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Brief, High-Intensity Interval Exercise Improves Selective Attention in University Students

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ABSTRACT

International Journal of Exercise Science 11(5): 152-167, 2018. This study aimed to investigate the effect of very brief, high-intensity interval exercise (HIIE) on selective attention in university students. As a follow-up, we investigated whether HIIE performed prior to a university lecture improves retention of lecture material. A single-group counterbalanced post-test only design was used for this study. 22 university students (19 females; age = 20.0 ±1.0 years) performed a HIIE and control visit on separate days. During the HIIE session, participants performed 4 separate body-weight exercises for 1 set each, consisting of eight 20 s intervals interspersed with 10 s rest, totaling 11 minutes in duration, including rest. 10 minutes following exercise cessation, participants completed the d2 test of attention. The control visit consisted of quiet reading followed by completion of the d2. Selective attention, as assessed by the d2 test of attention was significantly greater following a bout of HIIE compared to the control condition. Effect size analysis revealed a moderate effect in favour of HIIE compared to control (d = 0.459 [0.171, 0.747]). Study #2: 23 university students (17 females; age = 19.0 ±0.5 years) performed HIIE and a rest condition prior to attending an exercise physiology lecture on separate days. A quiz was administered 24-hours post-lecture to assess lecture retention. Quiz performance was not different between HIIE and control conditions (p = 0.18). HIIE is a time-effective exercise stimulus that improves selective attention. However, performing HIIE prior to a university lecture did not impact retention of lecture material.

KEY WORDS: Lecture retention, cognitive function, d2 test of attention, acute exercise, physical activity

INTRODUCTION

A physically active lifestyle confers numerous benefits on an individual across the lifespan including positive effects on brain health (16). Compared to other cognitive domains, top-down mental processes that govern decision-making, mental flexibility, self-discipline and other higher-ordered mental functions (10) show robust improvements following a period of exercise training (37). These processes, which collectively are categorized under the umbrella of executive functions, are similarly sensitive to acute exercise as a single bout of aerobic exercise potentiates executive functions during and up to an hour following the cessation of exercise (8, 12). Specifically, a recent meta-analysis found an effect size of d = 0.55 for improvements in executive functions following acute exercise in young adults (42).

Although not all areas of executive functions demonstrate equal benefit following a bout of exercise (8), measures of attention, a core executive function integral for higher-ordered cognitive processes including decision-making and learning (10), consistently improve following acute aerobic exercise (8), an effect that appears to result from potentiation of attentional networks (7, 25, 30). While the direct involvement of attention on learning has not been measured following a bout of exercise, attention is considered to be a “mechanism for active learning” (15) with evidence from other experimental paradigms highlight its importance on various indices of learning (15, 40). For example, in young adults a bout of running exercise improves learning new vocabulary by 20% compared to resting conditions (45), and a bout of cycling exercise facilitates greater retention of a newly learned motor task (36). Similarly, a single session of treadmill running significantly improves neuroelectric indices of attention in school-aged children with and without attention-deficit/hyperactivity disorder (ADHD) (31). Importantly, an increase in attentional resources following exercise was coupled with significant improvements in reading and arithmetic scores, suggesting that these domain-specific enhancements translate to improvements in academic performance (31). Together these findings suggest that a single bout of exercise could be strategically used to augment attentional resources and learning in an academic environment, such as a university lecture. Interestingly, the immediate benefits of acute exercise on cognition appear to be durable across the adulthood, suggesting that exercise can be used as a strategy for improving cognitive function before a cognitively engaging activity regardless of age (8, 17).

Lectures are the primary conduit for knowledge dissemination for university courses and represents a critical period during which students need to be cognitively engaged; however, students report waning attention and general distractibility during lecture (29) that is associated with impaired recall of lecture material (33). Given that a single bout of exercise increases attention and improves learning (45), it would seem wise to perform exercise prior to a university lecture. However, whether the facilitation of attention evoked by a bout of exercise has the same translational impact on retention of lecture material in university students is currently unknown. Further, while exercise has the potential to improve retention of lecture material, university students commonly cite lack of time and access to facilities as barriers to performing exercise (9), barriers that would be especially important to consider when prescribing exercise immediately prior to lecture.

Whole body, high-intensity interval exercise (HIIE) represents an accessible mode of exercise that is time effective and, when performed in the absence of traditional exercise equipment, eliminates the access to facilities barrier (26). While there is a wealth of evidence to support the benefits of continuous aerobic exercise on executive functions in young adults, only a handful of studies have examined how executive functions are impacted by HIIE. Recently, a single bout of HIIE was shown to improve neuroelectric indices of inhibitory control and attention (P300) in young adults (18), suggesting that a brief, intense dose of exercise is an effective stimulus for increasing cognitive function (18). In support of this, Alves et al., (1) found that a bout of 10 x 1 min HIIE corresponding with 80% heart rate reserve (HRR) significantly improved Stroop test and Digit Span test performance in middle aged adults. Consistent with these findings, Tsukamoto et al., (41) demonstrated that 4 x 4 min HIIE at 90% VO_{2peak} significantly improved Stroop test performance in young adults. Together, these findings support the use of HIIE as a strategic tool for augmenting cognitive function prior to a cognitively engaging activity, such as a university lecture. While the translational impact of improved cognitive function via HIIE on scholarly performance in university students is not known, four minutes of HIIE improves selective attention (23) and positively impacts classroom behaviour (22) in primary school-aged children. Currently, the ability of HIIE to acutely improve selective attention has yet to be confirmed in university-aged students, and the impact of HIIE on retention of lecture material in this population is currently unknown.

Therefore, the purpose of this study was to examine the effect of a single bout of HIIE on selective attention in university students, using the d2 test of attention. Further, as a first step towards stimulating translational research in a real-world setting, we measured the effect of a bout of HIIE on retention of lecture material 24-hours after an exercise physiology lecture.

METHODS

Participants

Study 1: Healthy undergraduate students volunteered for this study (n =22, 19 females; age = 20.0 ±1.0 years; BMI = 22.7 ±2.5 kg/m^2). Height and weight measurements were performed by a researcher during the first visit. Inclusion criteria for this study were participants free of any contraindications to performing intense whole-body exercise (i.e. no pre-existing musculoskeletal injury and/or medical conditions). Participants were excluded from this study if they self-reported having been diagnosed with ADHD or major depression. All participants read and signed a consent form, which explicitly detailed all of the experimental procedures and the associated risks. Recruitment for this study was performed via advertisements that were posted throughout Queen's University. Study procedures were in accordance with the Declaration of Helsinki and were approved by the Health Sciences Human Research Ethics Board at Queen's University.

Protocol

The present study used a single-group counterbalanced crossover design to control for order effects of repeated psychometric testing. The study took place over two separate visits where d2 test of attention performance was assessed following a period of rest (Control visit) and following a bout of HIIE (Exercise visit). Participants were randomly assigned to a group, such that half of the participants performed the Control visit for their first session and half performed the Exercise visit. After 1 week, participants subsequently performed the opposite protocol at the same time of day, after observing the same pre-experimental instructions. Participants were instructed to abstain from alcohol and exercise for 24 hours, and caffeine for

12 hours prior to each experimental visit. Otherwise, participants were instructed to maintain their regular activities between visits. d2 testing was performed in a 2:1 participant to examiner ratio.

Exercise Visit: Participants arrived at the lab at 09:00 h and were instrumented with a heart rate monitor in order to record heart rate responses to HIIE. The novel HIIE protocol used for this study was a modified Tabata design (38), consisting of 4 different whole-body exercises: 1) burpees, 2) jumping jacks, 3) mountain climbers, and 4) squat jumps performed for 4 sets (1 set per exercise) with a 1-minute rest period between exercises. Each HIIE set was comprised of four 20-second intervals and each interval was separated by 10 seconds of rest (Figure 1A).

The HIIE protocol took 11 minutes to complete with a total exercise time of 5.5 minutes. Participants were instructed to perform each exercise as fast as possible for each 20 second interval, while maintaining proper movement technique. Researchers provided continual motivation and feedback to participants throughout exercise sessions. Upon completion of the HIIE protocol, participants were given a 10-minute recovery period prior to administration of the d2 test. Heart rate was recorded at rest prior to commencement of HIIE, during the 1-minute rest period at the end of each HIIE set, and immediately before and after performance of the d2. All HIIE was performed in a group setting (maximum 4 participants).

Control Visit: For the Control visit, participants arrived to the lab at 09:00 h and were instrumented with a heart rate monitor. During this time, participants sat quietly and were instructed to read material of their choosing from a selection of exercise physiology textbooks or other school-related readings for 11 minutes followed by a 10 minute 'recovery period' prior to commencing the d2 test, in order to account for the elapsed time in the Exercise visit. Heart rate was recorded at the same time points as the Exercise visit.

d2 Test of Attention: The d2 test is an internally consistent and valid measure of attention, visual scanning accuracy, and visual scanning speed (3). The d2 is a timed pen and paper test wherein participants rapidly scan similarly presented visual stimuli and are tasked with cancelling out target stimuli, which are "d" with a total of two dashes placed above and/or below it, while ignoring non-target/distractor stimuli (i.e. "p" or "d" with varied dash placement and numbers). The test is comprised of 14 lines, each containing 47 stimuli (658 total stimuli). Participants are given 20 s to complete each line before being instructed to move on to the next line, for a total test time of 4 min and 40 s. Test score categories include: total number of characters processed (TN; sum of total characters processed), errors of omission (O; number of target stimuli not cancelled), errors of commission (C; number of non-target stimuli cancelled), percentage of errors (E%; proportion of both errors of omission and commission made within total attended stimuli), total number of items processed minus error scored (TN-E), and concentration performance (CP; number of correctly crossed out target stimuli minus errors of commission) (4). These outcomes provide a measure of scanning speed and accuracy, wherein TN represents a measure of scanning or processing speed (i.e., total number of items processed) and E% provides an indication of scanning accuracy as it accounts for the change in error rate with a change in number of items processed (3, 4). Prior to the first administration of the d2, participants were read standardized instructions by the same researcher and performed a practice session of the test using the designated practice space on the first page of the d2 test. The d2 test administrator was different from the protocol administrator; however, the d2 test administrator was not blinded given that participants did not change into non-athletic clothing before commencement of the d2 test.

Statistical Analysis
A paired t-test with a Bonferroni correction for multiple t-tests was used to compare d2 performance between Control and Exercise visits. In order to provide an indication of the magnitude of effect for the intervention, an effect size analysis was completed for each d2 parameter and for the d2 test as a whole. Effect size was calculated by separately converting each d2 parameter into a Z-score using the following equation: $Z = X - \overline{x} / SD$; where the Control condition mean and standard deviation are $\overline{x}$ and SD, respectively, and individual data from the Control and Exercise conditions are X. Using this approach, an effect size can be calculated for each d2 parameter and each parameter can be summed to calculate an overall effect size for the intervention. Prior to standardization of the data, each d2 parameter passed a test for normality using the Shapiro-Wilk test. Effect sizes were calculated on the standardized data in accordance with the methods detailed by Fritz, Morris, and Richler (14) with confidence intervals (CI) set at 95%. Heart rate data at time points Baseline, Post-Exercise, Pre-D2, and Post-D2 were analyzed for TIME x CONDITION using a 2-way RM ANOVA, with α set at 0.05. Sample size for Study #1 was calculated using a two-tailed paired *t*-test with α set at 0.05 and desired power of 0.90 using G*Power 3.1 statistical software (13). Using values from the 'active participant' subset reported by Budde et al. (5) with a desired minimum improvement in TN of 5%, we determined the required sample size for this study was $n = 21$.

METHODS: STUDY 2

Participants
Undergraduate students enrolled in a second-year exercise physiology class were recruited for this study (n =23, 17 females; age = 19.0 ±0.5 years; BMI = 22.8 ±3.0 kg/m^2). The inclusion criteria for Study #2 was the same as Study #1. All participants read and signed a consent form, which explicitly detailed all of the experimental procedures and the associated risks. Study procedures were approved by the Health Sciences Human Research Ethics Board at Queen's University.

Protocol
The present study used a single-group counterbalanced crossover design to control for order effects related to repeated test administration. Participants were randomly assigned to either the Control or Exercise condition for their first visit and subsequently would perform the other condition for their second visit. Participants were instructed to abstain from alcohol and exercise for 24 hours prior to each experimental visit and until completion of the quiz. The rationale for a 24-hour delay was based on the work by Schmidt-Kassow (35), who found that an single bout of exercise improved the recall of vocabulary learning when assessed 24 hours

later. The study took place over a two-week period, wherein participants performed either the Exercise or Control condition 20 minutes prior to commencement of a second-year undergraduate exercise physiology lecture that was 80 minutes in duration, held in the School of Kinesiology and Health Studies at Queen's University, Kingston, Canada. Participants attended their exercise physiology lecture on predetermined days and were instructed to refrain from reviewing material from lecture until completion of their quiz. For the Control condition, participants arrived at the lecture hall 20 minutes prior to the beginning of class and were instructed to remain seated and read class material of their choosing in a similar manner to the control condition in Study #1. For the Exercise condition, participants arrived at the lab 20 minutes prior to lecture and performed a bout of the HIIE described in Study #1 as a group. Following the HIIE bout, participants went straight to lecture. 24 hours following lecture, participants individually took a 10-question multiple choice quiz pertaining to the previous day's lecture material in a group setting in a quiet room, analogous to a university exam setting.

The Quiz: An experienced exercise physiology professor created two 10-question multiple choice quizzes, one for each lecture, pertaining to the respective lecture topics, which were blood glucose regulation and exercise metabolism. Retention of lecture material, as indicated by an individual's quiz mark, was the primary outcome of this study.

Statistical Analysis
A paired t-test was used to compare Control and Exercise condition mean quiz performance, with α set at 0.05. Sample size for Study #2 was calculated using a two-tailed paired *t*-test with α set at 0.05 and desired power of 0.90 using G*Power 3.1 statistical software (13). Given that the unique design of study, we consulted previous work by Saville et al. (34) and Risko et al. (33) as analogs for assessing lecture retention via quiz performance. Using these data, we calculated the required sample size for this study as n = 22 given a desired minimum improvement on quiz score of 12%.

RESULTS

Effect of HIIE on d2 Performance: Effect size analysis revealed that d2 performance was more favorably impacted by HIIE compared to Control (Figure 2). Specifically, we observed a moderate effect size of d = 0.459 [0.171, 0.747] in favour of HIIE for overall d2 performance. Furthermore, the total number of items processed was significantly greater following HIIE compared to Control (251.2 ±32.5 vs.232.6 ±33.8, p = 0.01, d = 0.560 [0.277, 0.843]) (Table 1).

Heart Rate Response to Exercise vs. Rest Due to unforeseen technical issues with the heart rate monitors, we report heart rate data from 10 participants. As expected, heart rate was significantly higher following a bout of HIIE compared to following quiet reading (Control condition; 182.1 ±15.1 bpm vs. 73.6 ±11.2 bpm, p < 0.001), Figure 1.B**.** Further, heart rate remained significantly higher immediately before (110.2 ±18.8 bpm vs. 76.1 ±12.0, p < 0.001) and after (110.6 ±16.5 bpm vs. 78.3 ±11.1 bpm, p < 0.001) performance of the d2 test following a bout of HIIE compared to Control, which corresponds with 73% recovery to resting HR levels following HIIE. To further characterize the intensity of the HIIE protocol, we estimated the percentage of maximum work rate (% WR_{max}) achieved using the post-HIIE HR expressed as a percentage of maximal HR (% HR_{max}) in accordance with Arts and Kuipers (2). From this, the average % WR_{max} achieved by the end of HIIE was 91.6 ±13.3%, which corresponded with a 93.9 ±7.6% HR_{max}.

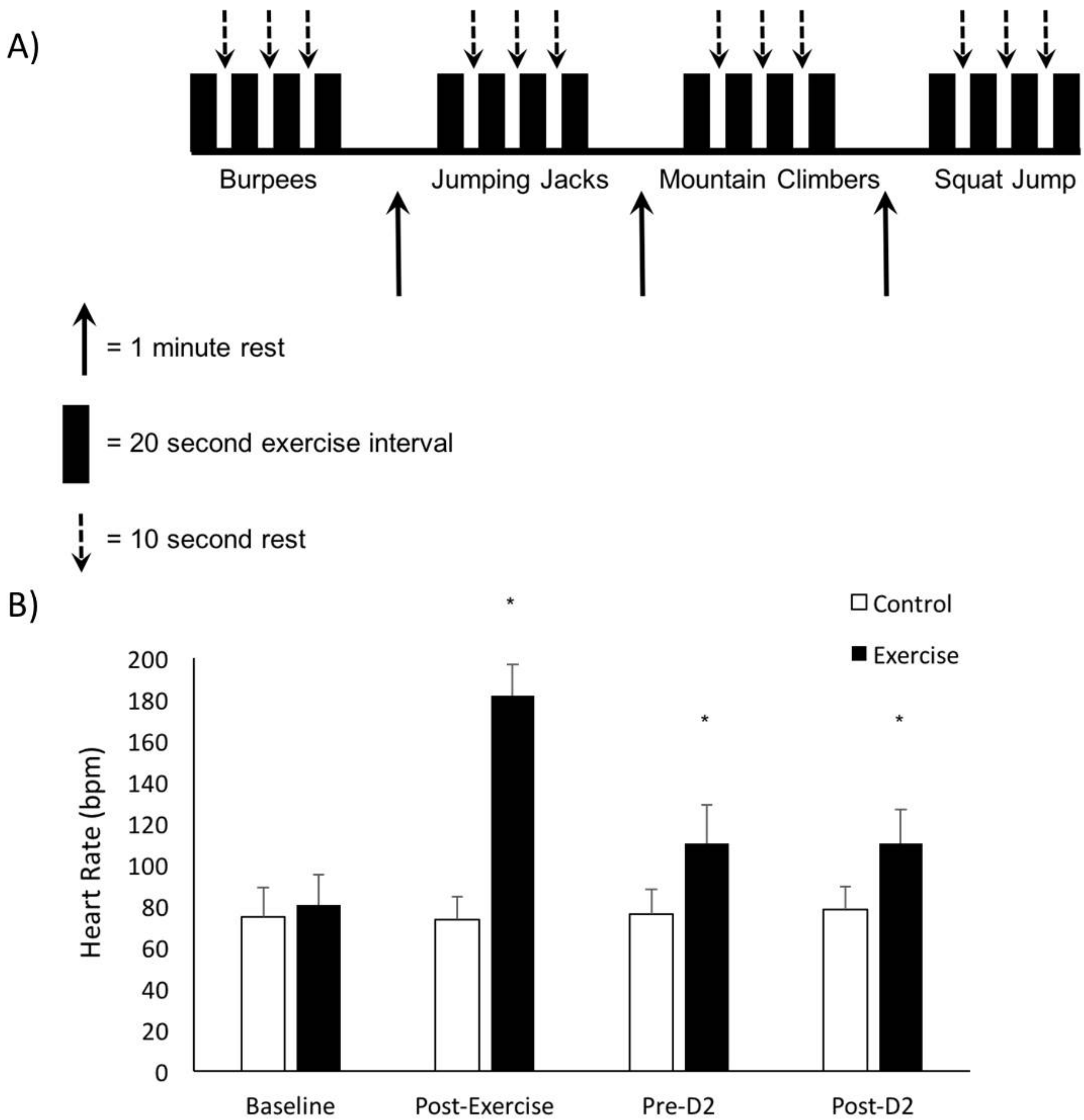

Figure 1. A) Schematic of the HIIE protocol. The exercise protocol consisted of 4 sets, each consisting of 4 intervals (reps). Each set was separated by a 1-minute break and each rep was separated by a 10 second break. B) Comparison of heart rate responses between conditions before and after exercise, as well as before and after performing the d2 test from Study #1; values are derived from n = 12. * significantly greater than Control, $p < 0.05$.

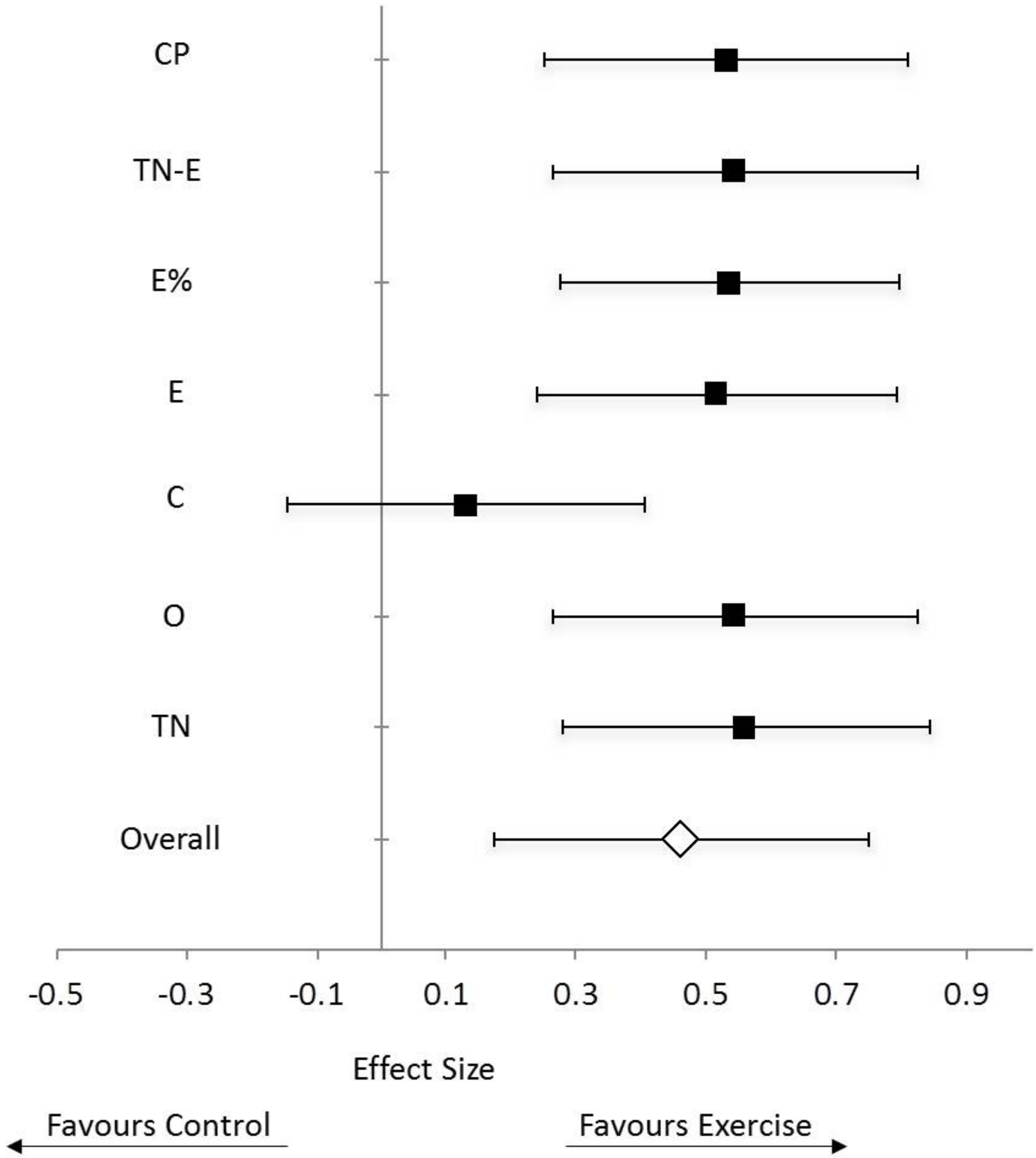

Figure 2. Forest plot depicting the effect size (black square) and associated 95% confidence intervals (error bars) for each d2 parameter from Study 1; n = 22. Abbreviations to the left of the y-axis represent effect sizes corresponding with the subcomponents of the d2 test. An overall effect size of 0.460 for the entire d2 test is represented by the white diamond. TN = total number of characters processed; O = errors of omission; C = errors of commission; E = total errors; E% = percentage of errors; TN-E = total number processed minus errors; CP = concentration performance. * significantly greater compared to Control condition, $p < 0.05$.

DISCUSSION

The transient facilitative effect of exercise on attention has been repeatedly demonstrated in response to numerous submaximal exercise protocols, whereas there is a dearth of studies that have investigated whether HIIE has similar modulatory effects on attention (8). This period of improved attention holds the potential to strategically use exercise as a primer for subsequent situations where attention is required, such as a university lecture. As such, the purpose of this study was to examine the effects of a single bout of HIIE on measures of selective attention and to test if our HIIE protocol could improve retention of lecture material. Results from this study show that a single bout of HIIE facilitates improvements in selective attention and visual processing speed, as indicated by performance on the d2 test of attention; however, performing HIIE prior to a university lecture did not impact performance on a lecture retention quiz. These results demonstrate that a bout of HIIE modulates selective attention in young adults and that further studies are warranted to investigate how this period of enhanced attention can benefit the learner in an academic setting.

Table 1. d2 performance values.

	Control	HIIE	% Difference	Corrected p-value
TN	232.6 (33.8)	251.2 (32.5)*	8.0%	0.04
O	70.7 (34.2)	52.6 (32.3)	25.6%	0.12
C	4.2 (4.4)	4.7 (4.0)	13.0%	
E	74.9 (35.3)	57.3 (32.4)	23.4%	0.16
% Errors	35.0 (21.0)	24.9 (16.8)	29.0%	0.14
TN-E	157.7 (68.6)	193.9 (64.4)	22.9%	0.09
CP	224.2 (35.5)	241.7 (32.4)	7.8%	0.16

Note: Data are Mean (SD). TN, total number of items processed; O, errors of omission; C, errors of commission; E, total errors; %Errors, percent of errors; TN-E, total number of items processed minus errors; CP, concentration performance. *Significantly different compared to Control, $p < 0.05$.

The major findings from the d2 test of attention in the current study was that improvements in scanning and processing speed following HIIE were coupled with greater accuracy compared to the Control condition. Specifically, participants demonstrated processing speed following HIIE compared to Control as there was an 8% increase in TN. This was accompanied by a 26% reduction in errors of omission, which may represent greater attentional control and performance accuracy following HIIE compared to control. However, we were likely underpowered to detect a statistically significant difference in error rate, as the 26% reduction in errors of omission was accompanied by a moderate effect size in favor of HIIE (d = 0.544, [0.263, 0.824]) suggesting a trend towards better performance following HIIE compared to control. Nonetheless, these findings suggest that HIIE facilitates overall greater efficiency in selective attention following a bout of HIIE compared to control.

At present, only a small body of literature has examined the effect of an acute bout of HIIE on measures of selective attention. Recently, Tsukamoto et al. (41) found that selective attention, as measured via Stroop interference, was significantly improved immediately after a bout of either HIIE at 90% VO_2peak (90% HR_{max} achieved) or moderate continuous exercise (MCE) at 60% VO_2peak (80% HR_{max} achieved) in young adults. Interestingly, the benefits garnered by HIIE appeared to be more durable than MCE, as improved Stroop test performance persisted 30 minutes following the cessation of HIIE whereas Stroop scores returned to pre-exercise levels 30 minutes after MCE. Similarly, Alves et al. (1) reported that HIIE consisting of 10 x 1 min intervals performed at 80% HRR improved selective attention in middle aged adults (age = 53.7 yrs). Our study extends the findings of Tsukamoto et al. (41) and Alves et al. (1), supporting the notion that HIIE transiently improves selective attention. However, in the context of developing a time-efficient exercise strategy for improving cognitive function, our work suggests that improved selective attention can be garnered via a comparatively smaller 'dose' of exercise, as the total exercise time of our HIIE protocol was significantly shorter than the aforementioned studies. Our HIIE protocol was 11 minutes in duration, with 5.5 minutes of exercise, whereas Alves et al. (1) was 20 minutes total with 10 minutes of exercise and Tsukamoto et al. (41) was 33 minutes total with 16 minutes of high-intensity exercise. In line with our findings, Kao et al. (18) recently found that a 9 minute HIIE protocol with 4.5 minutes of high-intensity treadmill running significantly improved neuroelectric measures of attention in young adults. Comparatively, our HIIE protocol may represent a more accessible approach to boosting attention, as our HIIE protocol did not require the use of any equipment and ostensibly could be performed anywhere with sufficient space. Importantly, the effect size produced by our HIIE protocol was moderate (d = 0.46), which is consistent with the findings from a recent meta-analysis for the effects of acute continuous exercise on executive functions (d = 0.55).

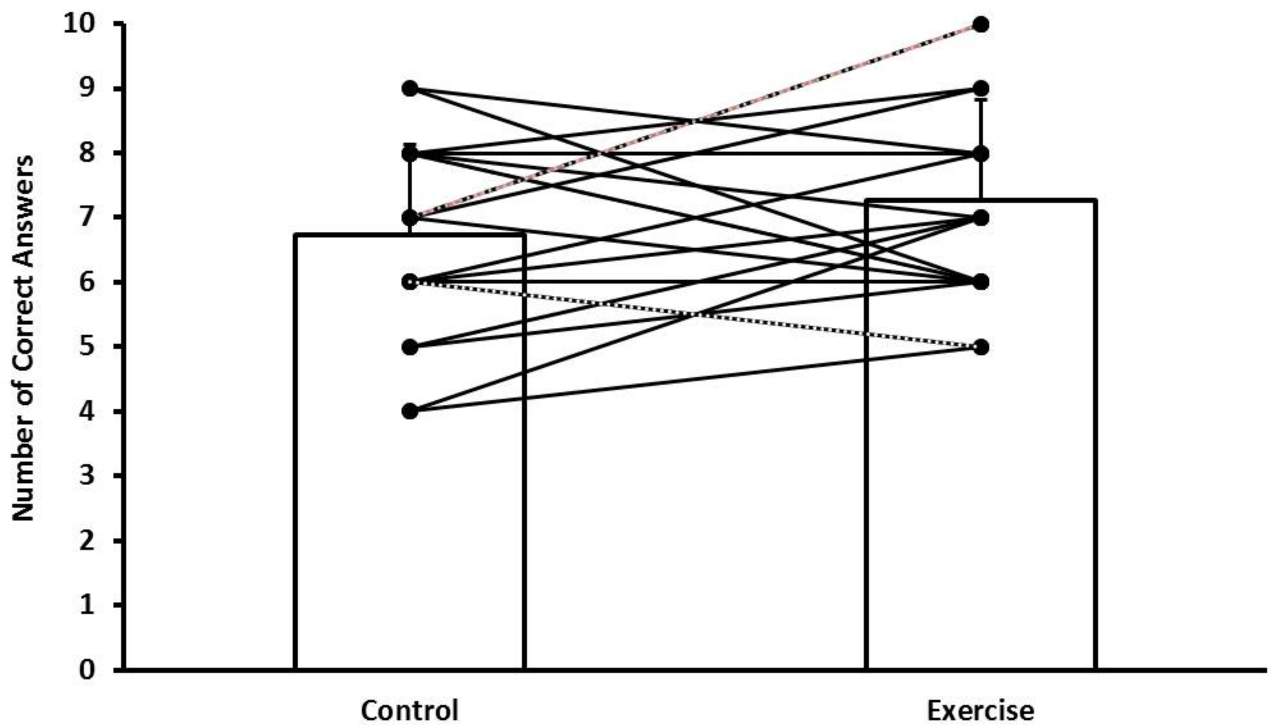

Figure 3. Bar graph representing group means and line plots representing individual performance on lecture retention quizzes from Study #2; n = 23. Hatched and dotted lines represent multiple participants with identical scores.

In contrast, Budde et al. (5) found a single bout of maximal intensity sprint exercise did not affect d2 performance in university students. However, when participants were stratified by physical activity levels, a significant time x condition interaction emerged wherein physically active individuals experienced an improvement in selective attention following HIIE compared to control condition. The authors suggest that the difference in d2 performance between active and non-active subjects is related to differences in exercise-induced arousal. It is postulated that increased allocation of attentional resources (7) via heightened arousal may be the primary mechanisms driving this transient improvement in selective attentions, rather than increased cerebral blood flow that is experienced in the preceding bout of exercise (11, 28). Previous meta-analysis suggests that there is an inverted-U dose-response between arousal and attention as moderate levels of arousal appear to be optimal and higher levels can be detrimental to performance (24); however, the emerging findings that HIIE improves executive functions challenge this notion (1, 18, 41, 45). It is plausible that fitness levels may buffer high levels of arousal following a bout of HIIE, thereby eliciting disparate effects on cognition at the group level (6, 11). Further, it is possible that the low-volume nature of HIIE may differentially impact the recovery from exercise compared to continuous aerobic exercise, such that arousal levels are within a facilitatory range when cognitive function is measured (i.e., 10 minutes post-HIIE); however, dedicated studies are required to elucidate this mechanism.

In the present study, we measured d2 performance 10 minutes following HIIE, as this time period may yield the greatest effect on behavioural measures of cognition (8), possibly via mechanisms of arousal (20). HR values were significantly higher than baseline at the beginning of the d2 test following HIIE, which we interpret as increased arousal due to exercise. It is possible that improved d2 performance was mediated by heightened arousal garnered by the preceding bout of HIIE. We did not characterize the fitness levels of our sample, and therefore cannot comment on potential mediation of fitness on d2 performance. As such, future HIIE studies should characterize fitness to further advance the understanding of how fitness may mediate the relationship between post-exercise arousal and cognitive function.

Previous studies indicate that mind wandering increases, while attention and arousal decline as a function of time during a 60 minute university lecture, and that waning of attention is associated with poorer retention of lecture material (33). As such, it follows that enhancing arousal and attention prior to a lecture should improve retention of lecture material; however, previous studies have yet to examine the effect of a single bout of exercise on lecture retention in a university lecture. It is important to acknowledge that improvements in selective attention via the d2 test may not directly translate to lecture-based learning, primarily due to the extent to which the individual is engaged in a learning task. Indeed, active engagement in a cognitive or learning task, such as the d2 or vocabulary learning (45) may differentially impact performance compared to traditional didactic methods commonly employed in lectures (27). Conversely, the degree of engagement on a learning task may differentially affect retention of material depending on the preferred learning style of individual (21). As such, more work is needed to investigate whether improvements in cognitive function translate to improvements in lecture-based learning.

Evidence from school-aged children represents the only body of work to have examined how exercise-derived improvements in attention impacts scholastic performance and other classroom parameters. Ma et al. (23) found that performing a very brief bout of HIIE ('Funtervals') significantly improved selective attention, as indicated by the d2 test, which was accompanied by a significant reduction in off-task behaviour during class (22). Similarly, Pontifex et al. (31) found that a 20-minute bout of moderate intensity treadmill exercise augmented neuroelectric indices of attention, which was coupled with significantly greater response accuracy on the Eriksen flanker task. Importantly, these authors report that the preceding bout of exercise significantly improved measures of reading and arithmetic, suggesting that behavioural improvements (i.e. flanker task performance) directly translate into functional improvements on tests of academic achievement. In contrast, we found that a bout of HIIE performed before a university lecture did not impact knowledge retention 24 hours after lecture, despite the fact that our HIIE protocol improves selective attention.

Attention is involved at every level of processing and perception, and is requisite for successful completion of higher-ordered tasks such learning (15), working memory (32), and other executive functions 9). However, despite the ability of our HIIE protocol to increase attentional resources we did not observe any change in lecture retention. A university lecture is a difficult environment to control experimentally, as there are a number of external dimensions (difficulty and structure of the lecture) and internal dimensions (motivation, prior knowledge of topic, perceived challenge) that can influence lecture retention (44). While we attempted to replicate as many external dimensions as possible between the two lectures, we were unable to control the internal dimensions. Further, it is possible that our quiz lacked appropriate sensitivity to assess lecture retention. Nevertheless, given the ability of HIIE to enhance selective attention, the strategic utilization of HIIE to improve attention prior to a cognitively engaging activity warrants further investigation and future studies are tasked with developing means by which lecture retention can be assessed in a naturalistic setting.

The 10-point nature of the quiz raises the potential for reduced sensitivity to detect changes for higher performers at baseline due to a potential ceiling and artificially boost low performers at baseline based on the law of initial values (43). We explored this potential in a secondary analysis and did not observe any obvious biases due to initial quiz scores (Figure 3). Nonetheless, future investigations into the translational effects of improved cognition should ensure appropriate sensitivity and account for the law of initial values when designing or selecting their testing instrument.

The current study is strengthened by the use of a counter-balanced crossover design, which allows for participants to act as their own controls and accounts for potential order effects due to condition allocation. This design could be strengthened by the use a pre-post test design on each experimental day in order to control for day-to-day variability that may impact performance (i.e., sleep, nutrition etc.). However, we provided standardized pre-experimental instructions for participants that should reduce the potential confounding effect of these behaviours.

Finally, we also acknowledge that the participants for both studies are heavily biased towards young adult females. We employed a convenience sampling method via advertisements posted around Queen's University and a majority of volunteers were female. Despite this, we do not believe that this influences the interpretation or generalizability of these results given that there does not appear to be sex differences in the acute effect of exercise on cognition in young adults (8, 39, 46). With respect to age, there are no difference in the effect of continuous aerobic exercise on cognitive improvement across adulthood (i.e., 18 - 60+ years) (8); however, whether this holds true in response to HIIE is currently unknown due to the paucity of studies in middle-aged and older adults. It is reasonable to suspect that HIIE would benefit cognition given that an acute bout of HIIE improves cognitive function in middle aged adults (41) and HIIE has shown to be well tolerated by a range of age groups (19). As such, more studies are needed to elucidate these effects in middle aged and older adults.

A very brief session of HIIE improves selective attention in university students, supporting a growing body of evidence. Despite this, performing HIIE prior to a university lecture did not impact retention of material 24 hours after lecture. However, we believe that HIIE has the potential to be an effective strategy for increasing the allocation of attentional resources prior to performing cognitively engaging activities, and as such, warrants continued investigation. From a practical perspective, the lack of equipment and time-effective nature of HIIE is an ideal tool for boosting cognition in a real-world setting; however, consideration must be given to the subsequent recovery from exercise (i.e., post-exercise sweating, breathing rate, subjective feelings, etc.) and how quickly an individual can reasonably transition to an educational/occupational task. Future research should work to elucidate the minimum effective dose for improving cognitive function that also allows for effective transition within an educational and/or occupational setting.

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