# ACUTE AEROBIC EXERCISE AND MEMORY OF YOUNGER ADULTS

# THE EFFECTS OF A SINGLE BOUT OF HIGH INTENSITY AEROBIC EXERCISE ON THE LONG-TERM MEMORY OF YOUNGER ADULTS

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TITLE: The effects of a single bout of high intensity aerobic exercise on the long-term memory of younger adults

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## ABSTRACT

University evaluations often reflect an individual's ability to memorize and recall lecture material during exams. Consequently, the ability to effectively encode, store, and later retrieve information is an integral part of learning and academic success. Notably, students who are more physically active tend to have better academic performance. The neurobiology of stress is a strong candidate for the mechanism underlying this exercise-cognition interaction. Given that exercise is a physical stressor, it is hypothesized that exercise-induced adrenocortical activations increase cortisol levels. Critically, cortisol increases memory consolidation for newly learned information. One hundred twenty-eight young adults (36 males; age: M±SD =19.47±1.55 years) viewed a video lecture before exercise (n = 41), after exercise (n = 42), or after rest (n = 45). The exercise was high intensity interval training on a cycle ergometer and memory for the lecture material was assessed using a multiple-choice quiz conducted 14 minutes and 48 hours after the lecture. There was a significant positive correlation between aerobic fitness and grade point average [$r(95) = 0.22, p < .05$], immediate recall [$r(100) = 0.39, p < .001$], and delayed recall [$r(98) = 0.28, p < .01$]. A mixed model ANOVA found a significant main effect of group on comprehension of the lecture material, $F(2, 96) = 3.34, p < .05$, revealing greater memory benefits at both 14 minutes and 48 hour delays for those who exercised compared to those who did not exercise; however, pairwise comparisons found this effect specific to the exercise post group. There was also a main effect of group on cortisol levels, $F(2, 107) = 3.97, p < .05$; however, only the exercise *prior* group exhibited significantly greater levels than the control group. Thus cortisol levels collected during the experimental session did not clearly differentiate the exercise conditions or reflect the observed memory benefits for the exercise post group. This may have resulted from the gradual increase in cortisol following exercise that had time to increase when exercise was completed at the beginning of the exercise session (exercise prior) rather than at the end (exercise post). Overall, this study suggests that both physical fitness and an acute bout of aerobic exercise are associated with academic and memory performance. More research is needed to understand the mechanism.

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| | |
|---|---|
| ANOVA | Analysis of variance |
| BDNF | Brain derived neurotrophic factor |
| GPA | Grade point average |
| HIIT | High intensity interval training |
| MC | Multiple choice |
| RPE | Ratings of perceived exertion |
| RPM | Revolutions per minute |
| USQ | Undergraduate stress questionnaire |
| $VO_2max$ | Maximum oxygen consumption |
| $W_{max}$ | Maximum wattage or peak power output |

# DECLARATION OF ACADEMIC ACHIEVEMENT

**H. Fang's role:**

- Author of ethics application at McMaster University
- Designed study protocol and selected measures
- Participant recruitment
- Preparation of lab settings and materials
- Trained and supervised placement and undergraduate thesis students with data collection
- Data collection, input, analysis, and interpretation

**Role of co-authors:**

- JJH obtained study funding
- JJH assisted HF with ethics application
- JJH assisted HF with study design and measure selection
- JJH assisted HF with data analysis
- JJH assisted HF with interpretation of data

# Introduction

Enrolment in post-secondary education is on the rise with full-time university students more than double that of 1980 (The Associations of Universities and Colleges of Canada, 2011). A driving force behind this growth is the increasing value society places on academic excellence. As a result, institutions are under increasing societal pressure to meet the demands of producing academically successful citizens. Critically, this targeted focus on scholastic activities has lead to a drastic reduction in time available for physical activity and physical education (Wilkins et al., 2003). However, this may be counterproductive. Physical activity is consistently shown to improve academic achievement in elementary and secondary students (Ardoy et al., 2014; Dwyer, Blizzard, & Dean, 1996; Trudeau & Shephard, 2008). Currently, it is unclear whether a similar relationship is observed for post-secondary students and what the mechanism is that underlies the relationship between physical activity and academic success. The present study addresses these two issues.

## Physical Activity and Academic Performance

Accumulating evidence reveals a positive relationship between physical activity and academic performance among elementary school students. Elementary students who are more physically active have higher academic achievement, as revealed by both classroom outcomes and standardized tests (Carlson et al., 2008; Grissom, 2004; Roberts, Freed, & McCarthy, 2010; Singh, Uijtdewilligen, Twisk, Van Mechelen, & Chinapaw, 2012). When given more time for physical activity, elementary students maintained or improved performance on standardized academic tests despite receiving less classroom instructional time (Trost, 2007). In contrast, reducing physical activity participation to allocate more time towards academic subjects did not result in improved grades (Trudeau & Shephard, 2008).

A similar positive association between physical activity and academic performance is also observed in secondary school students (Fox, Barr‐Anderson, Neumark‐Sztainer, & Wall, 2010; Nelson & Gordon-Larsen, 2006). Those who are more physically active achieve higher grade point averages (Field, Diego, & Sanders, 2001), while those who are more sedentary have poorer academic performance (Sigfsdttir & Allegrante, 2009). In a physical education intervention program (Ardoy et al., 2014), students who engaged in physical education classes four times per week that were designed to evoke a heart rate of at least 120 beats per minute had higher grades relative to those who engaged in physical education classes at a similar frequency or less frequently (i.e., 2 classes per week) that had no target intensity. This finding suggests that the intensity of the physical activity may be a key factor in promoting academic performance.

Indeed, it has been hypothesized that higher physical fitness resulting from moderate-to-vigorous physical activity participation may explain the association between physical activity and academic performance. Children scoring higher on physical fitness tests also score higher on standard academic tests (Grissom, 2004). Field tests of physical fitness are positively related to scores in mathematics, reading, and overall academic achievement (Castelli, Hillman, Buck, & Erwin, 2007). Higher-fit children also demonstrate greater relational memory task performance, as well as a greater ability to encode and retrieve relational material (Chaddock et al., 2010; Chaddock, Hillman, Buck, & Cohen, 2011). In adolescents, cardiovascular fitness shows a dose-response relationship with academic performance, such that higher fitness is associated with greater performance (Van Dusen, Kelder, Kohl, Ranjit, & Perry, 2011).

Although the relationship between physical fitness and academic performance has been consistently demonstrated in elementary and secondary students, the relationship among postsecondary students remains unclear. Physical fitness in university-aged adults has been found to be positively associated with long-term memory performance on simplified lab-based stimuli (Pereira et al., 2007). However, this has not been tested with complex academic material. Therefore, the first aim of this study was to examine the relationship between physical fitness and academic performance in a group of first-year university students by examining their acute in-lab performance on authentic educational material and their overall performance as indicated by grade-point-average.

## Understanding Mechanism

The cognitive benefits associated with physical fitness may be due to an accumulation of individual bouts of exercise. Acute aerobic exercise has been found to have a positive effect on general cognitive performance (Brisswalter, Collardeau, & René, 2002; Chang, Labban, Gapin, & Etnier, 2012). A single bout of aerobic exercise alone, improves learning (Winter et al., 2007) and long-term memory performance (Labban & Etnier, 2011; Roig, Nordbrandt, Geertsen, & Nielsen, 2013; van Dongen, Kersten, Wagner, Morris, & Fernández, 2016) for simplified lab-based stimuli. However, methodological inconsistencies across studies (including the timing, intensity, and duration of exercise bouts, as well as the length of the delayed recall) resulting from the absence of an overarching theory-driven approach, have contributed to several ambiguous findings.

For example, Labban and Etnier (2011) examined the effect of the timing of an acute 30-minute bout of moderate intensity aerobic exercise on long-term memory via 35 minute delayed paragraph recall. The *exercise prior* to learning group had better long-term paragraph recall than the non-exercise control group, whereas the exercise after exposure group did not.

In contrast, Roig, Skriver, Lundbye-Jensen, Kiens, and Nielsen (2012) found that compared to the control group, young adults who performed 15 minutes of high intensity cycling *prior and after* learning a visuomotor accuracy-tracking task showed better retention of the motor skill 24 hours and 7 days after practice. The *exercise post* group further demonstrated a better retention of the motor skill 7 days after practice compared to the exercise prior group.

Coles and Tomporowski (2008) examined the effect of 40 minutes of moderate intensity aerobic exercise on 12 minute delayed free-recall memory and found that both the exercise prior and after groups did not improve (but maintained) the number of items recalled in the primacy and recency portion of the word list, whereas memory for these items declined following the rest and non-exercise conditions.

van Dongen et al. (2016) found that a 35-minute bout of high intensity aerobic exercise performed immediately after learning had no effect on 48 hour delayed recall.

However, exercise performed *four hours after learning* improved long-term retention of picture-location associations.

We hypothesize that the neurobiology of stress as a framework may explain these inconsistent findings stemming from the varied timing, intensity, and duration of exercise bouts, and the length of the delayed recall. The neurobiology of stress is a strong candidate for the mechanism underlying the exercise-cognition interaction in learning and academics. Exercise is a physical stressor that induces adrenocortical activations, increasing glucocorticoids, corticosterone in animals and cortisol in humans (Mastorakos & Pavlatou, 2005; McEwen, 2007). These hormones are able to cross the blood brain barrier and bind to receptors in the brain. There are two receptor subtypes, the mineralocorticoid (Type I) and glucocorticoid (Type II) receptors. The highest levels of these receptors are found in the hippocampus and amygdala, two areas that play an important role in the formation of memories (De Kloet, Joëls, & Holsboer, 2005; Lupien, Maheu, Tu, Fiocco, & Schramek, 2007). Type I receptors have a tenfold higher affinity for glucocorticoids than Type II meaning that Type I receptors are occupied at rest and Type II receptors only become occupied following a stressor (Lupien et al., 2007). Critically, Type II activation is essential for consolidation of information into long-term memory (Lupien et al., 2007). Therefore, the release of glucocorticoids induced by exercise and the consequent activation of Type II receptors are expected to promote long-term memory and test performance.

A study by Lupien et al. (2002) tested the causal relationship between glucocorticoids and memory. They experimentally lowered the glucocorticoid levels in young adults by administering an inhibitor of glucocorticoid synthesis. This impaired memory. They then used hydrocortisone to restore glucocorticoid back to baseline and memory too was restored to baseline levels. This suggests that cortisol levels play a role in memory performance. It is hypothesized that this is a function of receptor occupation: greater levels of cortisol resulting from exercise stress may translate to higher activation of Type II receptors and greater memory consolidation, i.e., the transferring of the encoded memory trace into long-term memory, making it more stable and available for later recall (McGaugh, 2000).

Cortisol is believed to work two ways to improve memory consolidation in response to a stressful event. First, cortisol strengthens the long-term potentiation of synapses involved in the formation of memories for the stressful event that caused the release. Second, it initiates a gene-mediated signal that suppresses the encoding of new information that is unrelated to the stressful event to reduce the potential for memory interference (Joëls, Pu, Wiegert, Oitzl, & Krugers, 2006). Critically, this suggests that the time of exercise relative to learning and testing may be important, whereby peak cortisol levels should align with memory consolidation and not with initial learning.

With respect to exercise stress, cortisol levels gradually increase and peaks at 30 minutes after high intensity aerobic exercise (VanBruggen, Hackney, McMurray, & Ondrak, 2011) and so this time course may be important to consider when evaluating the effect of exercise on learning and memory. High intensity exercise causes a greater stress response resulting in a larger increase in cortisol levels (Hill et al., 2008) and when timed accordingly may result in greater long-term memory. It follows that if an acute bout of exercise is performed before learning, increasing cortisol may occur during the encoding stage, suppressing the formation of new memories and interfering with learning (McEwen, 2007). Also, performing retention tests too soon after encoding would disrupt the consolidation process and thus limit the exercise induced memory gains. A time interval of 24 hours to 48 hours between training and retention testing may be needed to observe the effect of cortisol on memory consolidation (Roozendaal, 2002). This might account for some of the prior discrepant results. Coles and Tomporowski (2008) used a short 12-minute delay and found no memory improvements whereas Labban and Etnier (2011) and Roig et al. (2012) used longer delays and found significant memory improvements. However, none of these studies examined cortisol, and so the current study was critical to directly test this hypothesis.

## Purpose and Hypothesis

The primary aim of this study was to examine the relationship between physical fitness and academic performance in a group of first year University students. We examined the students' acute performance on actual classroom material as well as their overall performance as indicated by grade-point-average. Fitness level, grade point average, and immediate and delayed recall scores of the participants were assessed. Based on previous literature with children and adolescents, we hypothesized a positive relationship between aerobic fitness and grade point average in university students. We also hypothesized a positive relationship between aerobic fitness and performance on the immediate and delayed tests.

The secondary aim was to examine whether fluctuations in cortisol with an acute bout of high intensity exercise impacted learning and memory. The same students viewed a video lecture prior to an acute bout of exercise, after an acute bout of exercise, or with no exercise. Their memory for this material was tested using multiple-choice tests immediately (14 minutes) and after a delay (48 hours). If the neurobiological stress system is the mechanism underlying the exercise-cognition interaction, high intensity exercise might improve long-term memory retention when appropriately timed. Therefore, we hypothesized that both exercise groups would experience a rise in cortisol relative to the control group but that the rise in cortisol for the exercise post-learning group would coincide with memory consolidation. In contrast, the rise in cortisol for the exercise prior to learning group would coincide with memory encoding and thus it was hypothesized that the exercise post group would have better recall performance relative to the exercise prior and control groups on both immediate and delayed tests.

## Method

### Participants

Based on the effects observed in previous studies examining the effects of acute exercise on long-term memory (Labban & Etnier, 2011), a medium large effect size was expected. A sample size of 90 participants is required to have 80% power to detect significant between group differences. However, the current study utilized complex academic material rather than simplified lab-based stimuli and thus aimed for a larger sample size, as there is greater variance in the performance of complex academic material.

One hundred twenty-eight young adults (36 males; age: M±SD =19.47±1.55 years; range= 18-27 years) in first year undergraduate at McMaster University participated in the study for two academic credits or monetary compensation of $20. They were recruited using an online portal designed for psychology research and were screened to ensure that they had not taken Introductory Psychology. Participants were randomly assigned to one of three groups: 1) no-exercise control, 2) exercise prior to learning, or 3) exercise post learning. McMaster Research Ethics Board approved all procedures.

## Procedure

The experimental procedure consisted of three sessions held at the same time of day within 24 to 48 hours of each other to control for diurnal variation of cortisol. A brief overview of the experimental structure is provided, followed by specific details for each session.

Briefly, Session 1 consisted of a series of questionnaires and a maximal aerobic fitness test. The exercise manipulation occurred during Session 2. Participants view an online lecture and depending on their group assignment they either: 1) did not exercise (control), 2) exercised prior to learning, or 3) exercised post learning. Then they complete an immediate recall task. Session 3 took place 48 hours after Session 2 and consisted of the delayed recall task. Student IDs were obtained from the participants in order to request grade point averages from the Office of the Registrar.

## Session 1

In Session 1, participants completed a set of questionnaires followed by a maximal aerobic fitness test.

**Questionnaires.** All participants completed the background questionnaire to control for age, program of study, gender, and psychological stress (assessed using the Undergraduate Stress Questionnaire, described below). The exclusion criteria of the study were also screened through this process, which excluded participants if they were not in the first year of university, were not between the ages of 18 and 30, or if they had previously taken Foundations to Psychology, Neuroscience, and Behaviour at McMaster University from which the study material was taken.

The Undergraduate Stress Questionnaire (USQ) is a life events checklist designed to measure stress among undergraduate students (Crandall, Preisler, & Aussprung, 1992). It was used to screen participants for any additional stressful events in their lives that may alter baseline cortisol levels. The details of the questionnaire ranged from major life crises (i.e. death of family member, or victim of a crime) to minor daily events (i.e. assignments due, or sat through a boring class). Participants were asked to indicate whether if any of these events occurred within the past two weeks. Responding “yes” to the questions were scored with a 1 and responding “no” or “no answer” was scored a 0. The sum of the responses can range from 0 to 82.

**Fitness Testing.** Baseline aerobic fitness and peak power output ($W_{max}$) were assessed using a ($VO_2max$) test. Prior to the $VO_2max$ test, clothed body weight and height were measured with a mechanical height and weight scale (Weigh Beam Eye-Level, Detecto, U.S.A.) and a wireless heart rate monitor and sensor was fitted (Polar FT1, Polar

T31 transmitter). Participants performed a graded exercise test to exhaustion on an electro-magnetic braking cycle ergometer (Corvical, Lode, The Netherlands). The test consisted of a 30 second warm-up at 50 watts, and the workload increased by one watt every two seconds. The test was terminated when volitional exhaustion was reached or cycling cadence of 40 revolutions per minute (RPM) could no longer be maintained. A metabolic cart with an online gas collection system (MOXU modular VO2 System; AEI Technologies, Pittsburgh, PA) was used to determine oxygen consumption and carbon dioxide production to compute $VO_2$max. Participants were instructed to pedal between 80 to 100 RPM as the target cycling cadence during the test. Maximum wattage on the cycle ergometer and heart rate was measured at the point of exhaustion. Verbal encouragements were given during the test. Trained research assistants supervised all tests.

**Session 2**

The exercise manipulation took place 24 to 48 hours after session one. Figure 1 shows the study protocol. All participants came into the lab and rested for five minutes. The control group then completed the nine-minute learning phase, followed by a 14-minute non-exercise control break, and ended with a multiple-choice (MC) quiz. The non-exercise control task required participants to fill in a preselected colouring page chosen by the research assistant in a quiet lab environment to control participants' activity during this period. This task was used to maintain the cortisol levels of the participants at baseline. The exercise conditions differed with regards to the timing of the acute bout of exercise with respect to learning material (i.e., the lecture). The exercise-prior group followed the same timing as the control group except that they performed the 14-minute acute bout of exercise prior to the learning phase. The exercise-post group also followed the same timing as the control group except that they performed the acute bout of exercise during the break after learning.

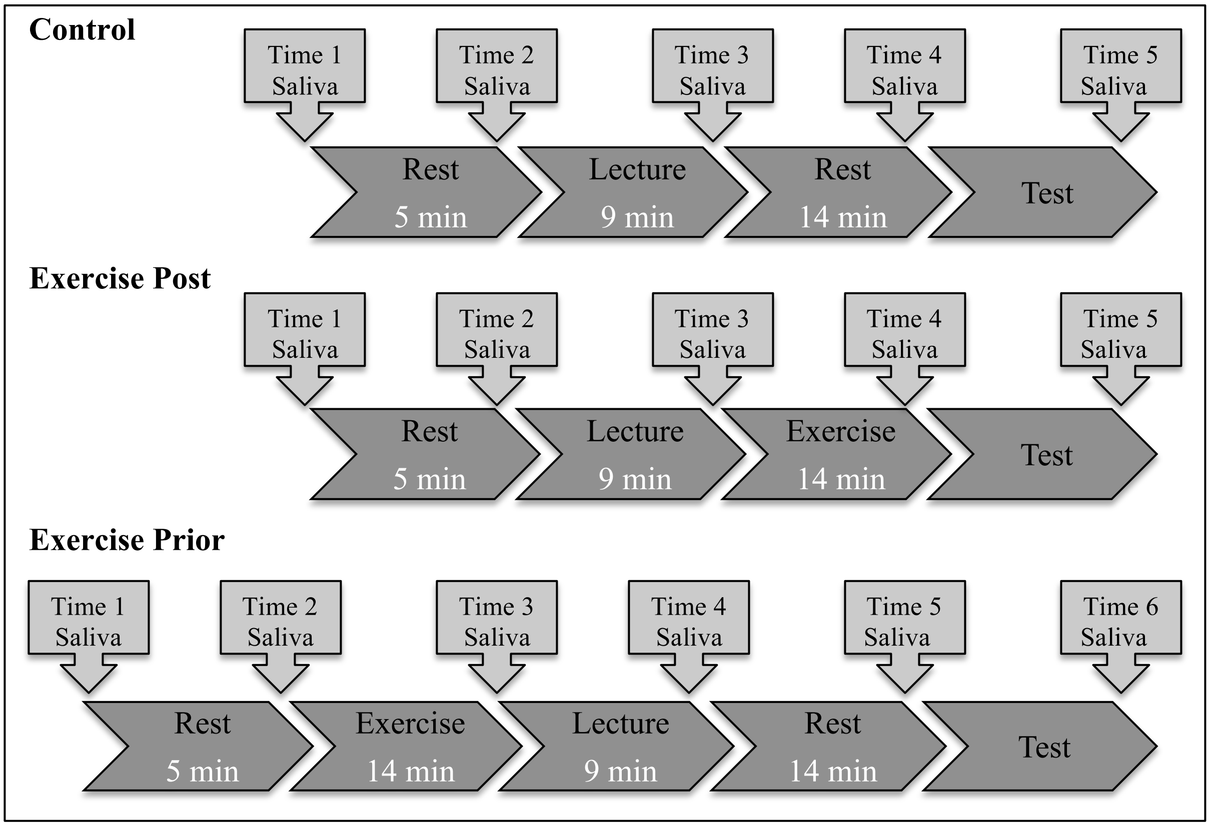

*Figure 1.* Timing of the study protocol for the control, exercise post, and exercise prior group.

**Learning phase and memory assessment.** The learning phase consisted of a nine-minute online lecture from Foundations to Psychology, Neuroscience, and Behaviour, a first year psychology course at McMaster University. The lecture consisted of a system-paced PowerPoint slideshow of the physiology, anatomy, evolution, and biochemical mechanisms of hunger. Participants individually viewed the web-module in a quiet laboratory on Dell desktop PCs with 19-inch displays and an attached headset (Sony Stereo MDR-XD150). Two versions of a 20-item, four-option (a-d) MC quiz corresponding to the online lecture were used to assess memory performance immediately (14 minutes after learning) and delayed (48-hours after learning). The two versions of the MC quizzes were counterbalanced. Participants were instructed to select the best answer for each question.

**Acute exercise bout.** High intensity interval training (HIIT) was used for the acute exercise bout. HIIT was the exercise protocol chosen to evoke a sufficient stress response (Hill et al., 2008) while still being tolerable for most fitness levels, including those that are sedentary (Gibala, Little, MacDonald, & Hawley, 2012). The HIIT protocol consisted of ten alternating high and low intensity intervals, flanked by a two-minute warm-up, and a two-minute cool-down. The same electro-magnetic braking cycle ergometer (Corvical, Lode, The Netherlands) used during maximal fitness testing was used for HIIT. The workload was individualized to 70% of $W_{max}$ for high intensity intervals and 12.5% of $W_{max}$ for the low intensity intervals, warm-up, and cool-down. Ratings of perceived exertion (RPE) using the Borg scale (scale from 6-20) and heart rates were obtained at the end of each high and low intensity interval, and after warm-up and cool-down. A Polar FT1 heart rate monitor and Polar T31 sensor collected heart rate during entire exercise session.

**Cortisol.** All experimental sessions were conducted between 12:00 pm and 4:00 pm to control for the diurnal variation of cortisol. Participants were asked not to consume any food or drink an hour prior to their scheduled testing session. Saliva samples were collected from participants using Salivettes (Sarstedt, Numbrecht, Germany) between each task (See Figure 1). Participants were instructed to chew on the swab for a minute or until moist, after which the swabs were placed back into the plastic tube of the Salivette. Five saliva samples were obtained from participants in the control and exercise-post groups, and six saliva samples from exercise-pre group. Saliva samples were stored in -20°C until analysis.

## Salivary Cortisol Assay Determinations

All saliva samples were transported on ice and stored at -20°C prior to assays. Saliva was centrifuged at 3000xg for 15 minutes and only the supernatant was assayed. All enzyme immunoassays were carried out on NUNC Maxisorb plates. Cortisol antibodies (R4866) and corresponding horseradish peroxidase conjugate were obtained from C. Munro of the Clinical Endocrinology Laboratory, University of California, Davis. Steroid standards were obtained from Steraloids, Inc. Newport, Rhode Island. Plates were first coated with 50 µl of antibody stock diluted at 1:8500 in a coating buffer (50 mmol/L bicarbonate buffer pH 9.6). Plates were sealed and stored for 12–14 hours at 4°C. 50 µl wash solution (0.15 mol/L NaCl solution containing 0.5 ml of Tween 20/L) was added to each well to rinse away any unbound antibody, then 50 µl phosphate buffer per well was added. The plates were incubated at room temperature for 2 hours before adding standards, samples, or controls. For each hormone, two quality control salivary samples at 30% and 70% binding (the low and high ends of the sensitive range of the standard curve) were prepared. 50 µl cortisol horseradish peroxidase conjugate were added to each well, with 50 µl of standard, sample, or control. After plate loading, plates remained incubated for 1 hour. Next, the plates were washed with 50µl wash solution and 100µl of a substrate solution of citrate buffer, H2O2 and 2,2′-azino-bis [3-ethylbenzthiazoline-6-sulfonic acid) was added to each well and the plates were covered and incubated while shaking at room temperature for 30–60 min. The plates were then read with a single filter at 405nm on the microplate reader (Titertek multiskan MCC/340). Blank absorbances were obtained, standard curves generated, a regression line was fit to the sensitive range of the standard curve (typically 40 – 60 % binding) and samples were interpolated into the equation to get a value in pg per well. Each sample was assayed in duplicate and averages were used. Interplate variation (CV) was 6.45% while intraplate variation was 6.51%.

### Session 3

Participants returned approximately 48 hours later to complete the alternate version of the MC quiz to assess delayed recall. The order of test version was counterbalanced across participants.

### Statistical Analysis

The data were checked for normality and outliers. Non-normal data were transformed and outliers were removed. Outliers were indicated by SPSS using the equation 1.5*interquartile range (IQR) (Field, 2013). Cortisol data were positively skewed and were log transformed to a normal distribution. Cortisol data were also removed if heart rate (HR) and ratings of perceived exertion (RPE) scores were outliers as this indicated inadequate exercise intensity to elicit the appropriate cortisol response. The immediate and delayed recall scores were negatively skewed and were reverse log transformed to a normal distribution and then converted to Z scores to assess performance relative to the average. Missing data also occurred due to participant drop out and nonresponses from participants to questionnaires.

Table 1

*Cortisol outliers by time point*

| Time 1 | Time 2 | Time 3 | Time 4 | Time 5 | Time 6 |
|---|---|---|---|---|---|
| 8.59 | 8.59 | 5.49 | 6.25 | 7.03 | 3.91 |

*Note.* Values are percentage of total

Table 2

*Missing data and outliers*

| | Missing | Outliers |
|---|---|---|
| Immediate Recall | 9.38 | 4.69 |
| Delayed Recall | 13.2 | 3.13 |
| $VO_2max$ | 3.91 | 1.56 |
| GPA | 2.91 | 0 |

*Note.* Values are percentage of total

**Manipulation Checks.** To confirm that groups did not differ in aerobic fitness or grade point average, one-way analysis of variance (ANOVA) was conducted with baseline fitness values and grade point average with a between subject factor of group.

To confirm that the acute bout of exercise was of similar intensity for the two exercise groups, mixed model ANOVAs with a between-subjects factor of group (exercise-prior, exercise-post) and a within-subjects factor of exercise interval (1-12) were conducted on HR and RPE.

**Physical Fitness and Academic Performance.** Pearson correlations were conducted to examine the relationship between physical fitness and academic performance using grade point average and performance on the immediate and delayed recall scores on the multiple-choice quizzes.

**Acute Exercise and Memory.** To determine the effect of an acute bout of exercise on memory, we conducted a mixed model ANOVA with a between-subjects factor of group (exercise-prior, exercise-post, control) and a within-subjects factor of test time (immediate, delayed) on multiple-choice quiz scores. Covariates of gender and MC test version were included to control for group differences.

**Acute Exercise and Cortisol.** To determine the effect of an acute bout of exercise on the cortisol levels, we conducted a mixed model ANOVA with a between-subjects factor of group (exercise-prior, exercise-post, control) and a within-subjects factor of time (pre-learning, post-learning, pre-test, post-test). Covariates were gender and baseline cortisol level to control for gender differences between groups and variability in baseline cortisol.

**Cortisol and Memory.** Pearson correlations were conducted to examine the relationship between cortisol and memory performance on the immediate and delayed recall scores on the multiple-choice quizzes separately for each group. Change in cortisol was computed by subtracting the baseline (Time 1) from Times 2 to 5 for the control group and exercise post group, and from Times 2 to 6 was used for the exercise prior group (See Figure 1).

## Results

### Demographics

Table 3

*Demographic characteristics of participants by group*

| | Control | Exercise Prior | Exercise Post |
|---|---|---|---|
| N | 45 | 41 | 42 |
| Gender (Males) | 14 | 12 | 10 |
| Age | 19.3(1.30) | 19.4(1.48) | 19.8(1.86) |
| $VO_2$max | 28.6(8.67) | 29.3(6.77) | 30.7(8.10) |
| Program | | | |
| Social Science | 7 | 8 | 6 |
| Health Science | 1 | 2 | 0 |
| Life Science | 19 | 19 | 18 |
| Nursing | 7 | 5 | 10 |
| Kinesiology | 0 | 4 | 2 |
| Engineering | 1 | 0 | 1 |
| Commerce | 1 | 2 | 0 |
| Humanities | 2 | 0 | 1 |
| Medical Radiation Science | 0 | 0 | 1 |
| Mathematics and Statistics | 1 | 0 | 0 |
| Maximum Wattage | 177.33(46.26) | 180.55(41.78) | 190.41(48.96) |
| USQ Score (max=50) | 24.49(8.99) | 18.70(9.40) | 22.23(9.26) |
| Baseline Cortisol | 0.42(0.29) | 0.37(0.25) | 0.43(0.34) |
| GPA (max=12) | 8.40(2.45) | 8.74(1.88) | 8.64(2.18) |

*Note*. Values in parentheses are standard deviations

## Manipulation Checks

One-way ANOVAs confirmed no significant difference between groups in baseline aerobic fitness [$F(2, 117) = 0.81, p > .05$] or grade point average [$F(2, 97) = 0.22, p > .05$] (See Table 1).

Exercise increased HR and RPE during the intense intervals as depicted in Figures 2 and 3, respectively. HR and RPE increased to values indicative of high intensity level of exercise (HR ≥ 80% of maximum HR, RPE >14), which is sufficient to induce an increase in cortisol (Jacks, Sowash, Anning, McGloughlin, & Andres, 2002). ANOVAs found no significant effect of group on HR [$F(1, 64) = 1.15, p > .05$] (See Figure 2) and RPE [$F(1, 68) = 0.03, p > .05$] (See Figure 3), indicating that the exercise post and exercise prior groups achieved similar exercise intensities.

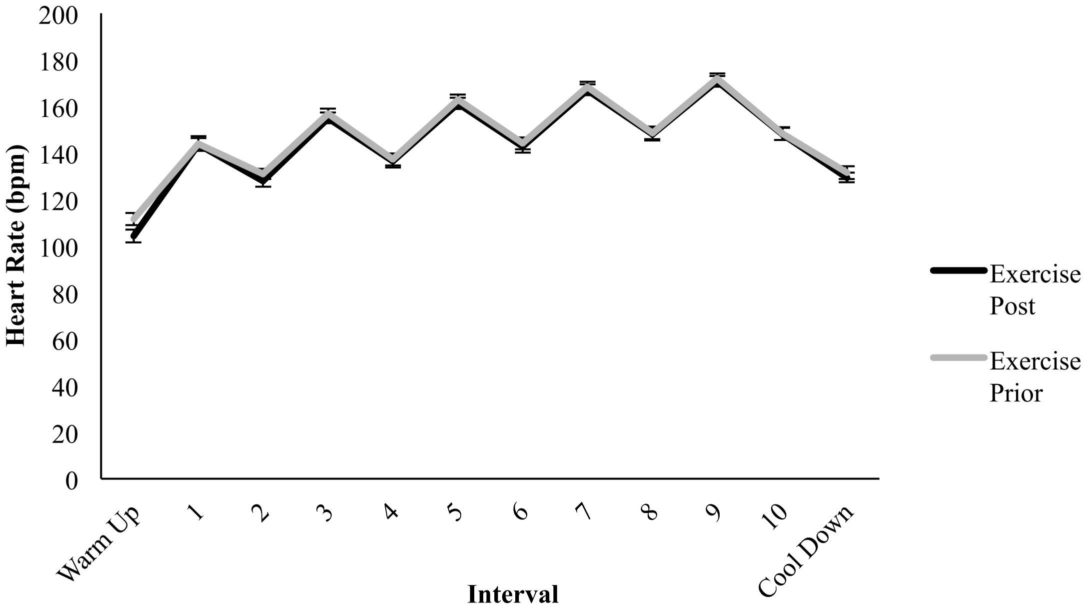

*Figure 2.* Mean heart rate for the exercise post and exercise prior groups.

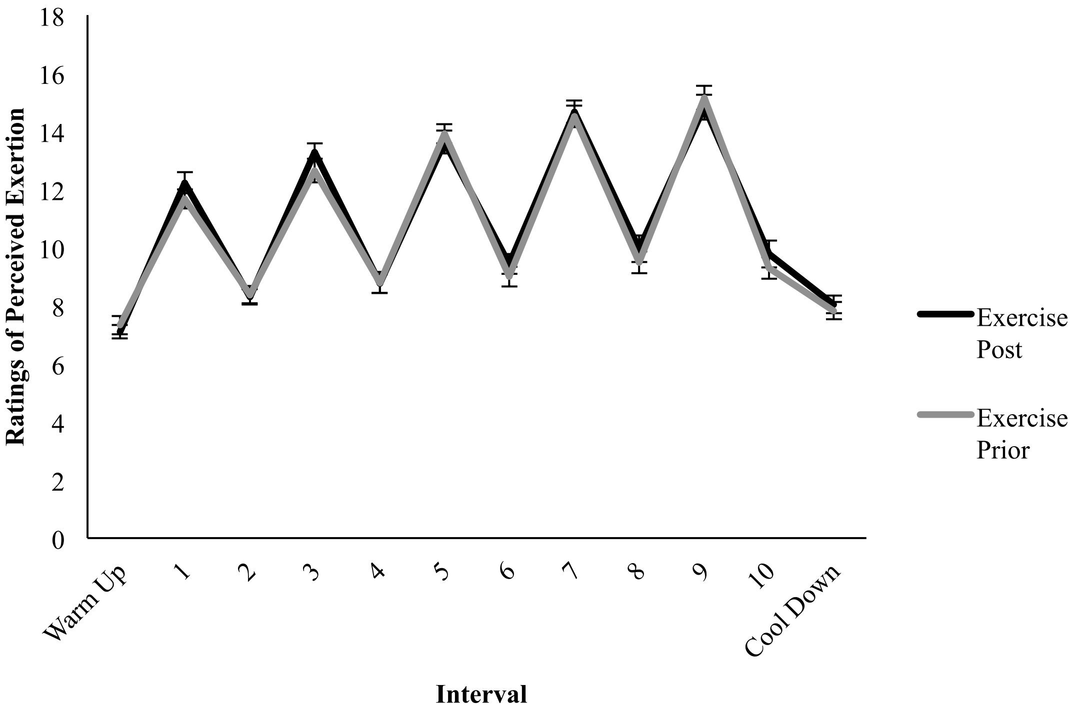

*Figure 3.* Mean ratings of perceived exertion for the exercise post and exercise prior groups.

**Physical Fitness and Academic Performance**

Significant positive Pearson correlations were found for the relationships between aerobic fitness with grade point average, $r(95) = 0.22, p < .05, R^2 = 0.05$, immediate recall [$r(100) = 0.39, p < .001, R^2 = 0.15$] and delayed recall [$r(98) = 0.28, p < .01, R^2 = 0.08$].

**Acute Exercise and Memory**

There was a significant main effect of group on memory performance, $F(2, 96) = 3.34, p = .04$. Both the exercise groups were above the mean, whereas the control group was below the mean; however, pairwise comparisons only revealed significantly better performance for the exercise-post learning compared to the control (*p* = .012; See Figure 4). There were no significant group by time interaction, *F*(2, 96) = 0.11, *p* = 0.90.

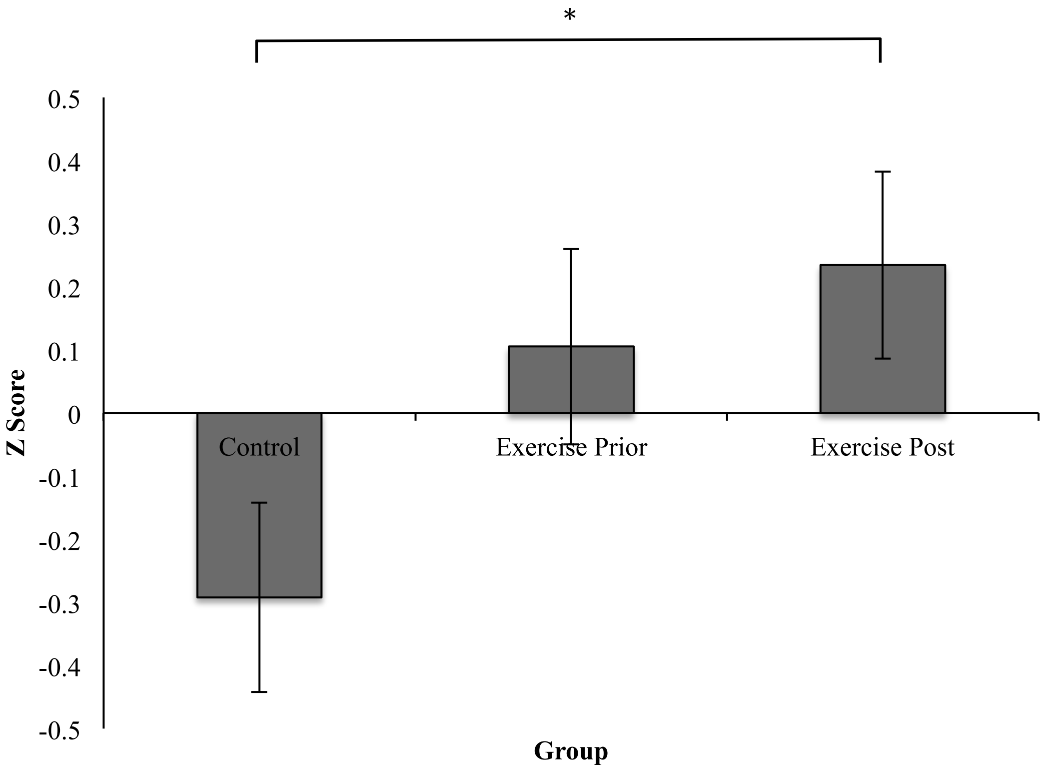

*Figure 4.* Z scored multiple choice test scores and standard error for the control, exercise prior, and exercise post groups.

Table 4

*Z scores for immediate and delayed multiple-choice quizzes and for control, exercise prior, and exercise post groups*

| | **Immediate** | **Delayed** |
|---|---|---|
| | Z Score | Z Score |
| **Control** | -0.30±0.16 | -0.29±0.17 |
| **Exercise Prior** | 0.13±0.16 | 0.08±0.17 |
| **Exercise Post** | 0.27±0.15 | 0.20±0.17 |

*Note.* Values are mean ± standard error

**Acute Exercise and Cortisol**

There was a significant main effect of group on cortisol, *F*(2, 107) = 3.97, *p* = .02 (See Figure 5). Pairwise comparisons found a significant difference between exercise prior to information exposure and control groups (*p* = .006).

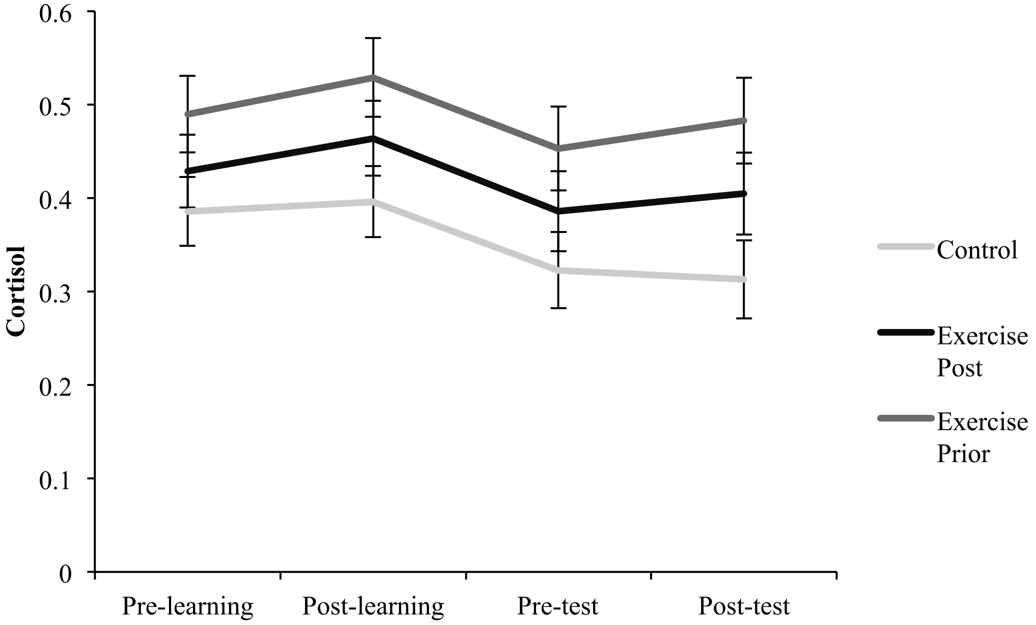

*Figure 5.* Cortisol levels during pre-learning, post-learning, pre-test, and post-test for the control, exercise post, and exercise prior groups.

**Cortisol and Memory**

For the exercise post group, change in cortisol at post-learning (Time 3) was marginally correlated  with immediate recall, *r*(32) = .33, *p* = .06, and a significantly correlation with delayed recall, *r*(30) = .36, *p* = .05 (See Figure 1 for time points). This time point occurred just prior to exercise.

## Discussion

The present study examined the relationship between physical fitness and academic performance in university students and explored the hypothesis that stress hormones activated by acute exercise act as a potential underlying mechanism linking physical fitness and academic performance. Physical fitness was positively correlated with grade point average as well as immediate and delayed test performance for the newly learned material. Students who exercised after learning had better test performance than those who did not exercise and their cortisol levels just prior to exercise correlated with their memory performance during both the immediate and delayed recall tests. The results suggest that the acute effects of a single bout of exercise on learning and memory may be contributing the overall relationship between fitness and academic performance.

Among our sample of university students, those with higher physical fitness also had higher grade point averages. This result extends previous findings from elementary and secondary school students (Carlson et al., 2008; Fox et al., 2010; Nelson & Gordon-Larsen, 2006; Roberts et al., 2010; Singh et al., 2012) and demonstrates that a similar relationship between physical fitness and academic performance persists into young adulthood. We also observed a significant positive correlation between physical fitness and both immediate and delayed test performance for newly learned material suggesting that the benefits of physical fitness are evident in a single academic test. Indeed, this is consistent with studies examining the benefits of an acute bout of exercise on learning and memory using more simplified lab based experiments (Pereira et al., 2007; van Dongen et al., 2016). The novel contribution of this study is that we used a lecture and multiple-choice tests that are authentic classroom materials, which strengthens the potential for transfer of these lab-based effects into real educational contexts. At a time when many schools are replacing physical activity time with more scholastic activities (that are also typically sedentary) (Marshall & Hardman, 2000), these results suggest that this approach may be counterproductive if the end goal is to improve test scores and overall academic performance.

When examining the role of each acute exercise bout on academic performance, both exercise groups outperformed the no-exercise control group on the immediate and delayed tests (Figure 4; Table 2); however, the timing of exercise in relation to learning was important. Performing a single bout of high intensity aerobic exercise after learning resulted in significantly better memory performance compared to the no-exercise control group. Critically, this performance enhancement for exercise post was predicted by the neurobiology of stress hypothesis.

Moreover, the neurobiology of stress hypothesis may help clarify the equivocal results of prior studies that have examined the role of exercise timing on learning. Like the present study, Roig et al. (2012) used intense exercise and found similar results in that exercise *after* learning resulted in better memory. In contrast, Labban and Etnier (2011) used moderate intensity exercise and found that exercise *before* learning resulted in better memory. This pattern of findings suggests that the benefits of exercise on learning may depend on the interaction between exercise intensity and exercise timing. Compared to moderate intensity exercise, higher intensity exercise elicits a greater increase in cortisol (Hackney & Viru, 1999), which may affect the time point at which cortisol peaks. Future research should directly examine the interaction between exercise intensity and timing with respect to learning to further test the neurobiology of stress hypothesis.

That said, the cortisol levels collected during the experimental session did not clearly differentiate the exercise conditions or map onto observed memory benefits for the exercise post group. Instead, the exercise prior group had highest level of cortisol. This may have resulted from the gradual increase in cortisol that occurs after high intensity exercise and peaks at 30 minutes (VanBruggen et al., 2011); the exercise prior group performed the acute exercise earlier and thus had more time for cortisol to accumulate during the experimental session. In contrast, the peak cortisol in the exercise post group would not have occurred until after the last saliva sample was taken. Moreover, activation of the stress response in all participants may have occurred as a result of the evaluation and testing (Dickerson & Kemeny, 2004). Critically, this may have masked potential group differences in cortisol levels related to the exercise manipulation. Therefore, we may not have captured the true rise and fall of cortisol in relation to exercise specifically. That said, the increase in cortisol post-learning for the exercise post group correlated with their memory performance, suggesting that the improved memory performance for this group may be related to the increase in cortisol in anticipation of the exercise rather than from the exercise itself. However, more research is needed to further examine this effect, and a complete timeline of cortisol is necessary to elucidate the true relationship between cortisol, exercise, and memory performance. Furthermore, given the temporal constraints of the experimental session, it is possible that cortisol may not be the best marker of the acute stress response due to the gradual progressive increase following exercise (Kudielka, Hellhammer, & Wüst, 2009). Epinephrine, which has a more rapid rise and fall (McEwen, 2007), may be a better marker of the stress system to capture the timing of exercise on cognition.

## Limitations

A limitation of this study is the lack of continuous cortisol monitoring after the experimental session. Cortisol peaks 30 minutes after high intensity exercise

(VanBruggen et al., 2011) and as such the complete time course was not captured by this study. Continuous monitoring of cortisol may provide further insights into the effects of acute aerobic exercise on memory consolidation. Further, salivary cortisol was used to represent cortisol levels in the brain; however, the measurement tool used to capture cortisol levels may not be detecting cortisol levels in the brain or receptor activation. Also, cortisol can be easily influenced by many factors and is highly variable in humans (Kirschbaum & Hellhammer, 2000). Although we accounted for several factors known to influence cortisol such as time of day, gender, and baseline cortisol levels, cortisol may not be the best measure to reflect the neurobiology of stress to capture the precise timing of the effects of exercise on learning and memory in humans.

Although the present study utilized genuine academic material, a possible limitation is that the use of a nine-minute lecture may not accurately reflect a true university lecture. The shorter lecture was used in order to control for the length of time spent in the lab; however, future work should extend this to examine the effect of exercise on full-length lectures.

## Future Directions

Further studies are required to investigate the mechanism responsible for the interaction between exercise and cognition. As noted, epinephrine may be a better measure to elucidate this relationship due to the faster response to stress. Other underlying physiological mechanisms such as brain-derived neurotrophic factor (BDNF) should also be investigated as they are implicated in a single bout of exercise and memory. BDNF has been found to improve hippocampal neurogenesis. This will permit a greater understanding and integration of mechanisms that may be involved in exercise and memory performance.

Additionally, as a decline in cognition and memory occurs with aging (Salthouse, 2009), conducting a similar study in older adults would be an important step to determine if the exercise-cognition relationship extends even later into the lifespan.

While there is accumulating evidence for the effect of aerobic exercise on cognition and memory, a systematic assessment of the timing, intensity, and duration is still required. This is needed to clarify the conflicting findings that exist in the literature due to the highly varied parameters used for the exercise bout. Further, the effects of resistance exercise are unclear. It is unknown whether an acute high intensity bout of resistance exercise will provide the same cognitive benefits or be complementary to an acute bout of aerobic exercise. A better understanding of these issues will provide a more comprehensive view of exercise and cognition and will help guide exercise prescriptions aimed at improving cognitive function.

## Conclusion

In summary, a single bout of high intensity exercise performed after learning improved memory for newly learned information. Although the role of the neurobiological stress system in this relationship remains unclear, this study revealed important associations in postsecondary students between physical fitness and performance on complex academic material and overall academic performance. Reducing time spent on physical activity for other academic subjects is indeed counterproductive. With the increasing value placed on academic excellence and increasing pressure to achieve academic success, schools would likely benefit from implementing physical activity breaks to improve learning and memory, and ultimately produce more successful students.

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