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## The Experimental Effects of Acute Exercise Intensity on Retrieval-Induced Forgetting

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EXPERIMENTAL EFFECTS OF ACUTE EXERCISE INTENSITY ON RETRIEVAL-  
INDUCED FORGETTING

by  
Joshua Franklin

A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of  
the requirements of the Sally McDonnell Barksdale Honors College.

Oxford  
May 2020

Approved by

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## ABSTRACT

JOSHUA CREED FRANKLIN: Experimental Effects of Acute Exercise Intensity on Retrieval Induced Forgetting  
(Under to direction of Paul Loprinzi)

Accumulating research has shown that acute exercise can enhance memory function. Although counterintuitive, acute exercise may also facilitate aspects of forgetting. Specifically, retrieving a subset of items from memory can facilitate the retention of retrieved items (retrieval practice; RP) and inhibit the subsequent retrieval of non-retrieved items (retrieval-induced forgetting; RIF). Given that acute exercise has been shown to enhance cognition-related inhibition, acute exercise may facilitate RIF. A sample of 225 young adults completed either a control (N=75), moderate-intensity acute exercise (N=75), or vigorous-intensity acute exercise session (N=75). Both acute exercise sessions lasted 20 minutes. Participants then completed a standard retrieval-induced forgetting protocol. Significant main effects for RP and RIF were observed, but no main effects for group, or RP by group or RIF by group interactions. In conclusion, large RP and RIF effects were observed but these effects did not vary as a function of exposure to acute exercise.

**Keywords:** cognition; cognitive function; executive control; inhibition; physical activity

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## BACKGROUND

Memory is an essential process in shaping how we comprehend the world around us, whether we are consciously aware of it or not. From simple information like a friend's phone number or where you last put your keys, to complex information like a favorite childhood experience or traumatic event, our ability to recall information allows us to execute everyday tasks, experience emotions, and so much more. Generally speaking, the process of creating a memory can be described in three simple steps: encoding, storage and retrieval. Although this is the basic life cycle of a memory, continued research is needed to determine how exactly each of these processes function. Encoding information describes the ability to convert information from one form to another in order to store that information for later use. When we acquire new information that we might need to remember, we must first be able to store this information in a way that our brains can easily extract it for later use. The human brain is a subset of a larger network of specialized cells called "neurons". Neurons communicate with one another via electrical impulses, which help send important information to and from the brain in order to carry out essential functions and processes throughout the body. One of these important processes is memory encoding. Studies conducted on mollusks as well as mammalian neural systems offers an explanation about how outside information is received and transduced into neuronal signals in the brain (Kandel, Dudai, & Mayford, 2014). When we receive outside information via sensory neurons, this information is sent to the brain to be processed. Serotonin is a chemical produced by neurons that allow cells in the nervous system to communicate with one another by sending electrical impulses from

one neuron to another. According to Kandel et al. (2014), the release of serotonin, among other neurotransmitters, in turn, signals an increase in another chemical messenger known as cyclic adenosine monophosphate (cAMP). This secondary messenger plays an important role in signal transmission in the central nervous system, especially in the brain. Once the electrical impulse reaches the brain, the chemical “glutamate” becomes the primary neurotransmitter between neurons. The increase in cAMP concentration signals an increase in the amount of glutamate within the signal pathway thus strengthening the connection between the neurons within the structure of the brain that is primarily responsible for processing memory, namely the hippocampus. This strengthening of the neural circuit thus forms a specific pathway for that stimulus which is the first step to what will later become an actual memory. The second phase in memory formation requires this information to be stored somewhere in the brain so that it may be recalled for later use. The process of memory storage involves several different complicated processes depending on what type of memory is being stored: whether it is short term or long term, implicit or explicit. The basis of memory consolidation, as Dudai (2004) states, begins with post-translational modifications caused by signal transduction cascades of the neuron. These modifications result in the synthesis of new proteins, including CREB, a transcription factor essential in memory storage and consolidation (p. 59). Once this information has been encoded and stored in a neuronal pathway in the hippocampus, among other structures, the last phase in the general life cycle of a memory is the ability to be able to retrieve that information at a later time. Much like memory storage, the processes for memory retrieval differs depending on the type of memory being recalled. The process of recalling a simple memory is different than recalling an



abstract thought, like recalling a phone number compared to recalling how you felt at your favorite birthday party as a child. Once again, however, there is a basic process involved in all memory retrieval. Generally, retrieval begins with a cue related to a specific memory that initiates a top-down processing of information and retrieval of the desired information to align with the given situation or cue (Kandel et al., 2014).

There are several different basic types of memory that we know of. Working memory, a type of short-term memory, involves encoding a small amount of information very quickly usually while we perform other cognitive processes, and may only last for a few seconds. An example of short-term memory would be trying to remember a friend's phone number as he is calling it out to you while you simultaneously enter the numbers into your phone. The next broader category of memories is called long-term memory, which can be divided into two subcategories, explicit and implicit memory. Long-term memory describes information that is intended to be stored over a long period of time which can include just a few minutes up to the rest of our lives. Explicit memory describes memories of facts and events that can be consciously recalled, information that is explicit, or definitive. Another term for explicit memory is declarative memories, which can be further divided into episodic and semantic memory. Episodic memory describes memories of our experiences and specific events that we can recall at a later time, often including spatial and temporal aspects of the memory. Examples of episodic memory would include events like family vacations, childhood birthday parties, or your first day of school. The other type of explicit, or declarative, memory is known as semantic memory. These memories refer to facts or general knowledge that we have learned about the world around us without any personal attachment or context. Some

examples of semantic memory include knowing who the president of the United States is, what color the sky is, or how to pronounce the letters of the alphabet. Going back to the two types of long-term memory, implicit memory refers to the retrieval of unconscious memories, information that we do not have to consciously recall when needed. Another term for this is procedural memory, which refers to things like knowing how to tie your shoe or how to write with a pencil.

It is important to note that not all information we encounter is stored in our brains to become a permanent memory. “Forgetting” a memory is a common process that can generally be defined as the inability to retrieve previously learned information (Dudai, 2004). Several theories give reasons as to why our brain chooses to remember some information and forget others. One theory suggests that our brain chooses to forget information that it finds useless in order to leave space in our memory for more important information to be stored. Another theory states that the memory engram, or the specific set of neurons that form in order to store the learned information, simply decays over time due to deterioration of biological substrate that encodes the engram. According to Davis & Zhong (2017), there are several known processes that describe how forgetting actually occurs after initial acquisition of information, which can be divided into “passive” and “active” forgetting (p 491-492). Passive forgetting describes the process of forgetting information without the involvement of internal or external factors, whereas active forgetting refers to the brain’s process of intentionally removing memory engrams that are not beneficial. There are currently three known mechanisms of passive forgetting: the loss of context cues, retrieval interference, and natural decay. Forgetting due to the loss of context cues occurs when the context between memory acquisition and memory

retrieval has changed. For example, if you memorize a poem while chewing a piece of bubblegum, but the next day you try to recite the poem without chewing any gum then it might be difficult to remember the poem because the context between encoding and retrieval is different. Retrieval interference refers to the type of passive retrieval that happens when retrieving similar memory items interfere with one another, making it more difficult to recall the desired memory. An example of this would be trying to remember where you parked your car in a parking lot that you use on a daily basis. Where you parked your car yesterday might interfere with where you parked your car today, thus making it harder to remember where your car is. The third type of passive forgetting is known as natural decay which can simply be defined as the natural loss of the biological memory engram due to the passage of time. This theory was first introduced by German psychologist Hermann Ebbinghaus after he performed a memory task on himself to learn how the passage of time affected his ability to remember. He first studied a long list of “nonsense trigrams”, or three random series of consonants and vowels, and tried to remember as many as possible. He found that after one day he could only remember about half of the original trigrams, and after one week he could only recall about one fourth of the original nonsense trigrams. He concluded that time has a negative effect on our ability to remember information. The process of active forgetting can be defined by forgetting caused by the active involvement of external or internal factors. There are currently four main mechanisms of active forgetting, which include interference-based forgetting, intrinsic forgetting, retrieval-induced forgetting, and motivated forgetting. Interference-based forgetting suggests that other competing information or activities, both before and after the learning event, can accelerate decay of

the memory engram. Calling your new pet dog by your old dog's name is an example of interference-based forgetting where your old dog's name interferes with your ability to remember the name of your new dog. Intrinsic forgetting involves the brain's natural biochemical pathway to degrade certain memory engrams. "Forgetting cells" release the neurotransmitter dopamine, which actively degrades the desired memory engram if the brain does not consider this memory to be important. Retrieval-induced forgetting is a type of active forgetting that occurs when recalling certain aspects of a memory leads to suppression of the other aspects of that memory. For example, when you tell a story about catching your first fish repeatedly to your friends, the important details of the story remain intact like what kind of fish it was and where you were fishing. However, minor details about the story, like what clothes you were wearing or what time of day it was, become harder and harder to remember. The fourth type of active forgetting is known as motivated forgetting, which occurs when cognitive mechanisms are deliberately ordered to weaken certain memories, either because we are told to or because that memory is unwanted. An example of motivated forgetting includes actively trying to forget an embarrassing moment from your childhood, like getting picked last in kickball. This memory is associated with negative emotions, and therefore, we want to forget these memories as soon as possible.

## INTRODUCTION

Our laboratory (Haynes IV, Frith, Sng, & Loprinzi, 2018; Loprinzi et al., 2019a; Loprinzi, Frith, & Edwards, 2018; Loprinzi, Frith, Edwards, Sng, & Ashpole, 2018; Ponce & Loprinzi, 2018; Siddiqui & Loprinzi, 2018), as well as other laboratories (Chang et al., 2015; Chang, Labban, Gapin, & Etnier, 2012; Etnier et al., 2016; Labban & Etnier, 2011, 2018), has demonstrated that acute exercise can enhance episodic memory function, or the retrospective recall of information from a spatial-temporal context. As we have detailed thoroughly (Loprinzi, 2019b; Loprinzi, 2019f; Loprinzi, Edwards, & Frith, 2017; Loprinzi, Ponce, & Frith, 2018), the mechanisms of this effect occur at multiple levels (El-Sayes, Harasym, Turco, Locke, & Nelson, 2019), including changes at the molecular and functional level. For example, acute exercise may upregulate levels of brain-derived neurotrophic factor (BDNF) (Loprinzi, 2019a; Loprinzi & Frith, 2019b) and insulin-like growth factor-1 (IGF-1) (Loprinzi, 2019e), which may help to facilitate long-term potentiation, (Loprinzi, 2019c) or the functional connectivity across neurons. Although research on the effects of acute exercise on episodic memory function is accumulating, much less research has examined the effects of exercise on forgetting (Ferguson, Cantrelle, & Loprinzi, 2018; Loprinzi, 2019d).

As detailed elsewhere (Davis & Zhong, 2017), forgetting is a multifarious and complex process, likely involving biological pathways that are unique from subserving the consolidation of episodic memories. Forgetting involves several passive and active processes (Davis et al., 2017; Storm, 2018). Passive forgetting may occur from the loss of contextual cues over time that make retrieval difficult, interference during retrieval from

other related memories, or the natural decay of memory traces over time due to the instability of biological materials. Active forgetting may occur from at least three forms, including memory interference (proactive and retroactive), motivated forgetting, and retrieved-induced forgetting. Active-related interference-based forgetting occurs when competing information occurs before (proactive) or after learning (retroactive), which may accelerate the decay or updating of the memory trace. Motivated forgetting occurs when cognitive mechanisms (e.g., executive control) are employed to weaken the memory trace, such as in the context of directed forgetting effects, or think/no-think memory-suppression effects. Lastly, retrieval-induced forgetting occurs when aspects of a memory are recalled, which suppresses the recall of other aspects related to the memory. The focus of this experiment relates to retrieval-induced forgetting.

Regarding retrieval-induced forgetting, empirical work suggests that retrieving a subset of items from memory can induce forgetting of other related items in memory (Anderson, Bjork, & Bjork, 1994; for a review of the many contexts in which retrieval-induced forgetting has been observed, see Storm et al., 2015). The mechanisms of this effect, however, are not clear, or at least are not universally agreed upon. It is uncertain as to whether retrieval-induced forgetting occurs from inhibition of the non-practiced items due to recall of the target items, strengthening of the memory trace associated with the target items during practice recall, competition across memory traces associated with the same cue during the attempted recall, or changes in context during the procedure that inhibits the recall of the non-target (non-practiced) items (for various reviews and perspectives, see Anderson, 2003; Jonker, Seli, & MacLeod, 2013; Murayama, Miyatsu, Buchli, & Storm, 2014; Storm & Levy, 2012; Verde, 2012). Emerging work provides

empirical support for the mechanism related to inhibition of the non-practiced items, as demonstrated by reduced blood flow in the cortical regions associated with the non-practiced items during the retrieval-induced forgetting protocol (Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015). Thus, inhibition-related executive control may be a key mechanism subserving retrieval-induced forgetting (Aslan & Bäuml, 2011; Román, Soriano, Gómez-Ariza, & Bajo, 2009; Levy & Anderson, 2002; Wu, Peters, Rittner, Cleland, & Smith, 2014). Inhibition may help resolve the competition that arises during item retrieval. In support of this inhibition-based mechanism, research demonstrates that, for non-practice items, forgetting is more likely to occur for memorable (vs. non-memorable) objects, or for items that are presumed to cause interference or competition during retrieval (Anderson et al., 1994; Reppa, Williams, Worth, Greville, & Saunders, 2017; Storm, Bjork, & Bjork, 2007). Further, the prefrontal cortex plays a critical role in inhibitory-based executive control, and research demonstrates that when neural activity in the prefrontal cortex is blocked, retrieval-induced forgetting is attenuated (Stramaccia, Penolazzi, Altoe, & Galfano, 2017).

As stated previously, very little research has evaluated the effects of exercise on forgetting (Ferguson et al., 2018; Loprinzi, 2019d), let alone retrieval-induced forgetting. A recent study (Padilla, Andres, & Bajo, 2018) demonstrated that adults who were physically active, compared to their sedentary counterparts, exhibited greater retrieval-induced forgetting, presumably as a result of greater executive control (individuals with greater working memory capacity and executive control have been shown to exhibit greater levels of retrieval-induced forgetting (Aslan & Bäuml, 2011; Schilling, Storm, & Anderson, 2014; Storm & Bui, 2016). Notably, acute exercise has been shown to enhance

executive control (Hsieh, Huang, Wu, Chang, & Hung, 2018). Other theoretical support for a relationship between exercise and retrieval-induced forgetting comes from shared affective mechanisms. Acute exercise, particularly moderate-intensity exercise, may induce a positive affective state (Edwards, Addoh, Herod, Rhodes, & Loprinzi, 2017), and some work has suggested that retrieval-induced forgetting is more likely to occur when individuals are not depressed or in a negative mood (Bäumel & Kuhbandner, 2007; Groome & Sterkaj, 2010; Storm & Jobe, 2012).

To our knowledge, only one study has evaluated the effects of acute exercise on retrieval-induced forgetting. In that experiment, we evaluated whether an acute bout of moderate-intensity exercise was associated (i.e., facilitated forgetting) with retrieval-induced forgetting (Cantrelle & Loprinzi, 2019). It did not. Specifically, we failed to observe a statistically significant difference in retrieval-induced forgetting between the exercise condition and the baseline condition. The present experiment seeks to address the main limitation of that previous study, which was the relatively small sample size ( $n = 20$  per group;  $N = 40$ ), which likely limited our statistical power to detect a statistically significant effect. Relatedly, we failed to observe a statistically significant retrieval-induced forgetting effect, which may have been a result of the small sample size and or limited number of retrieval practice trials we employed (i.e., 2 retrieval-practice sessions). As such, in the present experiment, we increased the number of retrieval-practice sessions to 4 and increased the sample size from 20 per group to 75 per group.

In addition to increasing the sample size and number of retrieval-practice sessions, herein we also evaluate whether there is an intensity-specific effect of acute exercise on retrieval-induced forgetting. An intensity-specific effect is plausible, as acute



exercise intensity may, potentially, have a differential effect on memory function and executive control. Through a systematic review (Loprinzi, 2018), we recently demonstrated that acute moderate-intensity exercise may favor executive-control-related working memory, whereas acute high-intensity exercise may favor episodic memory function. However, our recent experimental work suggests that acute high-intensity exercise may be more beneficial for executive-control-related working memory (Tillman & Loprinzi, 2019). These discrepant findings underscore the importance of additional work evaluating intensity-specific effects of acute exercise on memory and forgetting. Thus, a specific aim of this experiment was to evaluate the intensity-specific effects of acute exercise on retrieval-induced forgetting. It may be, for example, that the specific level of intensity employed in the previous study was suboptimal for enhancing retrieval-induced forgetting. Thus, in the current study, we employed moderate-intensity and high-intensity exercise conditions that were relatively less and more intense than the one we employed previously, respectively.

## METHODS

### **Study Design**

A three-arm, parallel-group randomized controlled intervention was employed. Participants were randomized into one of three groups, including two experimental groups and a control group. The experimental groups engaged in a 20-min bout of treadmill exercise (either moderate-intensity or vigorous-intensity), while the control group engaged in a seated task.

### **Participants**

Each group included 75 participants (N=225). The sample size was determined based on a power analysis utilizing results ( $\eta^2_p$  of 0.01) from our previous experiment using this paradigm, indicating a total sample size of 225 would be needed to achieve adequate statistical power (0.85, 1- $\beta$  error probability), with inputs of 0.05 ( $\alpha$  error probability), 3 groups, and an estimated effect size ( $\eta^2_p$ ) of 0.01. This sample size of 75 per group is also in line with other experiments on this paradigm (Storm & Bui, 2016).

Participant recruitment occurred via a convenience-based, non-probability sampling approach (classroom announcements and word-of-mouth). Participants included undergraduate and graduate students between the ages of 18 and 25 yrs.

Similar to other studies (Siddiqui et al., 2018; Yanes & Loprinzi, 2018), participants were excluded (not allowed to participate) if they:

Self-reported as a daily smoker (Jubelt et al., 2008; Klaming, Annese, Veltman, & Comijs, 2016)

Self-reported being pregnant (Henry & Rendell, 2007)

Exercised within 5 hours of testing (Labban et al., 2011)

Consumed caffeine within 3 hours of testing (Sherman, Buckley, Baena, & Ryan, 2016)

Had a concussion or head trauma within the past 30 days (Wammes, Good, & Fernandes, 2017)

Took marijuana or other illegal drugs within the past 30 days (Hindocha, Freeman, Xia, Shaban, & Curran, 2017)

Were considered a “heavy” alcohol user (>30/month for women; >60/month for men) (Le Berre, Fama, & Sullivan, 2017)

### **Exercise Protocol**

The acute bout of exercise lasted 20-minutes in duration, which aligns with our previous work demonstrating an effect of acute exercise on episodic memory (Delancey, Frith, Sng, & Loprinzi, 2018; Frith, Sng, & Loprinzi, 2017; Haynes IV et al., 2018; Sng, Frith, & Loprinzi, 2018). After the exercise bout, participants rested (sat and played Sudoku) for 5-minutes. After this resting period, they commenced the memory assessment.

Participants randomized into the moderate-intensity exercise group exercised at 50% of their heart rate reserve (HRR), whereas participants randomized into the vigorous-intensity exercise group exercised at 80% of their HRR.

The HRR equation used to evaluate exercise intensity is:  $HRR = [(HR_{max} - HR_{rest}) * \% \text{ intensity}] + HR_{rest}$ . To calculate  $HR_{rest}$ , at the beginning of the visit, participants sat quietly for 5 minutes, and HR was recorded from a chest-worn Polar HR monitor. To estimate  $HR_{max}$ , we calculated the participants estimated  $HR_{max}$  from the formula,  $220 - \text{age}$ .

### **Control Protocol**

Similar to other studies (McNerney & Radvansky, 2015), participants randomized to the control group completed a medium-level, on-line administered, Sudoku puzzle for 25-minutes (time-matched to the two experimental groups). The website for this puzzle is located here: <https://www.websudoku.com/>. We have experimental evidence that playing Sudoku does not prime or enhance memory function, and as a result, is a suitable control condition (Blough & Loprinzi, 2019).

### **Memory Assessment**

A standard retrieval-induced forgetting protocol was employed, which included a study phase, a retrieval-practice phase, and a final memory recall phase. In the study phase, participants were exposed to 72-word pairs, in which they were asked to memorize the paired words. In the retrieval-practice phase, participants were cued to retrieve half of the word pairs from half of the studied categories. Lastly, in the final recall phase, participants cue-recalled the 72 pairs that occurred during the study phase. In total, this task took about 10-minutes to complete. Details are described as follows.

Seventy-two category-exemplar pairs from previous research were used (Storm & Bui, 2016). The pairs consisted of 6 exemplars from 12 categories (clothing, drinks, fish, flavors, fruits, insects, metals, professions, sports, tools, trees, weapons), with half of the exemplars from each category being high-frequency exemplars (e.g., fruit-lemon, fish-trout), and the other half being low-frequency exemplars (e.g., fruit-guava, fish-puffer).

Participants viewed the 72 pairs, one at a time, in a blocked-randomized order, for 3 s each. Afterward, participants were cued to retrieve the low-frequency exemplars from half of the categories. They had up to 10 s to complete their response to each of the category-plus-two-letter-stem retrieval cues (e.g., fruit-gu\_\_\_). Participants were told that the answers would come from the earlier study phase. Four rounds of retrieval practice occurred.

After retrieval practice, participants engaged in the final recall task. This task involved the recall of all 72 pairs that had been presented during the study phase. Category-plus-one-letter-stem cues (e.g., fruit-l\_\_\_) were presented in a block-randomized order for all 36 high-frequency exemplars, which included the 18 non-practiced exemplars associated with the practiced categories (Rp- items), as well as the 18 high-frequency exemplars associated with the non-practiced categories (Nrp- items). The 36 low-frequency items, which included the 18 practiced exemplars associated with the practiced categories (Rp+ items), as well as the 18 low-frequency exemplars associated with the non-practiced categories (Nrp+), were tested subsequently. This testing order, which has been used frequently in the study of retrieval-induced forgetting, has the benefit of controlling for output interference at the time of the final test (Murayama et al., 2014). A Retrieval Induced Forgetting (RIF) effect occurs if Rp- items

are recalled less well than Nrp- items. A Retrieval Practice (RP) effect occurs if Rp+ items are recalled better than Nrp+.

### **Additional Measurements**

As a measure of habitual physical activity behavior, participants completed the Physical Activity Vital Signs Questionnaire, which reports time spent per week in moderate-to-vigorous physical activity (MVPA) (Ball, Joy, Gren, & Shaw, 2016), before beginning the study. Height/weight (BMI) was measured to provide anthropometric characteristics of the sample. Further, before, during and after the exercise and control conditions, heart rate (chest-strapped Polar monitor, F1 model) was assessed.

### **Statistical Analyses**

All statistical analyses were computed in JASP (v. 0.10). A 2 (Rp- vs. Nrp-) x 3 (Control vs. Moderate-Intensity vs. Vigorous-Intensity) RM-ANOVA was employed on the recall of the high-frequency items to assess RIF; a 2 (Rp+ and Nrp+) x 3 (Control vs. Moderate-Intensity vs. Vigorous-Intensity) RM-ANOVA was employed on the recall of the low-frequency items to assess RP. For the heart rate data, we employed a 6 (resting, 5-min, 10-min, 15-min, 20-min, post-exercise) x 3 (Control vs. Moderate-Intensity vs. Vigorous-Intensity) RM-ANOVA. When sphericity was violated, Huynh-Feldt corrections were applied. Statistical significance was set at an alpha of 0.05.

## RESULTS

Table 1 displays the demographic and behavioral characteristics of the sample.

Each group was similar regarding all participant characteristics.

Table 1. Participant characteristics.

<b>Variable</b>	<b>Control</b>	<b>Moderate-Intensity</b>	<b>Vigorous-Intensity</b>	<b>P-Value</b>
N	75	75	75	
Age, mean years	20.45 (1.16)	20.40 (1.32)	20.56 (1.21)	0.81
Gender, % Female	60.00	57.33	54.67	0.80
Race, % White	84.00	93.33	93.33	0.34
BMI, mean kg/m <sup>2</sup>	24.00 (3.36)	23.54 (3.10)	24.19 (4.05)	0.51
MVPA, mean/week	176.00 (151.8)	160.33 (126.5)	165.83 (159.1)	0.80

BMI, Body mass index

MVPA, Moderate-to-vigorous physical activity

Values in parentheses are standard deviations

ANOVA was used to calculate p-values for continuous variables (e.g., age), whereas chi-square was used for categorical variables (e.g., gender)

Figure 1 displays the physiological response (heart rate) to the exercise and control conditions. In a 3 (group) x 6 (time period) RM-ANOVA, there was a significant main effect for time period,  $F(3.32, 738.85) = 1235.1, p < .001, \eta^2 = .28$ , main effect for group,  $F(2, 222) = 993.0, p < .001, \eta^2 = .89$ , and a time period by group interaction,  $F(6.65, 738.85) = 326.7, p < .001, \eta^2 = .15$ .

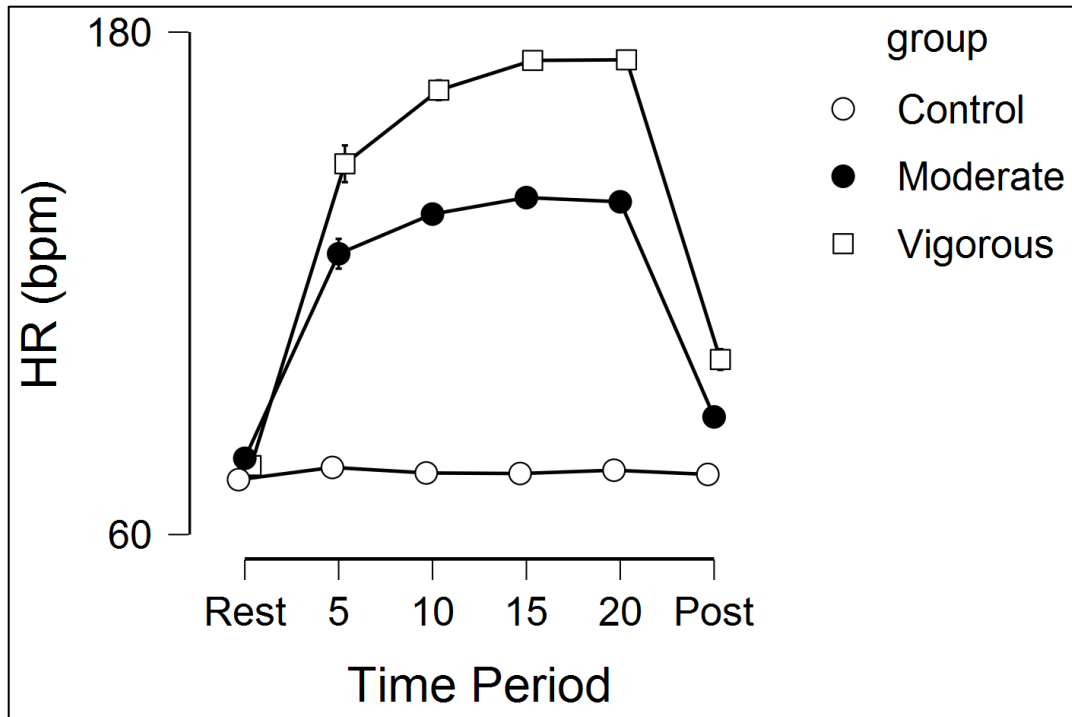


Figure 1. Heart rate (HR) responses to the exercise and control conditions. Error bars (minimally visible) represent 95% CI.

Figure 2 displays the psychological response (rating of perceived exertion) to the exercise and control conditions. In a 3 (group) x 6 (time period) RM-ANOVA, there was a significant main effect for time period,  $F(3.59, 798.1) = 707.2, p < .001, \eta^2 = .31$ , main effect for group,  $F(2, 222) = 403.7, p < .001, \eta^2 = .78$ , and a time period by group interaction,  $F(7.19, 798.1) = 177.5, p < .001, \eta^2 = .16$ .



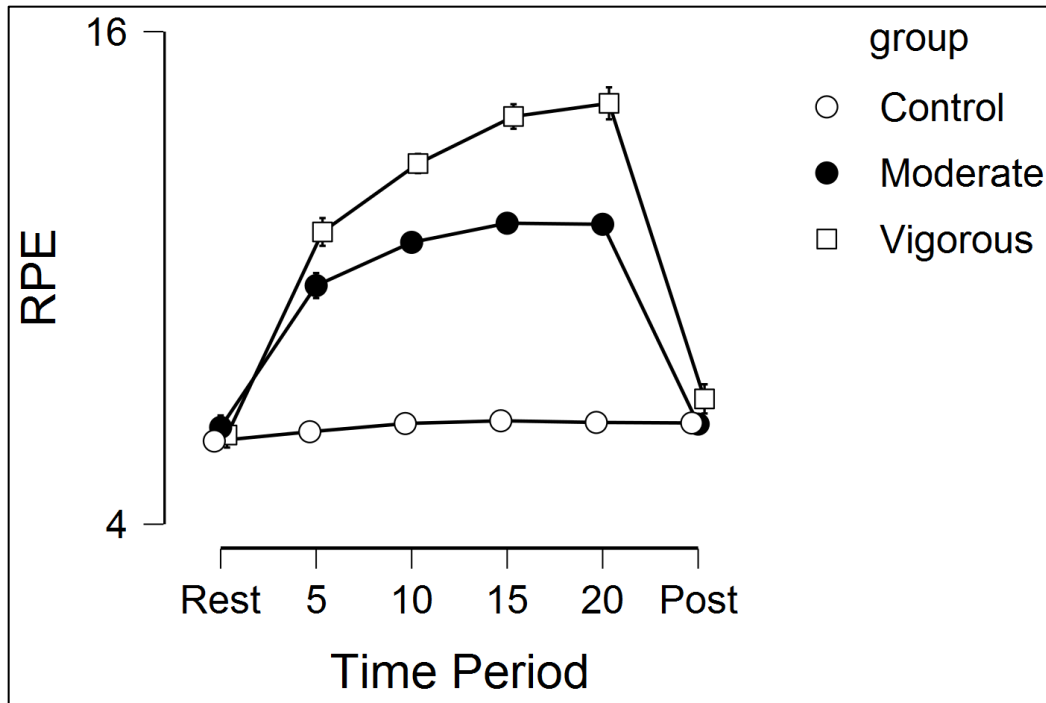


Figure 2. Rating of perceived exertion (RPE) responses to the exercise and control conditions. Error bars (minimally visible) represent 95% CI.

Table 2. RP and RIF estimates across the experimental conditions.

Condition	RP				RIF			
	Rp+	Nrp+	M <sub>diff</sub>	95% CI	Rp-	Nrp-	M <sub>diff</sub>	95% CI
Control	.593 (.164)	.226 (.117)	.367	.330-.404	.398 (.142)	.466 (.129)	-.068	-.097, -.038
Moderate	.606 (.144)	.237 (.135)	.369	.334-.403	.391 (.129)	.458 (.131)	-.067	-.097, -.037
Vigorous	.602 (.166)	.243 (.139)	.358	.322-.394	.403 (.135)	.499 (.148)	-.096	-.126, -.064

Values in parentheses are standard deviations. 95% CI represents the 95% confidence interval of the M<sub>diff</sub> (mean difference).

The left side of Table 2 displays the recall performance of the low-frequency exemplars (i.e., the items employed to measure the benefits of retrieval practice on subsequent memory) at final test across the exercise and control conditions. In a 3 (group) x 2 (Rp+ vs. Nrp+) RM-ANOVA, a significant main effect of RP was observed,  $F(1, 222) = 1244.4, p < .001, \eta^2 = .62$ , but no main effect for group,  $F(2, 222) = 0.25, p = .78, \eta^2 = .002$ , or RP by group interaction,  $F(2, 222) = .10, p = .90, \eta^2 = .0001$ . Regarding the main effect for RP, a Bonferroni-corrected post-hoc test indicated a significant difference between Rp+ and Nrp+,  $M_{diff} = -.365, SE = .01, t = 35.42, p < .001, d = 2.36$ .

The right side of Table 2 displays the recall of the high-frequency exemplars (i.e., the items employed to measure retrieval-induced forgetting) across the exercise and control conditions. In a 3 (group) x 2 (Rp- vs. Nrp-) RM-ANOVA, there was a significant main effect for RIF,  $F(1, 222) = 76.32, p < .001, \eta^2 = .07$ , but no main effect for group,  $F(2, 222) = 0.97, p = .38, \eta^2 = .009$ , or RIF by group interaction,  $F(2, 222) = 1.12, p = .32, \eta^2 = .002$ . Regarding the main effect for RIF, a Bonferroni-corrected post-hoc test indicated a significant difference between Rp- and Nrp-,  $M_{diff} = .077, SE = .009, t = 8.732, p < .001, d = .58$ .

## DISCUSSION

Accumulating research demonstrates that acute exercise may enhance memory function. Although perhaps counterintuitive, acute exercise may also help facilitate select aspects of forgetting via inhibitory-based processes. Specifically, retrieving a subset of previously encoded material may facilitate the retention of that information (RP) as well as inhibit the subsequent retrieval of the non-practiced items (RIF). Given that acute exercise has been shown to enhance cognition-related inhibition, we speculated that acute exercise may enhance the inhibition of the non-practiced items. That is, acute exercise would facilitate a RIF effect. The findings of the present experiment do not support this hypothesis.

The findings of the present experiment also align with the results of our previous preliminary experiment on this topic (Cantrelle et al., 2019). Our null exercise effects cannot, however, be a result a deficit RP or RIF effect, as our results demonstrate strong RP and RIF effects. In reflecting on our null exercise effects, several possibilities to explain these results arise. The most straightforward explanation is that acute exercise, at least within our evaluated population, simply does not have an effect on RIF. Future work on this topic will be needed to confirm or refute this assertion. As of now, however, there is no convincing evidence that an acute period of exercise influences the extent to which retrieval-induced forgetting is observed on the retrieval-practice paradigm. The current null results are compelling for multiple reasons. First, with over five times as many subjects as in the previous study, the lack of a significant effect seems unlikely to be the result of inadequate power. Second, the null effect has now been observed across three

different levels of exercise intensity, suggesting that the failure to observe an effect is unlikely due to not selecting the appropriate level of exercise intensity. Taken together, the two studies tentatively suggest that exercise may not influence executive control mechanisms in a way that has a meaningful impact on the way retrieval impacts memory. At the very least, we have found no evidence that exercise either affects the extent to which practiced items benefit from retrieval, or the extent to which non-practiced items are impaired by retrieval.

A potential alternative explanation of the current results may relate to the timing in which the memory task was implemented. In the present experiment, after exercising, participants rested (sat) for 5 min before completing the memory task. This was modeled after prior experimental work demonstrating that this is an acceptable recovery period to allow for exercise-induced enhancement effects on memory (Frith et al., 2017; Sng et al., 2018). However, perhaps any potential exercise-induced RIF effects are transient, and thus, this relatively short recovery period attenuated any possible effects. As such, future work should consider implementing this memory task during the bout of exercise. It may also be interesting to compare the consequences of exercise when isolated to particular phases of the retrieval-practice paradigm. Participants in all conditions could study the exemplars first, for example, before being administered the exercise intervention. Such a procedure would control for potential differences in how participants encode the items during study, and thus isolate potential differences in how people engage in retrieval practice (and the potential consequences of that retrieval practice). One limitation of such a design, however, is that exercise could constitute a kind of context-change manipulation, a factor which could influence whether retrieval-induced forgetting is

observed independent of the impact of exercise on executive control. Nevertheless, it does seem like an interesting avenue to explore.

In conclusion, in the present experiment, we demonstrated large retrieval-induced practice and retrieval-induced forgetting effects. However, these effects did not vary as a function of being exposed to acute exercise. Future experimental work on this under-investigated topic is needed.

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