute to neurogenesis and ultimately, neuroplastic improvements in cognitive function (Cassilhas et al., 2016). In addition to neurotrophic effects, aerobic exercise might enhance cognition on the basis that it represents a cognitively demanding task. Continuation of high intensity aerobic exercise has been proposed to influence neurocognitive processes that are generally relied upon by humans to maintain goal-oriented behavior (e.g., see Robertson & Marino, 2016). Evidence for this includes demonstration of poorer running performance following completion of a highly demanding cognitive task (Smith et al., 2015). Key neural networks that have been described as contributing to exercise regulation include areas such as the prefrontal cortex, the anterior and posterior cingulate cortices, insula, and the posterior parietal lobe (Bigliassi, 2021; Robertson & Marino, 2016). Exercise training has been shown to provide gains in inhibitory control (Sacco et al., 2016; Tsai, Wang, et al., 2014).

Mindfulness meditation as cognitive training

Mindfulness meditation techniques have been characterised as, “paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment” (Kabat-Zinn, 2003). This manner of attention establishes states of continuous and present awareness of both external and internal events and experiences (Brown et al., 2007; Malinowski, 2013). External experiences relate to sensory perceptions arising from the environment while internal experiences can include thoughts, imagery, and perceptions related to emotions, bodily sensations and physiological signals. The inclusion of body and physiological perception in mindfulness has led some to propose that mindfulness is closely linked to and shares overlapping neurocognitive processes with interoceptive awareness (e.g., see Gibson, 2019), which itself is described as moment-by-moment top-down perception and awareness of the physiological state of the body (Craig, 2009). Accordingly, mindfulness training has been shown to increase interoceptive awareness (Haase et al., 2015). Mindfulness training has also been shown to improve attention function (Chiesa et al., 2011; Jha et al., 2007; Malinowski, 2013; Tang et al., 2015; Tang & Posner, 2014). Of the different types of attention, top-down or executive types of attention control appear to especially benefit from mindfulness training (Chan et al., 2019; Gallant, 2016; Sumantry & Stewart, 2021). More specific to the present aim, mindfulness training has been shown to improve Go/NoGo task performance (Cheng et al., 2017; Pozuelos et al., 2019).

Potential for mindfulness meditation and aerobic exercise integrative cognitive training

Despite the apparent shared benefits of exercise training (Sacco et al., 2016; Tsai, Wang, et al., 2014) and mindfulness training (Chiesa et al., 2011; Malinowski, 2013) for executive function, there is little research aimed at investigating potential synergies from integrating these two cognitive training modalities. As an example of the little research in this area, Zwilling et al. (2019) conducted a trial that included a comparison of high intensity fitness training by itself with a multi-modal training approach that supplemented fitness training with cognitive task and mindfulness mediation modalities. While they reported further cognitive enhancement gains from the multi-modal training approach than that observed with unimodal fitness training, two limitations preclude any conclusion specific to consideration of integrating mindfulness meditation and aerobic exercise. First, the inclusion of cognitive training in the multi-modal approach makes it difficult to isolate what additional contribution to exercise was provided by mindfulness meditation in of itself. Second, in their multi-modal approach, exercise, cognitive task performance and mindfulness meditation were completed as discrete components of cognitive training. A more direct approach to understanding exercise-mindfulness synergies for cognitive training would involve simultaneous practice of mindfulness meditation and aerobic exercise tasks, as was used in clinical populations by Sacco et al. (2016), who demonstrated that cognitive enrichment of exercise provided further cognitive gains than exercise alone.

The present experiment

As stated above, the first aim of the present experiment was to investigate concurrent effects of mindfulness and exercise at differing intensities on Go/NoGo task performance as a correlate of inhibition control. Based on Smith et al. (2010), we predicted that task performance would be suppressed during hard exercise intensity relative to light and moderate intensities. Based on previous reports of enhanced cognitive function under moderate exercise intensity (Kamijo et al., 2004; McMorris & Graydon, 2000; Tomporowski, 2003), we predicted that Go/NoGo task performance would be higher under this level of exercise intensity relative to light and hard intensities.

The second aim was to compare cognitive enhancement effects of exercise training alone to an integrated cognitive training approach involving mindfulness and exercise. We predicted that relative to control conditions, both exercise and mindfulness + exercise training approaches would enhance Go/NoGo task performance during exercise, whether it be reducing task costs associated with hard exercise intensity or heightening task performance under moderated exercise intensity. If integrating mindfulness into exercise leads to a synergy of benefits, we expected to observe heightened task performance gains than exercise training alone.

Methods

Participants

Fifty-five apparently healthy adults (30 Females, Mean Age 23.2 ± 4 years, mean metabolic equivalent (MET) 2,661.3 ± 2,488.1 minutes/week) volunteered for participation. Participant inclusion criteria included being aged 18-45 years, right-hand dominant, having a body mass index equal to or between 18.5 and 30 kg/m^2, classified as moderately or highly active based on the International Physical Activity Questionnaire (IPAQ) – Short Form (Craig et al., 2003; Lee et al., 2011), and screened for readiness to participate in vigorous exercise based on the Australian Adult Pre-Exercise Screening System (APSS; Norton et al., 2012). Participants reported no history of tobacco or vaping use, no history of endocrine, metabolic, psychiatric, neurological, cognitive or language disorders, and normal to corrected-to-normal vision. Furthermore, participants had no prior formal experience with cognitive training involving exercise, meditation, brain stimulation, cognitive tasks or brain games. Because of reliance on communication in the English language (e.g., instructions for cognitive task, self-report measures, guided mindfulness), participants self-reported as proficient users of English language based on reference levels described by the Common European Framework of Reference for Languages Global Scale (Council of Europe, 2022).

The sample size was based on the research feasibility factors involving time for data collection and funding for research participation. The first thirty-nine participants were allocated to control, exercise or mindfulness + exercise cognitive training conditions through block random allocation based on participant declared gender. Block allocation by gender continued for the next 16 participants except these were allocated to only exercise or mindfulness + exercise cognitive training conditions with roughly twice as many allocated to the latter condition.

Ethics approval of the research protocol (protocol number: 5236) was obtained from Flinders University Human Research Ethics Committee prior to commencing participant recruitment and the study procedure. Participants were recruited via recruitment flyers and social media posts for a “brain, cognition and exercise research study”. The first seventeen participants who completed all sessions received an AUD$100 research honorarium. Due to slow progress in recruiting participants, the remaining thirty-nine participants received an AUD$200 research honorarium.

Self-report measures

Mindful Attention Awareness Scale (MAAS). Participant dispositional mindfulness was measured with the MAAS to control for potential confounding influences of mindfulness on cognitive task, exercise or mindfulness mediation performance or participation. The MAAS (Brown & Ryan, 2003) is a 15-item scale designed to assess dispositional mindfulness (Black et al., 2012; Brown et al., 2011; Carlson & Brown, 2005; Osman et al., 2016) and has demonstrated reliability with a Cronbach’s alpha of 0.82 (Brown & Ryan, 2003). Questions include items such as, "I find it difficult to stay focused on what’s happening in the present”, “I tend not to notice feelings of physical tension or discomfort until they really grab my attention”, “it seems I am “running on automatic,” without much awareness of what I’m doing.’

Pittsburgh Sleep Quality Index (PSQI). Sleep quality was measured as a potential participant characteristic that influences cognitive task, exercise or mindfulness mediation performance or participation. The PSQI (Buysse et al., 1989) is a self-report measure of background sleep quality over a 1-month time frame with a Cronbach’s alpha of 0.83. The PSQI has been demonstrated as a valid measure for sleep quality, correctly identifying 88.5% of good and poor sleepers and reporting in the original work (Buysse et al., 1989). The first part of the PSQI includes items related to sleep habits. For example, ‘During the past month, what time have you usually gone to bed at night?; During the past month, what time have you usually gotten up in the morning?’ The second part includes questions rated for sleep related difficulties, ‘During the past month, how often have you had trouble sleeping because you… Cannot get to sleep within 30 minutes… Wake up in the middle of the night or early morning,’ and overall sleep quality, ‘During the past month, how would you rate your sleep quality overall?’

Cued Go/NoGo task

Top-down selective attention and response inhibitory control processes at increasing levels of exercise intensity was assessed with a spatially Cued Go/NoGo task adapted from Hong et al. (2017). The task was conducted through OpenSesame (Mathôt et al., 2012) running on a Windows operating system. Stimulus output was displayed to the performer via head worn augmented reality (AR) glasses (Nreal Light, Nreal, Beijing, China) with 52° diagonal field of vision OLED display and a 60 Hz refresh rate. During stimulus display, the background remained translucent so that the participant can view the environment through the glasses. Left and right index finger responses were based on two customised response button boxes mounted on the cycle ergometer handlebar. Response buttons were mapped to keyboard input, which was read by OpenSesame.

The task stimulus display began with a central white fixation cross (about 1.38° x 1.38°) and two left and right location markers based on white hollow boxes (about 2.39° x 2.39°) located below and lateral to the fixation cross. Participants maintained central fixation throughout the task. At the start of each trial, a white arrowpoint spatial cue replaced the fixation cross for 200 ms. The participant was instructed to direct attention to the spatially cued location marker and ignore the opposite location marker. The spatial cue was then replaced with the fixation cross for a cue-target interval of 1,000 ms. Next, a white target “+” or “x” stimulus is presented within one location marker for 200 ms. If the “+” appeared in the attended location marker (AttendGo target), the participant pressed the key that spatially corresponds to the attended location marker. If the “x” appeared in the attended location marker (AttendNoGo target), the participant was not to press a key. For targets appearing in the ignored location marker, the participant did not press a key if a “+” (IgnoreGo target) or “x” (IgnoreNoGo target) was presented. After 200 ms, the target is replaced by the hollow location markers. Responses could be made immediately after target presentation but must have been made within 1500 ms following target presentation. Trials were spaced by a fixed 1500 ms inter-trial interval with the fixation cross and location markers displayed during this interval. See Figure 1 for example stimuli and timing of the Go/NoGo task.

The task involved eight experimental conditions based on two spatial cue conditions (left and right), two attend conditions (attend and ignore), and two go/nogo conditions (“+” and “x”). The eight experimental conditions were presented randomly with a 50% probability of spatial cue presentation and a 50% probability of go and nogo targets. The task was organised into a block of 72 trials with nine cycles of the task conditions presented in a randomized order. The duration of a block was about five minutes.

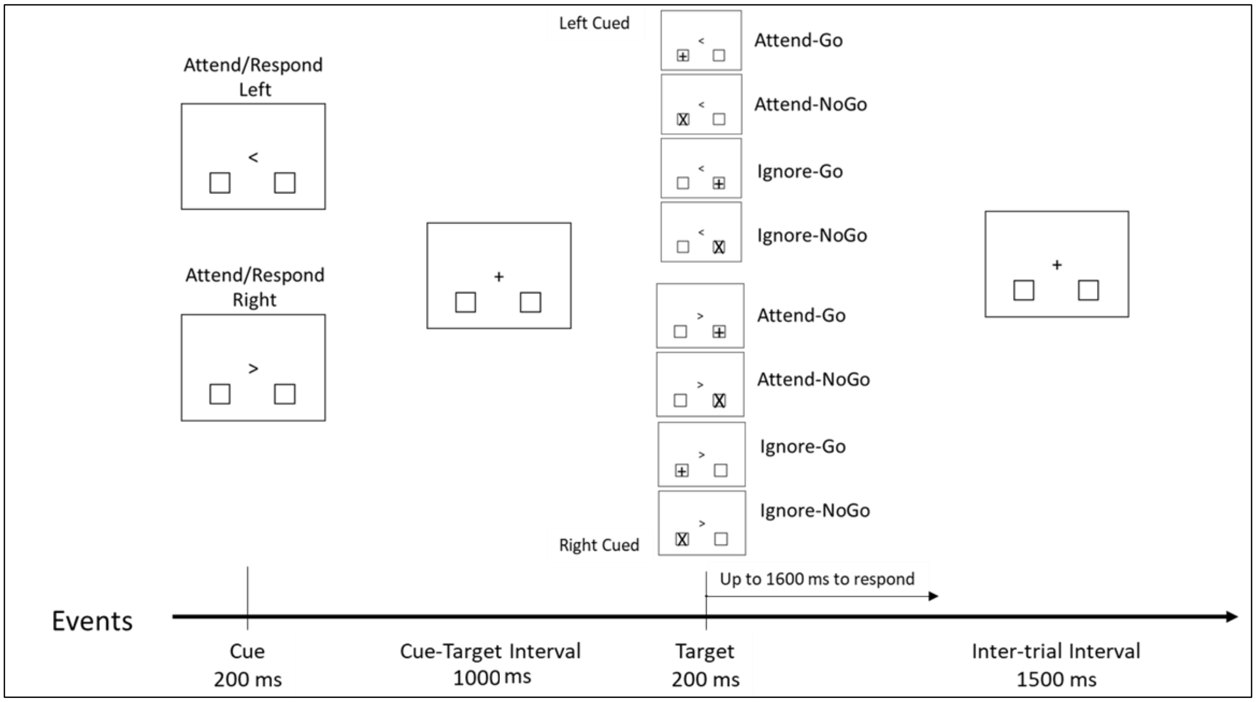

Figure 1. Cued Go/NoGo task trial event timing with cued and target conditions (Hong et al., 2017).

Graded exercise testing

Graded exercise testing (GXT) was conducted on an ergoselect 5 (ergoline GmbH, Bitz, Germany) upright electromagnetically braked cycle ergometer following standard testing protocols (Beltz et al., 2016; Fletcher et al., 2013). Prior to testing, participants completed a warm-up consisting of cycling at 25 W for 5 minutes. The GXT involved incremental power output increase at the rate of 25 W per 2-minute stages until volitional exhaustion while maintaining a pedal cadence between 50 and 80 rpm. Participants were able to view feedback indicating current pedal cadence but were not informed of target or current work output or interval duration. No verbal encouragement was provided. Volitional exhaustion was determined by the point at which the participant could not sustain the target power output while maintaining the target pedal cadence range or while remaining seated in the cycle saddle.

Rating of perceived exertion (RPE) was measured at warm-up and each increment of the GXT. RPE was collected based on Borg's $RPE_{6–20}$ Scale (Borg, 1982) in the final 45 seconds of each increment stage.

Cognitive training conditions

Exercise and mindfulness + exercise cognitive training conditions included individualized moderate and high exercise intensities determined by GXT. In moderately active adults, previous work has demonstrated cognitive enhancement from moderate and high (Dupuy et al., 2018; McMorris & Hale, 2015; Miller et al., 2019) exercise intensity levels, which correspond to the first (VT_1) and second (VT_2) ventilatory thresholds, respectively (McMorris & Hale, 2015). Moreover, on the Borg 6-20 RPE scale, VT_1 and VT_2 have been shown to correspond to RPE ranges of 12-13 (somewhat hard) and 15-16 (hard), respectively (Alberton et al., 2013). Basing exercise intensity on RPE is thought to be more reliable than heart rate since the former is more closely associated with an individual's maximal fitness capacity (Goss et al., 2011; Haile et al., 2015). In general, individuals choose to exercise at or just below VT_1 (Ekkekakis & Lind, 2006; Lind et al., 2005) and experience decreased pleasure and increased desire to cease exercise as intensities approach VT_2 (Ekkekakis et al., 2004; Hall et al., 2002). Thus, the inclusion of moderate and high ergometer workloads during intermittent exercise exposed participants to moderate and high levels of challenge to attention and inhibitory control processes associated with exercise self-regulation. In turn, that exposure was predicted to promote development of exercise-specific attention and inhibition control resulting in enhanced exercise tolerance at higher workload intensities and higher availability of attention and inhibition control resources for cognitive task performance during exercise.

An exercise training session commenced with a 5-minute pre-exercise seated rest period. Participants allocated to exercise cognitive training (ExCT) listened to a 5-minute audio recorded reading from the text *Your Mind and How to Use It* (Atkinson, 1911) while keeping their eyes closed. Audiobook listening has been previously used as an active control for mindfulness meditation to control for potential effects associated with listening to spoken information (Brown et al., 2021; Chan et al., 2020; Immink et al., 2017). In contrast, participants allocated to mindfulness + exercise cognitive training (MindExCT) completed an eyes closed 5-minute audio guided mindfulness meditation (Brown et al., 2021; Immink et al., 2017) involving the aim of establishing and monitoring interoceptive awareness of breathing. This meditation style, referred to as focused-attention meditation (FAM), is thought to increase top-down control, also referred to as cognitive control, during goal-oriented tasks (Chan et al., 2020; Lippelt et al., 2014).

Next, the participants in ExCT and MindExCT conditions mounted the cycle ergometer with the saddle set at their preferred height and then commenced a 5-minute warm-up period at a 25 W workload and pedal cadence between 50 and 80 rpm. Following the warm-up, participants completed two 5-minute cycles comprised of 1 and 2-minute intervals with individualised workloads set at RPE 12 – 13 (RPE_VT$_1$) and RPE 15 – 16 (RPE_VT$_2$) based on GXT. The order of interval duration and workload were pseudo-randomized to prevent anticipation. Within a cycle, a workload interval did not exceed 2-minute duration and across cycles, the sum of workloads was five minutes for each workload level. Participants were not informed of interval workload or duration or time remaining in an interval or cycle. Between the first and second cycle, and following the second cycle, participants pedalled at a slow cadence with no resistance on the ergometer. During intervals, the ExCT group participants received verbal reminders to maintain the pedal cadence within the target range. In contrast, participants in the MindExCT group received verbal reminders for pedal cadence maintenance and verbal cues to maintain interoceptive awareness of breathing in an open, receptive and non-judgemental manner. These verbal cues continued during slow pedalling following the first and second cycle. After completion of the second bout of slow pedalling, participants dismounted from the ergometer for an 8-minute seated post-exercise rest period with their eyes closed. Participants in the ExCT listened to the audiobook excerpt while those in the MindExCT completed an 8-minute FAM. See Figure 2 for example training session for each of the three cognitive training conditions.

To control for effects associated with repeated testing of the Cued Go/NoGO task during exercise, a control group attended the laboratory on four occasions over the 2-week cognitive training period for thirty minutes per session, a duration equivalent to ExCT and MindExCT sessions. Instead of intermittent exercise or mindfulness meditation, control group participants read general printed media (e.g., popular magazines).

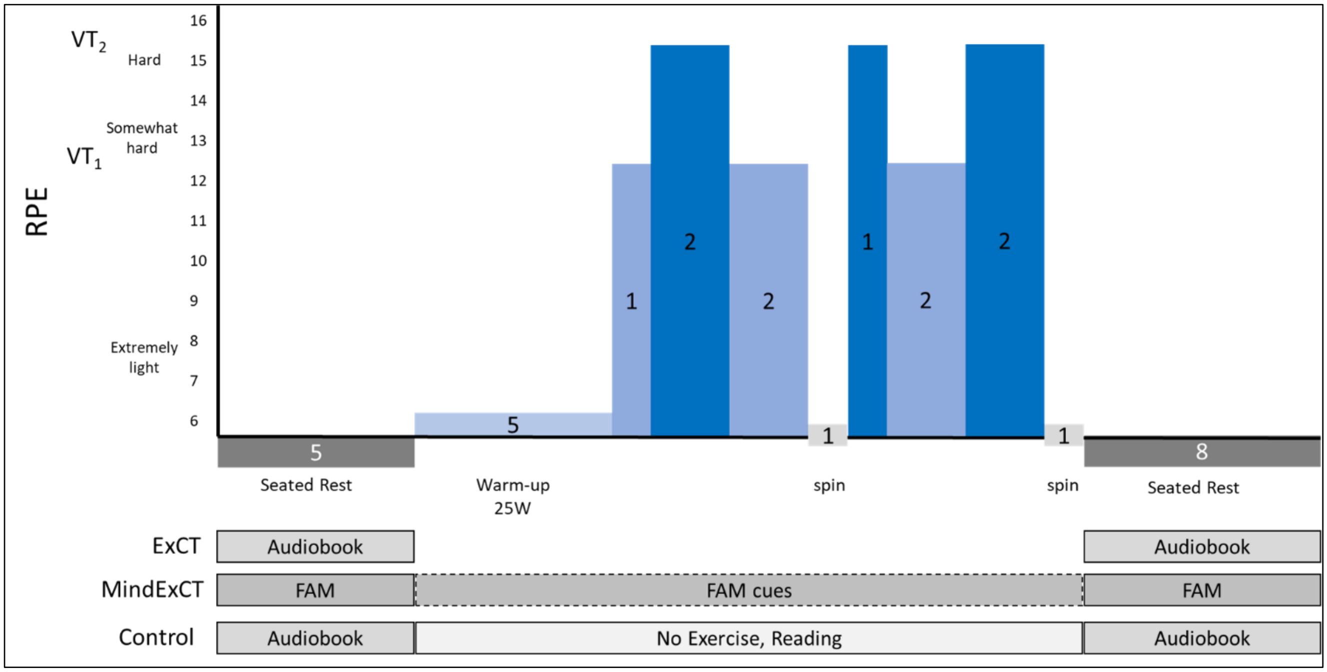

Figure 2. Cognitive training session for unimodal exercise (ExCT), integrative mindfulness exercise (MindExCT) and control groups.

Procedure

Prior to commencing testing sessions, participants completed an online survey where they provided written informed consent to participate in the experiment, and then completed the MAAS and PSQI self-report inventories. Participants then attended a university campus-based testing laboratory for seven sessions over about a 4-week period. During this period, participants were asked to not change their usual diet, sleep and physical activity behavior and were asked to minimise alcohol consumption and refrain from use of stimulant, depressant or psychoactive recreational substances. For each session, participants were requested to ensure they are well hydrated and to refrain from consumption of caffeine or food at least three hours prior to their session.

In the first GXT session participants were seated on the cycle ergometer and allowed to adjust the saddle to their preferred height. Instructions and familiarization with the Cued Go/NoGo task were then provided, including practice trials with response feedback using the AR glasses and handlebar mounted response buttons. Next, they were familiarized with using the RPE scale, including interpretation of the anchor points. They then completed the GXT protocol. After termination, the participant pedalled the ergometer slowly with no resistance for two minutes and then dismounted from the ergometer and completed a 6-minute rest while seated in a chair.

The second session involved a pre-cognitive training assessment of Cued Go/NoGo task performance at light, moderate and vigorous ergometer workloads. The participant mounted the ergometer with the seat set at their preferred height and completed a 5-minute warm-up pedalling 50-80 rpm at 25 W followed by three rounds of 7-minute ergometry under workloads that corresponded to their RPE of 7-8, 12-13 and 15-16 in the GXT protocol. Workload levels were randomized and each 7-minute workload bout was followed with a 5-minute recovery with slow pedalling and no resistance. In each workload bout, the participant first pedalled for 1.5 minutes to establish stable state at the workload intensity. They then simultaneously performed a block of the Cued Go/NoGo task for the next five minutes followed by RPE report in the final 30 seconds. After completion of the final recovery interval, the participant dismounted the ergometer.

About three to five days after completion of the second session, participants returned to the laboratory to complete the first of four cognitive training sessions over a 2-week period. A minimum of 48 hours duration intervened between sessions and no more than two sessions were completed within a 7-day period. In the fourth week, participants returned to the laboratory for completion of the post cognitive training assessment of Cued Go/NoGo task performance with EEG recording at rest, and light, moderate and vigorous individualised ergometer workloads.

Analysis

Participant characteristics. To inspect for any group differences in participant characteristics, participant age, body mass index, weekly metabolic equivalent minutes, and MAAS scores were separately submitted to one-way analysis of variance (ANOVA) with cognitive training group as the between-subject factor. Group differences in sex, exercise intensity testing order, an PSQI sleep quality category frequencies were inspected separately with chi-square analysis.

GXT workload and RPE. Group differences in ergometer workload and RPE from the GXT were analyzed based on one-way analysis of variance (ANOVA) with cognitive training group as the between-subject factor.

Cued Go/NoGo task performance. For each participant, testing session, and exercise intensity, an error proportion was measured based on the number of incorrect trials for the task block. Also, for each block, d prime was calculated based on the difference of z-normalized distribution of hit trials and false alarm trials (Swets et al., 1961). Hit trials were defined as when a response was accurately made to a go target presented in the attend spatial location. False alarms were defined as trials where a response was incorrectly made to stimuli presented in the ignore spatial location or a NoGo stimulus in the attend location. Higher d prime values index better ability to distinguish response stimuli from distractor stimuli. Based on accurate responses to Go stimuli in the attend location, response time mean and variance were calculated for each block. Proportion of errors, d prime, mean response time and response time variance were separately submitted to a 3 (Cognitive Training: Control, ExCT, MindCT) x 3 (Exercise Intensity: Light, Moderate, Hard) x 2 (Testing Session: Pre and Post) ANOVA with repeated measures on the latter two factors. Greenhouse-Geisser corrections were applied to violations of sphericity assumption. Post-hoc analyses with Bonferroni corrections were conducted for significant main effects of Cognitive Training or Exercise Intensity and any significant interactions. Estimates of effect size were calculated as partial η^2 for significant main effects or interactions. Statistical analyses were conducted in JASP (version 0.18.0, https://jasp-stats.org/).

Results

Participant characteristics

No significant group differences were found for sex (p = 0.99), participant age (p = 0.74), body mass index (p = 0.16), weekly physical activity (metabolic equivalent minutes, p = 0.48), dispositional mindfulness (MAAS, p = 0.39), sleep quality (p = 0.23) or exercise intensity testing order (p = 0.87). See Table 1 for sample characteristics by group allocation.

GXT workload, RPE and percent maximum heart rate

For Light, Moderate or Hard intensity levels, no significant group differences were observed for ergometer workloads (p = 0.74, 0.99, 0.90, respectively), RPE (p = 0.096, 0.84, 0.92, respectively) or percent predicted maximum heart rate (p = 0.23, 0.39, 069, respectively). See Table 2 for GXT workload, RPE and percent predicted maximum heart rate by group allocation and intensity level.

Table 1. Participant characteristics by cognitive training group.

Group	N	Females	Age (years)	Body Mass Index (kg/m^2)	Physical Activity MET minute/week	MAAS	PSQI sleep quality category
Control	13	7	22.7 (3.7)	22.0 (2.0)	3269.8 (3761.3)	3.3 (0.8)	Good: 10, Poor: 3
Exercise	18	10	23.8 (3.9)	23.8 (2.6)	2772.2 (1711.0)	2.9 (0.9)	Good: 9, Poor: 9
Mindfulness + Exercise	24	13	23.1 (4.3)	22.7 (2.9)	2698.5 (2142.7)	3.1 (0.8)	Good: 17, Poor: 7
	p	0.99	0.74	0.16	0.48	0.39	0.23

MAAS = Mindful Attention Awareness Scale (Brown & Ryan, 2003); PSQI = Pittsburgh Sleep Quality Index (Buysse et al., 1989). Age, Body Mass Index, Physical Activity MET and MAAS scores are presented as mean (standard deviation).

Table 2. Workload, ratings of perceived exertion, and predicted percent maximum heart rate from graded exercise testing.

		Work Output (Watts)			Rating of Perceived Exertion (Borg 6:20)		
		Exercise Intensity			Exercise Intensity		
Group	N	**Light**	**Moderate**	**Hard**	**Light**	**Moderate**	**Hard**
Control	13	25.0 (8.2)	83.1 (33.9)	121.2 (43.0)	7.9 (1.4)	12.3 (1.7)	15.6 (2.0)
Exercise	18	24.4 (6.8)	81.9 (28.0)	123.3 (32.2)	9.0 (1.8)	12.6 (1.7)	15.5 (1.5)
Mindfulness + Exercise	24	22.9 (10.3)	82.9 (20.5)	127.7 (50.0)	9.0 (1.3)	12.6 (1.9)	15.7 (15)
	p	0.74	0.99	0.9	0.096	0.84	0.92

Participant exercise work outputs were determined in a graded exercise test (GXT) cycle ergometer protocol. Light, Moderate and Hard intensities were based on work output where the participant reported a rating of perceived exertion (RPE) of 7-8, 12-13, and 15-16, respectively, on the Borg 6-20 scale. Work output and RPE values are presented as mean (standard deviation).

Go/NoGo task performance

No significant main effects or interactions were observed for analysis of the proportion of error responses. For all exercise intensity conditions and session, the mean proportion of errors was 0.0099 with a standard deviation of 0.015. There were no significant main effects or interactions for d’. The global mean of d’ was 6.5 with a standard deviation of 1.3. Analysis of mean response time revealed a significant main effect of Exercise Intensity, $F(2, 102) = 3.18$, $p = 0.046$, partial $\eta^2 = 0.056$. Despite this significant main effect, post-hoc tests did not indicate any significant differences in mean response time due to Exercise Intensity at the $p < .05$ level. Analysis of intraindividual response time variance revealed a significant main effect of Testing Session, $F(1, 51) = 5.43$, $p = 0.024$, partial $\eta^2 = 0.96$, and a significant Testing Sessions by Exercise Intensity interaction, $F(2, 102) = 4.17$, $p = 0.020$, partial $\eta^2 = 0.75$, see Figure 3. The source of the interaction was significantly lower response time variance in Session 2 (M = 7559.5, SD = 6355.4) than Session 1 (M = 13987.4, SD = 15318.8) for the Hard intensity level ($p = 0.006$). There were no other significant differences in response time variance including a Cognitive Training by Testing Session interaction (p = 0.50).

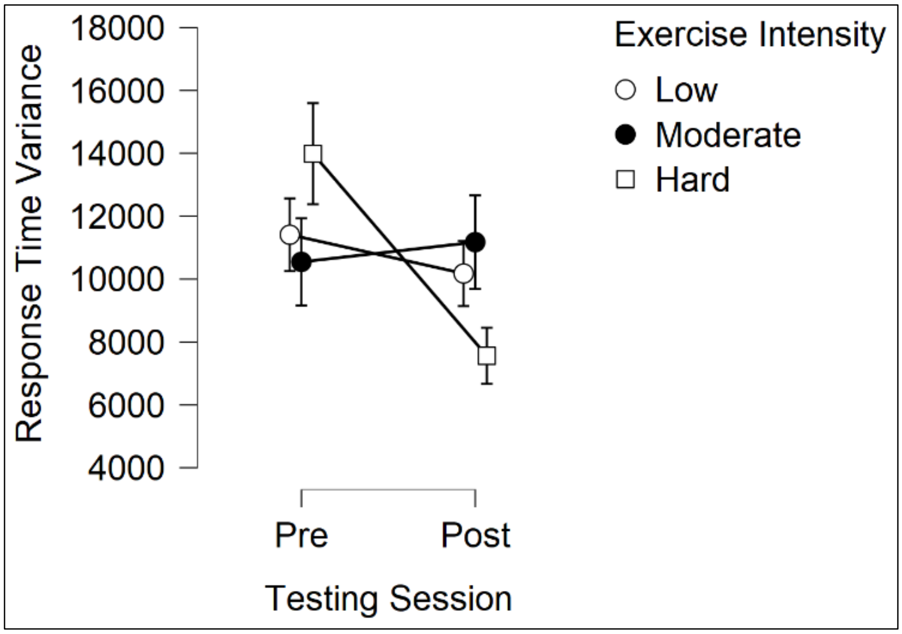

Figure 3. Intra-individual response time variance for "go" stimuli presented in the attend spatial location during the Cued Go/NoGo task completed under Light, Moderate and Hard exercise intensities. A significant Testing Session by Exercise Intensity interaction ($p = 0.20$) was based on significant reduction of response time variance for the Hard exercise intensity condition between Pre and Post-training time points. No significant Cognitive Training interaction with Testing Session was observed ($p = 0.50$).

Discussion

The first aim of the present work was to revisit findings reported in Smith et al. (2016), where hard but not moderate exercise intensity was shown to suppress concurrent Go/NoGo task performance. The present results are not consistent with Smith et al. (2016) as we did not observe significant effects of exercise intensity on task error rate, d', response time, or intraindividual response time variance. The absence of exercise intensity effects is more consistent with Kamijo et al. (2004) and Akatsuka, Mitsuzono and Yamashiro (2023) who reported no acute effects of exercise intensity on subsequent Go/NoGo task performance. That the present findings contrast with Smith et al. (2016) is in line with the mixed findings that have been reported with respect to acute and simultaneous effects of exercise on cognitive function (McMorris, 2016).

Methodological differences between the present experiment and Smith et al. (2016) could have contributed to contrasting findings. With respect to exercise intensity manipulation, Smith et al. (2016) reported RPE ranges of 15-17 and 18-19 for moderate and hard exercise intensities, respectively. At present, we based exercise intensity on self-reported RPE that corresponded with established definitions of light, moderate and hard (vigorous) exercise intensity (Norton et al., 2010). Of note, our moderate intensity condition corresponded to an RPE of 12.3-12.6 while the hard intensity condition corresponded to an RPE of 15.5-15.7. Thus, there is apparent discrepancy between the intensity levels that participants exercised at between the two studies. In the present study, hard exercise intensity corresponded to the moderate level of exercise intensity used by Smith et al. (2016) when comparing RPE. A second difference is the fact that in Smith et al. (2016), exercise was performed on a treadmill ergometer in contrast to the present use of a cycle ergometer. Maintain running gait coordination during exercise might place heightened demands on inhibitory control resources relative to seated cycling.

Our second aim was to compare exercise and mindfulness + exercise cognitive training approaches to enhancing inhibitory control during exercise. We did not observe any significant effects of the cognitive training modality on Go/NoGo task performance when comparing pre and post-training time points. The absence of task performance improvements from cognitive training might be ascribed to the high level of task performance in the pre-training time point and the potential that the exercise conditions did not sufficiently challenge inhibitory control. In summary, Go/NoGo task performance during exercise was sufficiently optimised in terms of error and response latency before training to the extent that it limited opportunity to improve performance with cognitive training. In comparison to response error and latency, significant reduction in intraindividual variance in response latency was observed between pre and post-training. Reduced variance appeared to be due to repeated exposure to the task under hard exercise intensities as opposed to any cognitive training effect since there was no significant interaction between cognitive training conditions and testing time points.

Conclusion

The present study suggests that in active, healthy young adults, performance in cognitive tasks integrating inhibitory control during exercise is not different between light, moderate or hard exercise intensity, and short-term training that combines mindfulness with aerobic exercise does not enhance performance in these tasks. Given the high level of task performance of the study participants, a more demanding cognitive and/or exercise task may be required to induce decrements in cognitive performance during exercise and ensure sufficient room for improvement following a training intervention.

References

Akatsuka, K., Mitsuzono, R., & Yamashiro, K. (2023). Effects of acute aerobic exercise on the motor inhibitory process in the go/no-go task in humans: a functional near-infrared spectroscopy study. *Neuroreport*, 34(4), 209–213. https://doi.org/10.1097/WNR.0000000000001876

Alberton, C. L., Antunes, A. H., Beilke, D. D., Pinto, S. S., Kanitz, A. C., Tartaruga, M. P., & Martins Kruel, L. F. (2013). Maximal and ventilatory thresholds of oxygen uptake and rating of perceived exertion responses to water aerobic exercises. *Journal of Strength and Conditioning Research*, *27*(7), 1897-1903. https://doi.org/10.1519/JSC.0b013e3182736e47

Atkinson, W. (1911). *Your Mind and How to Use it: A Manual of Practical Psychology* Library of Alexandria. https://archive.org/details/yourmindandhowt00atkigoog

Beltz, N. M., Gibson, A. L., Janot, J. M., Kravitz, L., Mermier, C. M., & Dalleck, L. C. (2016). Graded Exercise Testing Protocols for the Determination of VO(2)max: Historical Perspectives, Progress, and Future Considerations. *Journal of Sports Medicine*, *2016*, 3968393-3968393. https://doi.org/10.1155/2016/3968393

Bigliassi, M. (2021). Neural basis of attentional focus during endurance exercise. *International Review of Sport and Exercise Psychology*, *14*(1), 74-101. https://doi.org/10.1080/1750984X.2020.1762240

Black, D. S., Sussman, S., Johnson, C. A., & Milam, J. (2012). Psychometric Assessment of the Mindful Attention Awareness Scale (MAAS) Among Chinese Adolescents. *Assessment*, *19*(1), 42-52. https://doi.org/10.1177/1073191111415365

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sport and Exercise*, *14*(5), 377-381. https://www.ncbi.nlm.nih.gov/pubmed/7154893

Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. *Journal of Personality and Social Psychology*, *84*(4), 822-848. https://doi.org/10.1037/0022-3514.84.4.822

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research. *Psychiatry Research*, *28*(2), 193-213. https://doi.org/10.1016/0165-1781(89)90047-4

Cantelon, J. A., & Giles, G. E. (2021). A review of cognitive changes during acute aerobic exercise. *Frontiers in Psychology*, 12, 653158. https://doi.org/10.3389/fpsyg.2021.653158

Carlson, L. E., & Brown, K. W. (2005). Validation of the Mindful Attention Awareness Scale in a cancer population. *Journal of Psychosomatic Research*, *58*(1), 29-33. https://doi.org/10.1016/j.jpsychores.2004.04.366

Cassilhas, R. C., Tufik, S., & de Mello, M. T. (2016). Physical exercise, neuroplasticity, spatial learning and memory. *Cellular and Molecular Life Sciences*, *73*(5), 975-983. https://doi.org/10.1007/s00018-015-2102-0

Chan, J. S. Y., Deng, K., Wu, J., & Yan, J. H. (2019). Effects of Meditation and Mind–Body Exercises on Older Adults’ Cognitive Performance: A Meta-analysis. *The Gerontologist*, *59*(6), e782-e790. https://doi.org/10.1093/geront/gnz022

Chan, R. W., Alday, P. M., Zou-Williams, L., Lushington, K., Schlesewsky, M., Bornkessel-Schlesewsky, I., & Immink, M. A. (2020). Focused-attention meditation increases cognitive control during motor sequence performance: Evidence from the N2 cortical evoked potential. *Behavioural Brain Research*, *384*, 112536. https://doi.org/https://doi.org/10.1016/j.bbr.2020.112536

Cheng, K. S., Chang, Y. F., Han, R. P. S., & Lee, P. F. (2017). Enhanced conflict monitoring via a short-duration, video-assisted deep breathing in healthy young adults: an event-related potential approach through the Go/NoGo paradigm. *PeerJ*, *5*, e3857. https://doi.org/https://doi.org/10.7717/peerj.3857

Chiesa, A., Calati, R., & Serretti, A. (2011). Does mindfulness training improve cognitive abilities? A systematic review of neuropsychological findings. *Clinical Psychology Review*, *31*(3), 449-464. https://doi.org/https://doi.org/10.1016/j.cpr.2010.11.003

Craig, A. D. (2009). How do you feel--now? The anterior insula and human awareness. *Nature Reviews Neuroscience*, *10*(1), 59-70. https://doi.org/10.1038/nrn2555

Craig, C. L., Marshall, A. L., Sjostrom, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J. F., & Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity. *Medicine and Science in Sport and Exercise*, *35*(8), 1381-1395. https://doi.org/10.1249/01.MSS.0000078924.61453.FB

Council of Europe (2022). *Common European Framework of Reference for Languages (CEFR) Global Scale*. https://www.coe.int/en/web/common-european-framework-reference-languages/table-1-cefr-3.3-common-reference-levels-global-scale

Dupuy, O., Billaut, F., Raymond, F., Benraiss, A., Theurot, D., Bosquet, L., Fraser, S., & Tremblay, J. (2018). Effect of acute intermittent exercise on cognitive flexibility: the role of exercise intensity. *Journal of Cognitive Enhancement*, *2*(2), 146-156. https://doi.org/10.1007/s41465-018-0078-z

Ekkekakis, P., Hall, E. E., & Petruzzello, S. J. (2004). Practical markers of the transition from aerobic to anaerobic metabolism during exercise: rationale and a case for affect-based exercise prescription. *Preventive Medicine*, *38*(2), 149-159. https://doi.org/https://doi.org/10.1016/j.ypmed.2003.09.038

Ekkekakis, P., & Lind, E. (2006). Exercise does not feel the same when you are overweight: the impact of self-selected and imposed intensity on affect and exertion. *International Journal of Obesity*, *30*(4), 652-660. https://doi.org/10.1038/sj.ijo.0803052

Fletcher, G. F., Ades, P. A., Kligfield, P., Arena, R., Balady, G. J., Bittner, V. A., Coke, L. A., Fleg, J. L., Forman, D. E., Gerber, T. C., Gulati, M., Madan, K., Rhodes, J., Thompson, P. D., Williams, M. A., American Heart Association Exercise, C. R., Prevention Committee of the Council on Clinical Cardiology, C. o. N. P. A., Metabolism, C. o. C., Stroke, N., . . . Prevention. (2013). Exercise standards for testing and training: a scientific statement from the American Heart Association. *Circulation*, *128*(8), 873-934. https://doi.org/10.1161/CIR.0b013e31829b5b44

Gallant, S. N. (2016). Mindfulness meditation practice and executive functioning: Breaking down the benefit. *Consciousness and Cognition*, *40*, 116-130. https://doi.org/https://doi.org/10.1016/j.concog.2016.01.005

Gibson, J. (2019). Mindfulness, Interoception, and the Body: A Contemporary Perspective [Hypothesis and Theory]. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02012

Goss, F. L., Robertson, R. J., Gallagher, M., Jr., Piroli, A., & Nagle, E. F. (2011). Response normalized omni rating of perceived exertion at the ventilatory breakpoint in division I football players. *Perceptual and Motor Skills*, *112*(2), 539-548. https://doi.org/10.2466/05.25.Pms.112.2.539-548

Gramfort, A., Luessi, M., Larson, E., Engemann, D. A., Strohmeier, D., Brodbeck, C., Goj, R., Jas, M., Brooks, T., Parkkonen, L., & Hamalainen, M. (2013). MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience*, *7*, 267. https://doi.org/10.3389/fnins.2013.00267

Haase, L., May, A. C., Falahpour, M., Isakovic, S., Simmons, A. N., Hickman, S. D., Liu, T. T., & Paulus, M. P. (2015). A pilot study investigating changes in neural processing after mindfulness training in elite athletes [Original Research]. *Frontiers in Behavioral Neuroscience, 9*. https://doi.org/10.3389/fnbeh.2015.00229

Haile, L., Gallagher, M., & J. Robertson, R. (2015). Target RPE at the Ventilatory Threshold. In *Perceived Exertion Laboratory Manual: From Standard Practice to Contemporary Application* (pp. 75-87). Springer New York. https://doi.org/10.1007/978-1-4939-1917-8_7

Hall, E. E., Ekkekakis, P., & Petruzzello, S. J. (2002). The affective beneficence of vigorous exercise revisited. *British Journal of Health Psychology*, *7*(Pt 1), 47-66. https://doi.org/10.1348/135910702169358

Hillman C.H., Snook E.M., & Jerome G.J. (2003) Acute cardiovascular exercise and executive control function. *International Journal of Psychophysiology*, 48, 307-314. https://doi.org/10.1016/S0167-8760(03)00080-1

Hong, X., Wang, Y., Sun, J., Li, C., & Tong, S. (2017). Segregating Top-Down Selective Attention from Response Inhibition in a Spatial Cueing Go/NoGo Task: An ERP and Source Localization Study. *Scientific Reports, 7*(1), 9662. https://doi.org/10.1038/s41598-017-08807-z

Immink, M. A., Colzato, L. S., Stolte, M., & Hommel, B. (2017). Sequence Learning Enhancement Following Single-Session Meditation Is Dependent on Metacontrol Mode and Experienced Effort. *Journal of Cognitive Enhancement*, *1*(2), 127-140. https://doi.org/10.1007/s41465-017-0019-2

Jha, A. P., Krompinger, J., & Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. *Cognitive, Affective, & Behavioral Neuroscience, 7*(2), 109-119. https://doi.org/10.3758/CABN.7.2.109

Kabat-Zinn, J. (2003). Mindfulness-based interventions in context: past, present, and future. *Clinical Psychology: Science and Practice 10*, 144-156. https://psycnet.apa.org/doi/10.1093/clipsy.bpg016

Kamijo, K., Nishihira, Y., Hatta, A., Kaneda, T., Wasaka, T., Kida, T., & Kuroiwa, K. (2004). Differential influences of exercise intensity on information processing in the central nervous system. *European Journal of Applied Physiology*, *92*(3), 305-311. https://doi.org/10.1007/s00421-004-1097-2

Kamijo K., Nishihira Y., Higashiura T., Kuroiwa K. (2007) The interactive effect of exercise intensity and task difficulty on human cognitive processing. *International Journal of Psychophysiology*, 65, 114-121. https://doi.org/10.1016/j.ijpsycho.2007.04.001

Lambourne K. & Tomporowski P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, 1341: 12-24. https://doi.org/10.1016/j.brainres.2010.03.091

Lee, P. H., Macfarlane, D. J., Lam, T. H., & Stewart, S. M. (2011). Validity of the international physical activity questionnaire short form (IPAQ-SF): A systematic review. *International Journal of Behavioral Nutrition and Physical Activity*, *8*(1), 115. https://doi.org/10.1186/1479-5868-8-115

Lind, E., Joens-Matre, R. R., & Ekkekakis, P. (2005). What intensity of physical activity do previously sedentary middle-aged women select? Evidence of a coherent pattern from physiological, perceptual, and affective markers. *Preventive Medicine*, *40*(4), 407-419. https://doi.org/10.1016/j.ypmed.2004.07.006

Lippelt, D. P., Hommel, B., & Colzato, L. S. (2014). Focused attention, open monitoring and loving kindness meditation: effects on attention, conflict monitoring, and creativity – A review [Mini Review]. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.01083

Ludyga, S., Gerber, M., Pühse, U., Looser, V. N., & Kamijo, K. (2020). Systematic review and meta-analysis investigating moderators of long-term effects of exercise on cognition in healthy individuals. *Nature Human Behaviour*, *4*(6), 603-612. https://doi.org/10.1038/s41562-020-0851-8

Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation [Focused Review]. *Frontiers in Neuroscience*, *7*. https://doi.org/10.3389/fnins.2013.00008

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314-324. https://doi.org/10.3758/s13428-011-0168-7

McMorris, T. (2016). History of research into the acute exercise–cognition interaction: A cognitive psychology approach. In T. McMorris (Ed.), *Exercise-cognition interaction: Neuroscience perspectives* (pp. 1–28). Elsevier Academic Press. https://doi.org/10.1016/B978-0-12-800778-5.00001-3

McMorris, T., & Graydon, J. (2000). The effect of incremental exercise on cognitive performance. *International Journal of Sport Psychology*, 31(1), 66–81.

McMorris, T., & Hale, B. J. (2015). Is there an acute exercise-induced physiological/biochemical threshold which triggers increased speed of cognitive functioning? A meta-analytic investigation. *Journal of Sport and Health Science*, *4*(1), 4-13. https://doi.org/https://doi.org/10.1016/j.jshs.2014.08.003

Miller, M. G., Hanson, N., Tennyck, J., & Plantz, K. (2019). A Comparison of High-Intensity Interval Training (HIIT) Volumes on Cognitive Performance. *Journal of Cognitive Enhancement*, *3*(2), 168-173. https://doi.org/10.1007/s41465-018-0107-y

Netz, Y., Abu-Rukun, M., Tsuk, S., Dwolatzky, T., Carasso, R., Levin, O., & Dunsky, A. (2016). Acute aerobic activity enhances response inhibition for less than 30min. *Brain and Cognition*, 109, 59–65. https://doi.org/10.1016/j.bandc.2016.08.002

Norton, K., Norton, L., & Sadgrove, D. (2010). Position statement on physical activity and exercise intensity terminology. *Journal of Science and Medicine in Sport*, *13*(5), 496–502. https://doi.org/10.1016/j.jsams.2009.09.008

Norton, K., Coombes, J., Hobson-Powell, A., Johnson, R., Knox, C., Marino, N., & Piper, K. (2012). *Adult pre-exercise screening system (APSS)*. Exercise and Sports Science Australia.

Osman, A., Lamis, D. A., Bagge, C. L., Freedenthal, S., & Barnes, S. M. (2016). The Mindful Attention Awareness Scale: Further Examination of Dimensionality, Reliability, and Concurrent Validity Estimates. *Journal of Personality Assessment*, *98*(2), 189-199. https://doi.org/10.1080/00223891.2015.1095761

Pozuelos, J. P., Mead, B. R., Rueda, M. R., & Malinowski, P. (2019). Short-term mindful breath awareness training improves inhibitory control and response monitoring. *Progress in Brain Research*, *244*, 137-163. https://doi.org/https://doi.org/10.1016/bs.pbr.2018.10.019

Robertson, C. V., & Marino, F. E. (2016). A role for the prefrontal cortex in exercise tolerance and termination. *Journal of Applied Physiology*, *120*(4), 464-466. https://doi.org/10.1152/japplphysiol.00363.2015

Sacco, G., Caillaud, C., Ben Sadoun, G., Robert, P., David, R., & Brisswalter, J. (2016). Exercise Plus Cognitive Performance Over and Above Exercise Alone in Subjects with Mild Cognitive Impairment. *Journal of Alzheimer's Disease*, *50*, 19-25. https://doi.org/10.3233/JAD-150194

Simmonds, D. J., Pekar, J. J. & Mostofsky, S. H. (2008). Meta-analysis of Go/No-go tasks demonstrating that fMRI activation associated with response inhibition is task-dependent. *Neuropsychologia*, 46, 224–232. . https://doi.org/10.1016/j.neuropsychologia.2007.07.015

Smith, M., Tallis, J., Miller, A., Clarke, N. D., Guimarães-Ferreira, L., & Duncan, M. J. (2016). The effect of exercise intensity on cognitive performance during short duration treadmill running. *Journal of Human Kinetics*, *51*, 27–35. https://doi.org/10.1515/hukin-2015-0167

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental fatigue impairs intermittent running performance. *Medicine and Science in Sport and Exercise*, *47*(8), 1682-1690. https://doi.org/10.1249/mss.0000000000000592

Smith, P. J., Blumenthal, J. A., Hoffman, B. M., Cooper, H., Strauman, T. A., Welsh-Bohmer, K., Browndyke, J. N., & Sherwood, A. (2010). Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. *Psychosomatic Medicine*, *72*(3), 239-252. https://doi.org/10.1097/PSY.0b013e3181d14633

Swets, J., Tanner, W. P. J., & Birdsall, T. G. (1961). Decision processes in perception. *Psychological Review*, 68, 301–340.

Sumantry, D., & Stewart, K. E. (2021). Meditation, Mindfulness, and Attention: a Meta-analysis. *Mindfulness*, *12*(6), 1332-1349. https://doi.org/10.1007/s12671-021-01593-w

Tang, Y.-Y., Hölzel, B. K., & Posner, M. I. (2015). The neuroscience of mindfulness meditation. *Nature Reviews Neuroscience*, *16*(4), 213-225. https://doi.org/10.1038/nrn3916

Tang, Y. Y., & Posner, M. I. (2014). Mindfulness in the context of the attention system. In K. W. Brown, J. D. Creswell, & R. M. Ryan (Eds.), *Handbook of Mindfulness: Theory, Research, and Practice* (pp. 81-89). Guildford Press.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica*, 112(3), 297-324. https://doi.org/10.1016/S0001-6918(02)00134-8

Tsai, C.-L., Chen, F.-C., Pan, C.-Y., Wang, C.-H., Huang, T.-H., & Chen, T.-C. (2014). Impact of acute aerobic exercise and cardiorespiratory fitness on visuospatial attention performance and serum BDNF levels. *Psychoneuroendocrinology*, *41*, 121-131. https://doi.org/https://doi.org/10.1016/j.psyneuen.2013.12.014

Tsai, C.-L., Wang, C.-H., Pan, C.-Y., Chen, F.-C., Huang, T.-H., & Chou, F.-Y. (2014). Executive function and endocrinological responses to acute resistance exercise [Original Research]. *Frontiers in Behavioral Neuroscience*, *8*. https://doi.org/10.3389/fnbeh.2014.00262

Vaynman, S., Ying, Z., & Gomez-Pinilla, F. (2004). Hippocampal BDNF mediates the efficacy of exercise on synaptic plasticity and cognition. *European Journal of Neuroscience*, *20*(10), 2580-2590. https://doi.org/10.1111/j.1460-9568.2004.03720.x

Wang, C.-H. (2020). The cognitive gains of exercise. *Nature Human Behaviour*, *4*(6), 565-566. https://doi.org/10.1038/s41562-020-0856-3

Woodworth, R. S., & Thorndike, E. (1901). The influence of improvement in one mental function upon the efficiency of other functions. (I). *Psychological Review*, *8*(3), 247-261.

Zwilling, C. E., Daugherty, A. M., Hillman, C. H., Kramer, A. F., Cohen, N. J., & Barbey, A. K. (2019). Enhanced decision-making through multimodal training. *npj Science of Learning*, *4*(1), 11. https://doi.org/10.1038/s41539-019-0049-x