Abstract word count: 177
Text word count: 5,511
References: 70
Tables: 3 Figures: 1

Effects of Acute Exercise Intensity on Source Episodic Memory and Metamemory Accuracy

[1]Paul Loprinzi PhD, [2]Brandon Rigdon MS, [3]Amir-Homayoun Javadi PhD, [4]William Kelemen PhD

[1]Associate Professor, Department of Health, Exercise Science and Recreation Management, University of Mississippi, Oxford, MS, USA; pdloprin@olemiss.edu

[2]Department of Health, Exercise Science and Recreation Management, University of Mississippi, Oxford, MS, USA; btrigdon@go.olemiss.edu

[3]Senior Lecturer in Cognitive Psychology and Cognitive Neuroscience, School of Psychology, University of Kent, Canterbury, United Kingdom; Institute of Neuroscience, Department of Experimental Psychology, University College London, London, United Kingdom; School of Rehabilitation, Tehran University of Medical Sciences, Tehran, Iran; a.h.javadi@gmail.com

[4]Professor and Chair, Department of Psychology, Texas State University, San Marcos, TX, USA; wkelemen@txstate.edu

Disclosures. None

Short Title: Acute Exercise on Source Memory

Corresponding Author:

Paul D. Loprinzi, PhD
Associate Professor of Health and Exercise Science
Director of Exercise & Memory Laboratory
University of Mississippi
Oxford MS, 38655
pdloprin@olemiss.edu

Abstract

Prior research suggests that behavioral (e.g., exercise) and psychological factors (e.g., metamemory; monitoring and control of one's memory processes) may influence memory function. However, there is conflicting results on the optimal intensity of acute exercise to enhance memory and whether acute exercise can also enhance metamemory. Further, very limited research has evaluated whether acute exercise can influence *source* episodic memory. The objective of this study was to evaluate whether there is an intensity-specific effect of acute aerobic exercise on source episodic memory and metamemory accuracy. Thirty young adults participated in a three condition (Control/Moderate/Vigorous-Intensity Exercise), within-subject counterbalanced experimental study. After each intervention, participants completed source episodic memory and metamemory tasks. Results demonstrated that acute exercise, relative to control, was effective in enhancing source episodic memory, but not metamemory accuracy. Vigorous-intensity acute exercise was the most optimal intensity to enhance source episodic memory. Overall, our findings suggest that there is an intensity-specific effect of acute exercise on source episodic memory. Further, when exercise-related improvements in memory occur, young adults may be unaware of these memory benefits from exercise.

Keywords: cognition; free recall; judgement of learning; learning; physical activity; recognition

Acknowledgments: We have no conflicts of interest and no funding was used to prepare this manuscript.

Effects of Acute Exercise Intensity on Source Episodic Memory and Metamemory Accuracy

Episodic memory, or the remembrance of one's own previous experience, involves integrating the context of the memory (Madan, 2020). Source memory, in particular, is an important aspect of episodic memory and includes the ability to remember the context of the memory (Johnson, Hashtroudi, & Lindsay, 1993). An example of source memory would be remembering the color a word is printed in and whether the word is new or old (i.e., previously encoded). Other, more real-world examples of source memory, include remembering where you were located when you were first introduced to a friend, or how you learned a particular fact or piece of information (e.g., from a tabloid or a news article).

The effects of acute exercise on cognition have been of great interest over the last several decades (Brisswalter, Collardeau, & Rene, 2002; Chang, Labban, Gapin, & Etnier, 2012; Gomez-Pinilla & Hillman, 2013; Lambourne & Tomporowski, 2010; Tomporowski, 2003; Tomporowski, Ellis, & Stephens, 1987). Generally, these studies provide evidence that moderate-intensity acute exercise may improve global levels of post-exercise higher-order cognition (Chang et al., 2012), with vigorous-intensity acute exercise improving post-exercise lower-order cognitions (McMorris, 2016); examples of higher-order cognitions include problem solving and decision making, whereas lower-order cognitions involve more simplistic cognitions, such as remembering and applying information (Anderson & Krathwohl, 2001). Research evaluating the specific effects of acute exercise on post-exercise episodic memory, however, has only recently started to accumulate (Loprinzi, Roig, Etnier, Tomporowski, & Voss, 2021; Most, Kennedy, & Petras, 2017; Pyke et al., 2020; Roig, Nordbrandt, Geertsen, & Nielsen, 2013). This body of research demonstrates that, among young adults, acute exercise may improve post-exercise episodic memory function (Loprinzi et al., 2019). Potential mechanisms of this effect have been discussed recently (Loprinzi et al., 2021), including, for example, encoding (e.g., attention), consolidation (e.g., increases in neurotrophins), and retrieval-based mechanisms (e.g., decisional processes).

Although accumulating research suggests that acute exercise may enhance episodic memory, limited research has specifically evaluated the effects of acute exercise on source episodic memory. Etnier et al. (2016) had participants engage in different acute exercise intensities, then encoded words from two different lists, and then 24-hours later, participants had to determine which lists (source memory) the words emanated from. Their results demonstrated that a bout of maximal acute exercise, when compared to lower exercise intensities, was optimal in enhancing attribution (source) memory performance. This finding suggests that the exercise intensity may influence source memory. The present study extends this Etnier et al. (2016) study by increasing the complexity of the source memory task by including four different potential sources, as opposed to two (lists) sources. Follow-up work on this topic has evaluated other types of source memory, including linking names with faces and remembering the color of stimuli.

A recent experiment evaluated whether acute, moderate-intensity aerobic exercise was associated with an increased ability to remember face-name pairs (Farris & Loprinzi, 2019); no significant differences were observed between exercise and control conditions. Similar results were obtained in a follow-up experiment (Gilbert & Loprinzi, 2021). A different experiment evaluated if moderate-intensity aerobic exercise was associated with source episodic memory, assessed via a word-list memory task, with half of the words in green font and the other half in red font (Rigdon & Loprinzi, 2019). Although the acute exercise group recalled more total words than the control group, there was no difference in source memory recognition (recognition of red vs. green words) between the two groups. These prior studies (Etnier et al., 2016; Farris et al., 2019; Rigdon & Loprinzi, 2019, Gilbert & Loprinzi, 2021) suggest that there may be an intensity-specific effect of exercise on source memory. However, additional work is needed to confirm this possibility. In a recent systematic review, Loprinzi (2018) demonstrated that moderate-intensity exercise was optimal for enhancing working memory (higher-order cognition), whereas vigorous-intensity exercise was optimal for enhancing memory on simple list-learning paradigms. A recent meta-analysis also suggested that vigorous-intensity exercise was the most optimal intensity to improve memory on simple list-learning paradigms (Loprinzi et al., 2019). These intensity-specific findings also align with past research focusing on global cognition, with moderate-intensity exercise being optimal for higher-order cognitions (Chang et al., 2012; McMorris, 2016). However, unlike simple memory recall tasks, which may require fewer cognitive resources, source memory tasks require integration of multiple aspects of episodic memory (e.g., semantic information). As such, it is less clear as to whether the previous findings demonstrating that vigorous-intensity exercise is optimal in enhancing episodic memory would extend to source memory paradigms.

Although research evaluating the effects of acute exercise on episodic memory is accumulating, very little research has integrated metamemory judgements (monitoring and control of one’s memory processes) into this exercise-memory context (Palmer et al., 2019; Salas, Minakata, & Kelemen, 2011; Zuniga, Mueller, Santana, & Kelemen, 2019), despite observations showing metamemory is associated with memory performance in verbal learning tasks (e.g., Schwartz & Efklides, 2012). Metamemory judgements are thought to occur from a direct-access and/or inferential approach; direct access refers to judgements being based on the perceived strength of the memory trace, whereas for the inferential approach – which provides the most support for influencing metamemory judgements – monitoring judgements are rendered from experienced-based cues (Koriat, 1997). Considering these approaches, perceptual experiences from exercise may augment metamemory judgements. For example, when rendering judgements of learning, people may rely on their beliefs about their memory abilities in different contexts; they may expect exercise to improve their memory performance, which may directly influence their metamemory judgements. Exercise may also indirectly influence these judgements. Metamemory judgements can be indirectly influenced from internal cues, such as the ease of which information comes to mind; exercise may play a role here based on select effects (e.g., enhanced information processing) of exercise on cognition. Similarly, participants may rely on experiential cues that are diagnostic of future memory performance; for example, enhanced alertness from exercise may augment metamemory judgements. Ultimately, judgements of learning may be influenced by a variety of exercise-related cues that feed into the computation of these judgements. Empirically, Palmer et al. (2019) had participants engage in 30-minutes of moderate-intensity exercise before or after studying a series of word pairs and then completed judgement evaluations before cued and recognition tasks. Their results showed that when exercise (relative to control) does not improve memory accuracy, exercise may help to increase predictions about memory performance relative to actual performance. In contrast, however, they showed that when exercise does improve memory performance, it has no effect on the accuracy of metacognition.

As stated, there is limited research evaluating the effects of acute exercise on source episodic memory and metamemory accuracy. To address these gaps in the literature, the aims of the present study are to evaluate whether there is an intensity-specific effect of acute exercise on source episodic memory and metamemory accuracy. We hypothesized that vigorous-intensity acute exercise would be optimal in enhancing source memory and metamemory.

Method

Participants

Participants were recruited from undergraduate and graduate courses at the University of Mississippi. Thirty participants (18 women) comprised the sample (see Table 1 for demographics). Using an effect size of .08 (η^2_p) (Crawford & Loprinzi, 2019), 27 participants were needed to achieve a power (1-β error probability) of 0.80 and an α of 0.05 for a 3 (Condition: Control/Moderate/Vigorous-intensity) x 2 (Time: Immediate/Delayed) repeated-measures design.

Participants were excluded if they (1) self-reported as a daily smoker (Jubelt et al., 2008; Klaming, Annese, Veltman, & Comijs, 2016); (2) self-reported being pregnant (Henry & Rendell, 2007); (3) exercised within 5 hours of testing (Labban et al., 2011); (4) consumed caffeine within 3 hours of testing (Sherman, Buckley, Baena, & Ryan, 2016); (5) took medications used to regulate emotion (e.g., SSRI's) (Bauer, 2015); (6) had a concussion or head trauma within the past 30 days (Wammes, Good, & Fernandes, 2017); (7) took marijuana or other mind-altering drugs within the past 2 days (Hindocha, Freeman, Xia, Shaban, & Curran, 2017); (8) were considered a daily alcohol user (> 30 drinks/month for women; > 60 drinks/month for men) or consumed alcohol in the past 12 hours (Le Berre, Fama, & Sullivan, 2017); or (9) answered "yes" to any of the questions (e.g., "*do you feel pain in your chest at rest, during your dailiy activities of living, or when you do physical activity*?") on the PAR-Q (Physical Activity Readiness Questionnaire); answering "yes" to items on the PAR-Q would suggest that it might not be safe to exercise and individuals should consider further advice from a qualified exercise professional or physician before exercising. These exclusion criteria were selected as they may influence memory function, and in turn, potentially confound the effects of exercise on memory function. Notably, none of the participants were excluded, as these criteria were discussed during recruitment, and thus, no participants meeting any of these criteria signed up to participate.

Study Design and Procedures

This study was approved by the ethics committee at the University of Mississippi. All participants provided written consent prior to participation. The present experiment included a three condition, within-subject counterbalanced experimental design that occurred over four sessions. The first session (Visit 1) included a maximal treadmill-based exercise protocol, used to evaluate the participant's cardiorespiratory fitness (see below for details). During this first visit, prior to the maximal exercise test, participants were familiarized to the source episodic memory task (i.e., completed a practice assessment that did not include items for the subsequent sessions). Visit 2 occurred 48-72 hours after Visit 1. Visits 2-4 occurred in a counterbalanced order, and for these three visits, which occurred 24-72 hours apart, participants engaged in either a control scenario, moderate-intensity exercise protocol, or a vigorous-intensity bout of treadmill exercise. Allocation concealment occurred by both the researcher and participant not knowing which condition was to be completed until arriving in the lab.

In each experimental session (Visits 2-4), participants completed 25 minutes of the intervention (Control/Moderate/Vigorous-intensity Exercise), followed by the memory protocol.

Cardiorespiratory Fitness Assessment

The first laboratory visit (Visit 1) included a maximal treadmill-based cardiorespiratory fitness assessment (via indirect calorimetry). The specific VO_{2max} (volume of maximum oxygen consumption) assessment included an individualized protocol (Mier & Gibson, 2004). Participants warmed-up for 3 minutes by walking at 3.5 miles per hour. Following this, they engaged in a constant speed throughout the test while the grade increased by 2% every 2 minutes. Participants were asked to select an initial running speed (0% incline) that elicited a rating of perceived exertion of 12-13 (somewhat hard) on a 6-20 Borg scale (Borg, 1982).

During the maximal treadmill test, VO_2 and heart rate (HR) were monitored throughout the test. Heart rate was measured every minute using a portable HR monitor (Polar, H10, Lake Success, NY, USA) and metabolic measurements were made every 30 seconds with an automated metabolic measurement system (Parvo Metabolic Cart). Analyzers were calibrated with medical-grade calibration gas (16.01% O2; 3.97% CO2); a Rudolph 3-L calibration syringe (Shawnee, OK, USA) was used for volume calibrations as per manufacturer specifications. Similar to other work (Loprinzi & Brodowicz, 2008), the criteria used to define VO_{2max} included (a) a respiratory exchange ratio >1.10, (b) a plateau in VO_2 (increase < 150 mL/min with increase in treadmill speed or incline), (c) a HR_{max} within 10% of the age-predicted maximum (220 - age), and (d) a rating of perceived exertion > 16 on a 6-20 point scale. In the present sample, 68% of the participants reached a max, with the remaining 32% achieving a peak. VO_{2max} was determined as the highest 30-second VO_2 measured when at least three of the four criteria are satisfied.

Five participants (out of 30) did not have metabolic data, as the final five participants were recruited after COVID-19 started, and to minimize safety concerns, metabolic data was not collected among these participants; these five participants, however, still completed the initial exercise visit to determine their maximal heart rate. Participants (n = 5) recruited after the outbreak of COVID-19 were required to wear a mask through the entire protocol of the study to comply with mandates. Masks were used during the exercise protocols and participants were screened for COVID-19 as well.

Exercise Intensity Assessments

Visits 2-4 involved three counterbalanced visits involving a control condition, moderate-intensity exercise, and vigorous-intensity exercise. The control visit involved a time-matched (25 minute) seated task (self-selected video, either The Office or The Big Bang Theory). There is experimental evidence suggesting that this type of control task (video viewing) does not prime or enhance memory function (Blough & Loprinzi, 2019) and has also been used in other related experiments (McNerney et al., 2015).

The Moderate and Vigorous-intensity conditions consisted of 20 minutes of moderate or vigorous-intensity continuous (not intermittent) exercise followed by 5 minutes of seated rest, respectively; a 5 minute recovery period was selected based on prior work (Frith, Sng, & Loprinzi, 2017; Loprinzi et al., 2021) demonstrating that acute exercise can enhance memory following a 5 minute recovery period. In the Moderate and Vigorous exercise conditions, participants exercised at 64-76% and 77-95% of their HR_{max} (based on the measurements in Visit 1), respectively (Garber et al., 2011). The target heart rate was the mid-point of the range (i.e. 70% and 86% of their HR_{max} for the two conditions), with the goal of reaching this target heart rate by the midpoint of the exercise bout. The treadmill speed and incline were adjusted to achieve the target heart rate.

At baseline, every 5 minutes during the 20-min exercise, and at 5 minutes post-exercise, heart rate and rating of perceived exertion (RPE) were assessed. Heart rate was measured via a chest-strap Polar heart rate monitor (H10 model) and RPE was measured using a 6-20 Borg scale

(Borg, 1982); 6 represents "no exertion at all", 9 "very light", 13 "somewhat hard", 15 "hard", 17 "very hard", 19 "extremely hard", and 20 "maximal exertion".

Source Episodic Memory Assessment.

Protocol. A schematic of the source episodic memory protocol is shown in Figure 1. An identical protocol of the source episodic memory assessment was administered across the three experimental conditions, with different stimuli included in each session. Modeled after recent research looking at predictors (e.g., stress, diet) of source memory performance (Cansino et al., 2019), the source episodic memory task, administered on a computer, included an encoding and retrieval phase of natural (e.g., fern) and artificial (e.g., table) common objects. All images came from an image-bank used in prior research (Cansino et al., 2019). During the encoding phase, participants were exposed to 16 different images (8 natural and 8 artificial common objects), with each image presented on the screen, one at a time, for 3 seconds; this number of images (i.e., 16) aligns with other studies showing that acute exercise can improve memory using memory tasks involving a similar number (e.g., 15) of items (Frith, Sng & Loprinzi, 2017; Loprinzi et al., 2021). The image was placed in either quadrant 1, 2, 3, or 4 (counterbalanced). Participants were instructed to try to memorize the object and where the object was placed.

After the first round of encoding (i.e., being exposed to all 16 images), participants completed a second round of encoding, which was identical to the first round. During this second round of encoding, after viewing each image (same images as in the first round), participants completed a judgement of learning (JOL; Salas et al., 2011). Participants were asked to indicate their confidence in response to this question, "*On a scale of 0 (definitely will not) to 100 (definitely will), how likely are you to remember this image and which quadrant it is located in?*" Six response options were allowed (0%, 20%, 40%, 60%, 80%, and 100% confidence).

After the second round of encoding, participants completed a free recall (i.e., they were asked to recall (verbally) as many of the images as possible; Immediate Free Recall Phase). Following this, they were exposed to 32 images (presented in a random order), half of which were old (i.e., 16 images from the encoding phase) and half were new (eight natural and eight artificial new images). Each image was presented in the middle of the screen, one at a time, for 10 seconds. At this time, they were asked, "*Is this image old or new? If old, what quadrant was it previously in?*" Once the 10 second period elapsed, a new image appeared.

Subsequently, participants engaged in a 20-minute distractor task, involving watching a 20 min video clip (either The Office or The Big Bang Theory), which is similar to other studies (Javadi, Cheng & Walsh, 2012). They were instructed to watch the video closely, as at the end of the video, they would be asked to write down details about three different scenes from the video. This was employed to minimize potential rehearsal of the previously viewed images from the source memory encoding phase.

After this 20-minute distraction phase, participants engaged in a free recall task (Delayed Free Recall Phase). Following this, they completed a source memory recognition task (Delayed Source Memory Recognition Phase) by viewing all 32 images, and after each image, they were asked, "*Is this image old or new? If old, what quadrant was it previously in?*" They were instructed that "old" images were those shown during the encoding phase. Notably, for the present experiment, we implemented both an immediate and delayed memory assessment, as, at this point, it is unclear if the long-term memory benefits from acute exercise are influenced by exercise-induced short-term memory effects (Moore, Ryu & Loprinzi, 2020). To allow for a more comprehensive assessment of acute exercise on memory, both short- (immediate) and long-term (delayed) memory assessments were employed.

The primary dependent measures, for both the immediate and delayed assessments, included (1) free recall, (2) d-prime (d′), (3) JOL magnitude, and (4) metamemory accuracy. The d′ was calculated as: (z(hit) – z(false alarm)) (Stanislaw & Todorov, 1999); hits defined as identifying the correct quadrant and false alarms as identifying new items as old. Judgement of learning magnitude was calculated as the mean proportion from the JOL assessment. Bias scores were computed to evaluate metamemory. Specifically, free recall bias was calculated as: (JOL mean % - free recall %). Recognition bias was calculated as: (JOL mean % - Recognition Percent Correct %). Recognition percent correct was calculated as: ((Hit + Correct Rejection) / 32). These free recall and recognition bias scores greater than zero reflect over-confidence, whereas bias scores less than zero reflect under-confidence.

Statistical Analyses

All analyses were computed in JASP (v 0.14.0.0, University of Amsterdam, Netherlands). For the memory analyses, in a repeated measures ANOVA (rANOVA), factors included: Time (two levels: Immediate and Delayed) and Condition (three levels: Control, Moderate, and Vigorous-intensity). Both factors were within-subject factors. For the rANOVA analyses, eta-square (η^2) estimates are provided as estimates of effect size. For the simple effect analyses, Cohen's d estimates are provided as estimates of effect size. Statistical significance was established as an alpha less than .05.

Results

Table 1 displays the demographic, behavioral and metabolic characteristics of the sample. The participants, on average, were 22.1 (SD = 2.6) years of age (range = 18-30), predominately female (60%), sufficiently active (156.5 min/week), and varied on their cardiorespiratory fitness.

Manipulation Check

Table 2 displays the heart rate (HR) and rating of perceived exertion (RPE) data across the study conditions. As a manipulation check, our results demonstrate that HR and RPE were stable in the Control condition, but differentially increased in the Moderate- and Vigorous-intensity conditions. In a 5 (Time: baseline, 5 min, 10 min, 15 min and endpoint) × 3 (Condition: Control, Moderate, Vigorous-intensity) rANOVA with HR as the outcome, we observed a significant main effect for Condition, $F(2, 56) = 499.1$, $p < .001$, $\eta^2 = .58$, and a significant main effect for Time, $F(4, 112) = 148.1$, $p < .001$, $\eta^2 = .19$, which was qualified by a significant interaction effect, $F(8, 224) = 99.9$, $p < .001$, $\eta^2 = .12$. Results were similar for ratings of perceived exertion.

Source Episodic Memory

Recall. Table 3 displays the source episodic memory results. In a 2 (Time: Immediate and Delayed) × 3 (Condition: Control, Moderate, Vigorous-intensity) rANOVA with free recall as the outcome, we observed a significant main effect for Condition, $F(2, 58) = 3.39$, $p = .04$, $\eta^2 = .06$, but no significant main effect for Time, $F(1, 29) = .18$, $p = .68$, $\eta^2 < .001$, or interaction effect, $F(2, 58) = 1.14$, $p = .33$, $\eta^2 = .01$. Collapsed across time, Control was not significantly different than Moderate-Intensity, $M_{diff} = .016$, $p = .49$, d = .13, and Moderate-Intensity was not different than Vigorous-Intensity, $M_{diff} = .042$, $p = .14$, d = .33, but Control was significantly worse than Vigorous-Intensity, $M_{diff} = .057$, $p = .04$, d = .46.

d-Prime. In a 2 (Time: Immediate and Delayed) × 3 (Condition: Control, Moderate, Vigorous-intensity) rANOVA with d' as the outcome, we observed a significant main effect for Condition, $F(2, 58) = 3.83$, $p = .03$, $\eta^2 = .09$, but no significant main effect for Time, $F(1, 29) = 2.08$, $p = .16$, $\eta^2 = .006$, or interaction effect, $F(2, 58) = 1.52$, $p = .23$, $\eta^2 = .004$. Collapsed across time, Control was not significantly different than Moderate-Intensity, $M_{diff} = .37$, $p = .09$, d =

.36, and Moderate-Intensity was not different than Vigorous-Intensity, M_{diff} = .12, *p* = .53, d = .12, but Control was significantly worse than Vigorous-Intensity, M_{diff} = .48, *p* = .03, d = .48.

Metamemory. Table 3 displays the metamemory results. In a one-way rANOVA, there was no significant difference in JOL magnitude across the three Conditions, $F(2, 56) = 2.61$, $p = .08$, $\eta^2 = .08$. In a 2 (Time: Immediate and Delayed) × 3 (Condition: Control, Moderate-Intensity, and Vigorous-Intensity) rANOVA with free recall bias as the outcome, we did not observe a significant main effect for Condition, $F(2, 58) = .399$, $p = .67$, $\eta^2 = .01$, main effect for Time, $F(1, 29) = .17$, $p = .68$, $\eta^2 = .0001$, or Condition × Time interaction, $F(2, 58) = 1.14$, $p = .33$, $\eta^2 = .01$. Similarly, with recognition percent correct bias as the outcome, we did not observe a significant main effect for Condition, $F(2, 58) = 2.11$, $p = .13$, $\eta^2 = .06$, main effect for Time, $F(1, 29) = .17$, $p = .23$, $\eta^2 = .002$, or Condition x Time interaction, $F(2, 58) = 1.51$, $p = .22$, $\eta^2 = .001$.

In addition to making comparisons across conditions, we also compared the mean bias scores within each condition to zero by using 95% confidence intervals. As can be seen from the 95% confidence intervals shown in Table 3, across all conditions, recall bias scores differed from zero for at least one of the time periods (i.e., immediate or delayed). Relatedly, all recognition bias scores differed from zero across all conditions and time periods. Lastly, in addition to calculating absolute accuracy of metamemory judgements (i.e., difference between mean JOLs and mean memory accuracy), we also calculated relative accuracy of metamemory judgements (gamma correlations), but we did not observe any associations between exercise and relative accuracy of metamemory judgements, *p*’s > .05 (see Appendix). For completeness, additional sensitivity analyses (e.g., moderation effects) and results for source memory and metamemory are shown in the appendix.

Discussion

The aims of the present experiment were to evaluate whether there is an intensity-specific effect of acute exercise on source episodic memory and metamemory accuracy. Our findings demonstrate that vigorous-intensity acute exercise was more beneficial in enhancing source episodic memory when compared to no exercise. Acute exercise did not influence metamemory accuracy.

Several previous reviews have evaluated the effects of acute exercise on cognition (Basso & Suzuki, 2017; Brisswalter et al., 2002; Chang et al., 2012; McMorris, 2016; Pontifex et al., 2019; Tomporowski, 2003). Regarding global cognition, Chang et al. demonstrated that light- and moderate-intensity exercise were favorable in improving global cognition when cognition was performed immediately after exercise; when there was a delay, light, moderate, and vigorous-intensity exercise improved cognition. However, as demonstrated by McMorris (2016), lower-level cognitive tasks may benefit more from vigorous-intensity exercise. Importantly, as pointed out by Pontifex et al. (2019), it may be premature to make strong statements about the intensity-dependent findings on cognition given that the majority of studies have failed to provide sufficient details to determine the intensity of the activity. Thus, these collective findings underscore the importance of interpreting intensity-dependent findings based on the cognitive task type and accuracy of the intensity of the activity.

One strength of this study was that we utilized intensity-thresholds based on maximal heart rates observed during the initial cardiorespiratory fitness test rather than employing a prediction equation to estimate exercise intensity. As noted earlier, prior research suggests that vigorous-intensity acute exercise may benefit lower-level cognitions. In contrast, higher-order cognitions, such as interference or inhibitory control, may benefit from low- to moderate-intensity acute exercise. According to a qualitative review by Loprinzi (2018), when acute exercise occurs before the memory task, vigorous-intensity exercise may be less favorable for working memory but may favor episodic memory. This also aligns with a meta-analysis by Loprinzi et al. (2019) showing that vigorous-intensity acute exercise (vs. control) was more effective in enhancing episodic memory when compared to moderate-intensity acute exercise (vs. control).

The present experiment aligns with the findings of these review papers, as well as with a recent experiment by Crawford and Loprinzi (2019) showing that vigorous-intensity acute exercise (vs. control) was more optimal in enhancing paired-associative memory when compared to moderate-intensity acute exercise (vs. control). Other related research shows that maximal exercise intensity may even have greater effects on memory when compared to vigorous-intensity acute exercise (Etnier et al., 2016). Importantly, the timing of acute exercise (i.e., the rest period between exercise and memory encoding) may play an important role on the relationship between exercise intensity and memory (Labban et al., 2011, 2018; Roig et al., 2016; Slutsky-Ganesh, Etnier, & Labban, 2020; Loprinzi et al., 2021). Couched within the above, the present experiment extends prior work by also showing that vigorous-intensity exercise favors source memory. In addition to an evaluation of source memory, our evaluated task also reflects aspects of spatial memory. Although limited research has evaluated the effects of acute exercise on spatial memory in humans, our results support the general pattern of findings in animal models, showing enhanced spatial memory following (chronic) exercise engagement (Zou, Yu, Liu, & Loprinzi, 2020).

The mechanisms through which vigorous-intensity acute exercise may favor episodic memory remain unclear (El-Sayes, Harasym, Turco, Locke, & Nelson, 2019; Loprinzi, Edwards,

& Frith, 2017; Loprinzi, Ponce, & Frith, 2018). Winter et al. (2007) demonstrated that vigorous-intensity acute exercise improved learning, which was correlated with exercise-induced increases in brain-derived neurotrophic factor (for opposing results, see Etnier et al., 2016, and Loprinzi, 2019), dopamine and epinephrine. Alterations in these proteins and catecholamines may help facilitate encoding and consolidation mechanisms of memory (Roozendall & Hermans, 2017). Further, and as discussed by Brisswalter et al. (2002), high levels of adrenaline are associated with an improvement in memory capacity or information processing efficacy (Clark, Geffen, & Geffen, 1989). The inverted arousal-cognition hypothesis suggests that moderate levels of arousal may be optimal in enhancing cognition; for further details on specific mechanisms of exercise-related arousal on cognition, the reader is referred to the reviews of McMorris (2016) and Pontifex et al. (2019). However, the complexity of the cognitive task may play an important role in how arousal influences cognition; lower-level cognitions may benefit more from higher levels of arousal. Memory tasks including free, cued, and source recall may vary in the level of cognitive engagement. Assuming a link between effort-based decision making and cognitive resources (Westbrook & Braver, 2015), while also assuming that source memory tasks may require greater cognitive effort, source memory may require greater cognitive resources than free- and cued-recall. Indeed, neuroimaging research demonstrates that various brain regions (e.g., medial temporal lobe, prefrontal cortex) are involved in source memory, including the integration of several complex features (e.g., perceptual information, spatial details, semantic information) that make up the episodic memory (Mitchell & Johnson, 2009). As such, our findings suggest that even vigorous-intensity acute exercise may benefit more complex cognitions, such as source episodic memory. Nevertheless, it would be interesting for future research to re-evaluate this topic by manipulating aspects of arousal and source memory complexity. Unlike the present study, which implemented a 5-minute recovery period after exercise, altering the post-exercise recovery period prior to memory encoding may impact the effect of vigorous-intensity acute exercise on source memory. For example, implementing 1-, 5-, 10-, 15-, and 30-minute rest periods between the cessation of exercise and memory encoding should induce different levels of exercise-induced arousal prior to memory encoding. Altering the complexity of the source memory task may also be worth considering. This could be evaluated by altering perceptual information (e.g., size/color of the objects), spatial information (e.g., using more spatial configurations or more involved environmental scenarios), semantic information (e.g., paired-associative items), emotional information (e.g., neutral and emotional items), and/or the cognitive operations engaged during the task (e.g., mental imagery). Further, the degree of cognitive engagement not only during the cognitive task, but during the bout of exercise, would be worth exploring in future research (Elkana, Louzia-Timen, Kodesh, Levy, & Netz, 2020).

We did not observe any exercise-related effect on metamemory; JOL magnitude did not differ across the conditions. Similarly, bias scores (JOL magnitude – recall/recognition) were not different across conditions. Further, there was no consistent observation that bias scores were less likely to differ from zero within a particular condition (control, moderate, or vigorous). Consequently, these results suggest that our observed effects of vigorous-intensity exercise on memory were not driven by judgements of learning. Our findings are similar to those of Salas et al. (2011) and Zuniga et al. (2019). For example, Salas et al. demonstrated that walking before memory encoding was effective in enhancing free recall when compared to a seated condition, but metamemory was not different between conditions. Collectively, these findings suggest that when exercise-related improvements in memory occur, individuals may be unaware of these memory benefits from exercise. An important note of these metamemory results was the unexpected finding that participants, in general, had reduced confidence in their subsequent ability to accurately recall and recognize the information learned in the study phase. Generally, participants demonstrate overconfidence in calibration for item-by-item judgements of learning (Koriat, 1997). Although speculative, it is possible that our metamemory results demonstrating under-confidence may be due to our relatively high recall and recognition rates. Overconfidence results when confidence perceptions exceed memory performance, and in our case, relatively high levels of memory performance may make it challenging to observe higher levels of confidence. Future work on this topic may wish to create a more challenging memory task, or extend the retention interval, in order to avoid this issue. Another interesting possibility is that perhaps acute exercise indirectly influenced metamemory via the *hard-easy effect* (Ferrell & McGoey, 1980; Gigerenzer, Hoffrage, & Kleinbölting, 1991); factors that impair memory performance may induce overconfidence, whereas factors (e.g., exercise) that increase memory performance may reduce overconfidence, or in our case, induce under-confidence.

Notable strengths of our experiment include the direct measurement of cardiorespiratory fitness via indirect calorimetry, employing a maximal bout of exercise to guide the thresholds used to evaluate the different exercise intensities, implementing a within-subject design, evaluating multiple exercise intensities, and evaluating an under-investigated outcome (i.e., source memory and metamemory) within the exercise-memory literature. Despite these strengths, design manipulations in future research can help further our understanding of this topic. It is possible that the timing of our JOL assessment may have been less than ideal. Although prior research demonstrates that immediate judgements of learning show above-chance accuracy, delayed judgements of learning demonstrate a stronger correlation with memory accuracy (Bui, Pyc, & Bailey, 2018; Townsend & Heit, 2011). As such, future work on this topic may wish to include delayed, rather than immediate, judgements of learning. Another design-related issue to consider in future research is whether our two memory assessments (immediate and delayed) within a relatively short time period (i.e., 20 minutes) may have potentially masked select effects of acute exercise on memory. However, we intentionally implemented these two assessment periods as recent work suggests that acute exercise may not only enhance long-term memory (reason for delayed assessment) via consolidation-based mechanisms, but may also enhance immediate memory (reason for immediate assessment) through encoding-based mechanisms (Loprinzi et al., 2021). Relatedly, in some cases, the delayed memory performance was greater than the immediate memory performance, suggesting that the immediate memory assessment may have provided an opportunity for retrieval practice which, in turn, may have benefited delayed memory performance. This area of research would also benefit from additional long-term follow-up assessments, which would allow for forgetting curves to be fit and predictions about the effect of acute exercise on future memory performance. Further, although our memory task was modeled after prior work (Cansino et al., 2019), future research should consider a more comprehensive assessment of source memory. For example, a systematic assessment of stimulus (e.g., what the stimulus is) and context (e.g., spatial-temporal aspects of where the stimulus was encountered and whom it was received from) features would extend our understanding of the effects of acute exercise on source memory. Additionally, careful consideration should be made when incorporating recall and recognition assessments. In the present experiment, stimuli were encoded visually, which matched the recognition assessment, but mismatched the free recall, which was a verbal assessment. This potential concern, however, may have been less of an issue in the present experiment, as acute vigorous-intensity exercise improved both free recall and recognition performance. Additionally, to better align with our recall measure, which was expressed on a continuous scale, future work may wish to use a continuous sliding scale for the JOL assessment. Regarding sample characteristics, our sample was relatively active and fit, which may not generalize to other young adult samples. Another area worth noting is that our observed rating of perceived exertion values for the moderate- and vigorous-intensity conditions were lower than expected (Garber et al., 2011). It may be useful for future work to prescribe intensity not off of maximal heart rate or ratings of perceived exertion, but rather, from submaximal anchors, such as the ventilatory threshold (Jamnick, Pettitt, Granata, Pyne, & Bishop, 2020). Regarding exercise intensity, we employed a gradual approach to increase the heart rate to the target value. This approach allowed us to ensure that participants exercised for the full duration (20 minutes), but a limitation is that participants did not exercise for the full 20 minutes within the respective intensity zone. Lastly, we cannot fully discount the possibility that our results, in some way, may be driven by an expectation-induced effect. As demonstrated recently (Blough & Loprinzi, 2019), acute exercise (v control) may increase expectations that exercise may improve memory.

In conclusion, our findings provide suggestive evidence that vigorous-intensity acute exercise, when compared to a seated rest condition, may be effective in enhancing free recall and source memory. Individuals may also be unaware of the memory benefits from acute exercise.

References

Anderson, L. W. & Krathwohl, D. R. (2001). A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives. New York: Longman.

Ball, T. J., Joy, E. A., Gren, L. H., & Shaw, J. M. (2016). Concurrent Validity of a Self-Reported Physical Activity "Vital Sign" Questionnaire With Adult Primary Care Patients. *Preventing Chronic Diseases*, *13*, E16. https://doi.org/10.5888/pcd13.150228

Basso, J. C., & Suzuki, W. A. (2017). The Effects of Acute Exercise on Mood, Cognition, Neurophysiology, and Neurochemical Pathways: A Review. *Brain Plastisticity, 2*(2), 127-152. https://doi.org/10.3233/BPL-160040

Bauer, E. P. (2015). Serotonin in fear conditioning processes. *Behavioral Brain Research, 277*, 68-77. https://doi.org/10.1016/j.bbr.2014.07.028

Blough, J., & Loprinzi, P. D. (2019). Experimental manipulation of psychological control scenarios: Implications for exercise and memory research. *Psych, 1*(1), 279-289. https://doi.org/10.3390/psych1010019

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377-381. http://dx.doi.org/10.1249/00005768-198205000-00012

Brisswalter, J., Collardeau, M., & Rene, A. (2002). Effects of acute physical exercise characteristics on cognitive performance. *Sports Medicine, 32*(9), 555-566. https://doi.org/10.2165/00007256-200232090-00002

Bui, Y., Pyc, M. A., & Bailey, H. (2018). When people's judgments of learning (JOLs) are extremely accurate at predicting subsequent recall: the "Displaced-JOL effect". *Memory, 26*(6), 771-783. https://doi.org/10.1080/09658211.2017.1406523

Cansino, S., Torres-Trejo, F., Estrada-Manilla, C., Ramirez-Barajas, L., Perez-Loyda, M., Nava-Chaparro, A., . . . Ruiz-Velasco, S. (2019). Predictors of Source Memory Success and Failure in Older Adults. *Frontiers in Aging Neuroscience, 11*, 17. https://doi.org/10.3389/fnagi.2019.00017

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Research, 1453*, 87-101. https://doi.org/10.1016/j.brainres.2012.02.068

Clark, C. R., Geffen, G. M., & Geffen, L. B. (1989). Catecholamines and the covert orientation of attention in humans. *Neuropsychologia, 27*(2), 131-139. https://doi.org/10.1016/0028-3932(89)90166-8

Crawford, L., & Loprinzi, P. D. (2019). Effects of intensity-specific acute exercise on paired-associative memory and memory interference. *Psych, 1*(1), 290-305. https://doi.org/10.3390/psych1010020

El-Sayes, J., Harasym, D., Turco, C. V., Locke, M. B., & Nelson, A. J. (2019). Exercise-Induced Neuroplasticity: A Mechanistic Model and Prospects for Promoting Plasticity. *The Neuroscientist, 25*(1), 65-85. https://doi.org/10.1177/1073858418771538

Elkana, O., Louzia-Timen, R., Kodesh, E., Levy, S., & Netz, Y. (2020). The effect of a single training session on cognition and mood in young adults – is there added value of a dual-task over a single-task paradigm? *International Journal of Sport and Exercise Psychology*. https://doi.org/10.1080/1612197x.2020.1854821

Etnier, J. L., Wideman, L., Labban, J. D., Piepmeier, A. T., Pendleton, D. M., Dvorak, K. K., & Becofsky, K. (2016). The Effects of Acute Exercise on Memory and Brain-Derived

Neurotrophic Factor (BDNF). *Journal of Sport Exercise Psychology, 38*(4), 331-340. https://doi.org/10.1123/jsep.2015-0335

Farris, A., & Loprinzi, P. D. (2019). Experimental investigation of the effects of acute exercise on real-world ecological memory. *Journal of Science in Sport and Exercise, 1*(1), 88-93. https://doi.org/10.15171/hpp.2018.28

Ferrell, W. R. & McGoey, P. J. (1980). A model of calibration for subjective probabilities. *Organizational Behavior and Human Performance*, 26, 32–53.

Frith, E., Sng, E., & Loprinzi, P. D. (2017). Randomized controlled trial evaluating the temporal effects of high-intensity exercise on learning, short-term and long-term memory, and prospective memory. *European Journal of Neuroscience, 46*(10), 2557-2564. https://doi.org/10.1111/ejn.13719

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I. M., . . . American College of Sports, M. (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Medicine and Science in Sports and Exercise, 43*(7), 1334-1359. https://doi.org/10.1249/MSS.0b013e318213fefb

Geurten, M., Vincent, E., Van der Linden, M., Coyette, F., & Meulemans, T. (2016). Working memory assessment: Construct validity of the Brown-Peterson Test. *Canadian Journal of Behavioural Science / Revue canadienne des sciences du comportement, 48*(4), 328–336.

Gigerenzer, G., Hoffrage, U. & Kleinbölting, H (1991). Probabilistic mental models: A Brunswikian theory of confidence. *Psychological Review*, 98, 506–528.

Gilbert, M. & Loprinzi, P. D. (2021). The effects of high-intensity acute exercise on face-name memory in healthy young adults. Journal of Science in Sport and Exercise. https://doi.org/10.1007/s42978-021-00120-6

Gomez-Pinilla, F., & Hillman, C. (2013). The influence of exercise on cognitive abilities. *Comprehensive Physiology, 3*(1), 403-428. https://doi.org/10.1002/cphy.c110063

Henry, J. D., & Rendell, P. G. (2007). A review of the impact of pregnancy on memory function. *Journal of Clinical and Experimental Neuropsychology, 29*(8), 793-803. https://doi.org/10.1080/13803390701612209

Hindocha, C., Freeman, T. P., Xia, J. X., Shaban, N. D. C., & Curran, H. V. (2017). Acute memory and psychotomimetic effects of cannabis and tobacco both 'joint' and individually: a placebo-controlled trial. *Psychological Medicine*, 1-12. https://doi.org/10.1017/S0033291717001222

Jamnick, N. A., Pettitt, R. W., Granata, C., Pyne, D. B., & Bishop, D. J. (2020). An examination and critique of current methods to determine exercise intensity. *Sports Medicine*, 50, 1729-1756.

Javadi, A. H., Cheng, P., & Walsh, V. (2012). Short duration transcranial direct current stimulation (tDCS) modulates verbal memory. *Brain Stimulation*, 5(4), 468-474.

Johnson, M. K., Hashtroudi, S., & Lindsay, D. S. (1993). Source monitoring. *Psychological Bulletin, 114*(1), 3-28. https://doi.org/10.1037/0033-2909.114.1.3

Jubelt, L. E., Barr, R. S., Goff, D. C., Logvinenko, T., Weiss, A. P., & Evins, A. E. (2008). Effects of transdermal nicotine on episodic memory in non-smokers with and without schizophrenia. *Psychopharmacology (Berl), 199*(1), 89-98. https://doi.org/10.1007/s00213-008-1133-8

Klaming, R., Annese, J., Veltman, D. J., & Comijs, H. C. (2016). Episodic memory function is affected by lifestyle factors: a 14-year follow-up study in an elderly population. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology, and Cognition*, 1-15. https://doi.org/10.1080/13825585.2016.1226746

Koriat, A. (1997). Monitoring one's own knowledge during study: A cued-utilization approach to judgements of learning. *Journal of Experimental Psychology-General*, 126, 349-370.

Labban, J. D., & Etnier, J. L. (2011). Effects of acute exercise on long-term memory. *Research Quarterly for Exercise and Sport, 82*(4), 712-721. https://doi.org/10.1080/02701367.2011.10599808

Labban, J. D., & Etnier, J. L. (2018). The Effect of Acute Exercise on Encoding and Consolidation of Long-Term Memory. *Journal of Sport and Exercise Psychology, 40*(6), 336-342. https://doi.org/10.1123/jsep.2018-0072

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

Le Berre, A. P., Fama, R., & Sullivan, E. V. (2017). Executive Functions, Memory, and Social Cognitive Deficits and Recovery in Chronic Alcoholism: A Critical Review to Inform Future Research. *Alcoholism Clinical & Experimental Research*. https://doi.org/10.1111/acer.13431

Loprinzi, P. D. & Brodowicz, G. R. (2008). Physiological adaptations and analysis of training content in high school cross-country runners. *Research in Sports Medicine*, 16, 189-202.

Loprinzi, P. D. (2018). Intensity-specific effects of acute exercise on human memory function: considerations for the timing of exercise and the type of memory. *Health Promotion Perspectives, 8*(4), 255-262. https://doi.org/10.15171/hpp.2018.36

Loprinzi, P. D. (2019). Does brain-derived neurotrophic factor mediate the effects of exercise on memory? *The Physician and Sportsmedicine*, 1-11. https://doi.org/10.1080/00913847.2019.1610255

Loprinzi, P. D., Blough, J., Crawford, L., Ryu, S., Zou, L., & Li, H. (2019). The temporal effects of acute exercise on episodic memory function: Systematic review with meta-analysis. *Brain Sciences, 9*(4), 87. https://doi.org/10.3390/brainsci9040087

Loprinzi, P. D., Edwards, M. K., & Frith, E. (2017). Potential avenues for exercise to activate episodic memory-related pathways: a narrative review. *European Journal of Neuroscience, 46*(5), 2067-2077. https://doi.org/10.1111/ejn.13644

Loprinzi, P. D., Ponce, P., & Frith, E. (2018). Hypothesized mechanisms through which acute exercise influences episodic memory. *Physiology International*, *105*(4), 285-297. https://doi.org/10.1556/2060.105.2018.4.28

Loprinzi, P. D., Day, S., Hendry, R., Hoffman, S., Love, A., Marable, S., … Gilliland, B. (2021). The effects of acute exercise on short- and long-term memory: Considerations for the timing of exercise and phases of memory. *Europe's Journal of Psychology*, 17, 85-103. https://doi.org/10.5964/ejop.2955.

Loprinzi, P. D., Roig, M., Etnier, J. L., Tomporowski, P. D., & Voss, M. (2021). Acute and chronic exercise effects on human memory: What we know and where to go from here. *Journal of Clinical Medicine*, 10(21), 4812. doi: 10.3390/jcm10214812

Madan, C. R. (2020). Rethinking the definition of episodic memory. *Canadian Journal of Experimental Psychology, 74*(3), 183-192. https://doi.org/10.1037/cep0000229

McMorris, T. (2016). Developing the catecholamines hypothesis for the acute exercise-cognition interaction in humans: Lessons from animal studies. *Physiology & Behavior*, *165*, 291-299. https://doi.org/10.1016/j.physbeh.2016.08.011

McNerney, M. W., & Radvansky, G. A. (2015). Mind racing: The influence of exercise on long-term memory consolidation. *Memory, 23*(8), 1140-1151. https://doi.org/10.1080/09658211.2014.962545

Mier, C. M., & Gibson, A. L. (2004). Evaluation of a treadmill test for predicting the aerobic capacity of firefighters. *Occupational Medicine (Lond), 54*(6), 373-378. https://doi.org/10.1093/occmed/kqh008

Mitchell, K. J., & Johnson, M. K. (2009). Source monitoring 15 years later: what have we learned from fMRI about the neural mechanisms of source memory? *Psychological Bulletin, 135*(4), 638-677. https://doi.org/10.1037/a0015849

Moore, D. C., Ryu, S. & Loprinzi, P. D. (2020). Experimental effects of acute exercise on forgetting. *Physiological International*. doi: 10.1556/2060.2020.00033

Most, S. B., Kennedy, B. L., & Petras, E. A. (2017). Evidence for improved memory from 5 minutes of immediate, post-encoding exercise among women. *Cognitive Research: Principles and Implications*, 2, 33. https://doi.org/10.1186/s41235-017-0068-1.

Ong, Y. W., & Milech, D. (2001). The style of processing scale: normative and reliability data. *Perceptual and Motor Skills, 93*(3), 595-598. https://doi.org/10.2466/pms.2001.93.3.595

Palmer, M., Stefanidis, K., Turner, A., Tranent, P. J., Breen, R., Kucina, T., . . . Sauer, J. D. (2019). Acute Physical Exercise Can Influence the Accuracy of Metacognitive Judgments. *Scientific Reports, 9,* 12412. https://doi.org/10.1038/s41598-019-48861-3

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise, 40,* 1-22. https://doi.org/10.1016/j.psychsport.2018.08.015

Pyke, W., Ifram, F., Coventry, L., Sung, Y., Champion, I., & Javadi, A. H. (2020). The effects of different protocols of physical exercise and rest on long-term memory. *Neurobiology of Learning and Memory, 167,* 107128. https://doi.org/10.1016/j.nlm.2019.107128

Rigdon, B., & Loprinzi, P. D. (2019). Experimental effects of acute exercise on source memory recognition. *Journal of Behavioral Health, 8*(2), 59-65.

Roig, M., Nordbrandt, S., Geertsen, S. S., & Nielsen, J. B. (2013). The effects of cardiovascular exercise on human memory: a review with meta-analysis. *Neuroscience & Biobehavioral Reviews, 37*(8), 1645-1666. https://doi.org/10.1016/j.neubiorev.2013.06.012

Roig, M., Thomas, R., Mang, C. S., Snow, N. J., Ostadan, F., Boyd, L. A., & Lundbye-Jensen, J. (2016). Time-Dependent Effects of Cardiovascular Exercise on Memory. *Exercise and Sport Sciences Reviews, 44*(2), 81-88. https://doi.org/10.1249/JES.0000000000000078

Roozendall, B., & Hermans, E. J. (2017). Norepinephrine effects on the encoding and consolidation of emotional memory: improving synergy between animal and human studies. *Current Opinion in Behavioral Sciences, 14,* 115-122. https://doi.org/10.1016/j.cobeha.2017.02.001

Salas, C. R., Minakata, K., & Kelemen, W. L. (2011). Walking before study enhances free recall but not judgement-of-learning magnitude. *Journal of Cognitive Psychology, 23*(4), 507-513. https://doi.org/10.1080/20445911.2011.532207

Schwartz, B. L., & Efklides, A. (2012). Metamemory and memory efficiency: Implications for student learning. *Journal of Applied Research in Memory and Cognition, 1*(3), 145-151. https://doi.org/10.1016/j.jarmac.2012.06.002

Sherman, S. M., Buckley, T. P., Baena, E., & Ryan, L. (2016). Caffeine Enhances Memory Performance in Young Adults during Their Non-optimal Time of Day. *Frontiers in Psychology, 7,* 1764. https://doi.org/10.3389/fpsyg.2016.01764

Slutsky-Ganesh, A. B., Etnier, J. L., & Labban, J. D. (2020). Acute exercise, memory, and neural activation in young adults. *International Journal of Psychophysiology, 158*, 299-309. https://doi.org/10.1016/j.ijpsycho.2020.09.018

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, & Computers*, 31(1), 137-149.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica (Amst), 112*(3), 297-324. https://doi.org/10.1016/s0001-6918(02)00134-8

Tomporowski, P. D., Ellis, N. R., & Stephens, R. (1987). The immediate effects of strenuous exercise on free-recall memory. *Ergonomics, 30*(1), 121-129. https://doi.org/10.1080/00140138708969682

Townsend, C. L., & Heit, E. (2011). Judgments of learning and improvement. *Memory & Cognition, 39*(2), 204-216. https://doi.org/10.3758/s13421-010-0019-2

Wammes, J. D., Good, T. J., & Fernandes, M. A. (2017). Autobiographical and episodic memory deficits in mild traumatic brain injury. *Brain and Cognition, 111*, 112-126. https://doi.org/10.1016/j.bandc.2016.11.004

Westbrook, A. & Braver, T. S. (2015). Cognitive effort: A neuroeconomic approach. *Cognitive, Affective, & Behavioral Neuroscience*, 15, 395-415.

Winter, B., Breitenstein, C., Mooren, F. C., Voelker, K., Fobker, M., Lechtermann, A., . . . Knecht, S. (2007). High impact running improves learning. *Neurobiology of Learning and Memory*, *87*(4), 597-609. https://doi.org/10.1016/j.nlm.2006.11.003

Zou, L., Yu, Q., Liu, S., & Loprinzi, P. D. (2020). Exercise on visuo-spatial memory: Direct effects and underlying mechanisms. *American Journal of Health Behavior*, 44, 167-179. https://doi.org/10.5993/AJHB.44.2.5

Table 1

Demographic and behavioral characteristics of the sample

Variable	**Point Estimate**	**SD**
Age, mean years	22.1	2.6
Gender, % Female	60.0	
Measured body mass index, mean kg/m^2	25.0	4.6
MVPA, mean min/week	156.5	95.3
CRF, mean mL/kg/min	39.2	8.8
% Low Fitness	20.0	
% Moderate Fitness	43.3	
% High Fitness	36.7	

Note. CRF: Cardiorespiratory fitness; fitness classification based on age- and gender-percentiles from the American College of Sports Medicine (≤ 19^{th}, 20-59^{th}, and ≥ 60^{th} percentile, respectively, for low, moderate, and high fitness). MVPA: Moderate to vigorous physical activity based on the Physical Activity Vitals Sign questionnaire.

Table 2

Physiological and psychological responses (mean [SD]) to the study conditions

Variable	**Control**	**Moderate**	**Vigorous**	**Maximal**
Heart Rate, mean				
Resting	71.6 (11.4)	79.5 (14.4)	76.7 (14.0)	77.0 (14.7)
5 min	68.2 (9.5)	123.0 (18.8)	140.0 (21.2)	157.1 (15.7)
10 min	67.9 (10.2)	124.9 (15.2)	147.5 (22.4)	179.5 (14.6)
15 min	68.5 (9.9)	130.0 (13.2)	154.8 (16.0)	-
Endpoint	68.9 (8.6)	135.8 (16.9)	159.4 (16.0)	184.5 (13.7)
5 min post	69.1 (8.7)	86.1 (11.4)	95.7 (13.1)	-
RPE, mean				
Resting	6.0 (0.0)	6.1 (.2)	6.0 (.2)	6.0 (0.0)
5 min	6.0 (.2)	8.9 (1.5)	10.7 (1.8)	-
10 min	6.1 (.2)	9.9 (1.5)	11.5 (1.6)	-
15 min	6.1 (.2)	10.9 (1.5)	12.3 (1.5)	-
Endpoint	6.1 (.4)	11.8 (2.4)	13.1 (2.2)	17.5 (1.4)
5 min post	6.1 (.4)	6.5 (1.4)	6.5 (1.2)	-

Note. RPE: Rating of perceived exertion. Measurements reported for Maximal are from Visit 1. The rest of the measures are from Visits 2-4.

Table 3

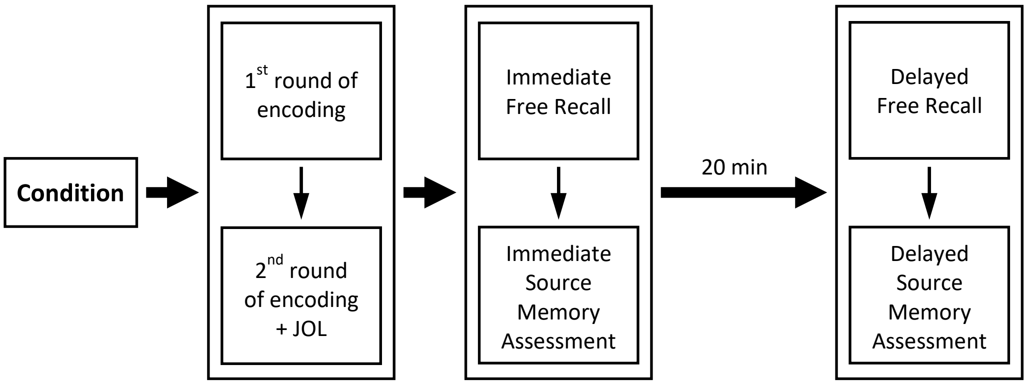
Mean source episodic proportions (95% CI) across the experimental conditions

Memory Metric	Control	Moderate	Vigorous
Free Recall			
Immediate	.69 (.63, .75)	.69 (.63, .75)	.73 (.67, .79)
Delayed	.67 (.61, .74)	.71 (.63, .78)	.75 (.68, .82)
d-prime			
Immediate	3.9 (3.5, 4.3)	4.2 (3.8, 4.5)	4.3 (4.0, 4.6)
Delayed	3.7 (3.2, 4.2)	4.2 (3.8, 4.5)	4.2 (3.8, 4.6)
RPC			
Immediate	.87 (.83, .91)	.90 (.87, .93)	.89 (.84, .94)
Delayed	.85 (.81, .90)	.90 (.86, .93)	.88 (.83, .94)
JOL Magnitude	.59 (.53, .66)	.58 (.50, .65)	.64 (.57, .71)
Recall Bias			
Immediate	-.10 (-.18, -.01)	-.11 (-.20, .02)	-.09 (-.19, .01)
Delayed	-.08 (-.16. .01)	-.13 (-.23, -.02)	-.11 (-.22, -.002)
Recognition Bias			
Immediate	-.28 (-.34, -.21)	-.32 (-.40, -.24)	-.25 (-.34, -.17)
Delayed	-.26 (-.33, -.19)	.32 (-.39, -.24)	-.24 (-.33, -.15)

Note. RPC: Recognition Percent Correct

Figure 1

Schematic of the source episodic memory protocol



Note. The conditions included Control, Moderate or Vigorous-intensity exercise. In the free recall task, participants recalled as many pictures as they could remember. In the source memory task, participant indicated whether the image was old or new, and if old, what quadrant the picture was in.

Supplementary Information

For exploratory purposes, and based on their potential to influence the exercise-memory relationship (for some examples, see Chang et al., 2012), evaluated moderators included (1) age (years), (2) gender (male/female), (3) self-reported weekly moderate-to-vigorous physical activity, (4) working memory capacity, (5) verbal/picture processing, (6) the time of day in which the conditions occurred, (7) self-reported levels of mental fatigue, and cardiorespiratory fitness (measured via indirect calorimetry from the first visit).

Self-reported moderate-to-vigorous physical activity (minutes/week) was assessed at the beginning of the first visit and evaluated using the Physical Activity Vital Signs survey (Ball, Joy, Gren, & Shaw, 2016). At the beginning of the first visit, working memory was assessed via the Brown Peterson memory task, which has demonstrated evidence of construct validity (Geurten, Vincent, Van der Linden, Coyette & Meulemans, 2016). Participants memorized 3 letters and then counted backwards by 3 starting at a given number. Participants had to count backwards for 4 given time points (0, 9, 18, and 36 s), with 5 trials for each time point. The total number of correctly recalled letters for the 9, 18, and 36 second time periods were summed to reflect a total working memory score. As a measure of the participants preferred processing style (i.e., verbal or visual), participants completed the Style of Processing survey (Ong & Milech, 2001) at the beginning of the first visit. A three-level categorical variable was created to indicate the time of day in which the conditions took place; all in the morning, all in the afternoon, or a combination of the two. Lastly, at the start of each condition, participants self-reported their level of mental fatigue using a 7-point Modified USAFSAM Mental Fatigue Scale (e.g., 1, fully mentally alert; 7, completely mentally exhausted).

Potential Moderators. In a 2 (Time: Immediate and Delayed) × 3 (Condition: Control, Moderate-Intensity, and Vigorous-intensity) rANOVA with free recall as the outcome, as stated, there was a significant main effect for Condition ($p = .04$). None of the potential moderators (i.e., gender, age, self-reported moderate-to-vigorous physical activity, working memory capacity, verbal/picture processing, time of day of the assessments, mental fatigue, or cardiorespiratory fitness) interacted with Condition or Condition × Time, all *p*s > .05. We also did not observe any interaction effects of the evaluated moderators for the other memory outcomes (e.g., d', metamemory). We also evaluated if the order (6 possibilities: ABC, ACB, BAC, BCA, CAB, CBA) in which the visits occurred influenced the results. Notably, there was no main effect for order and order did not interact with condition, time, or higher-level interactions (e.g., condition*time), all *p*s > .05.

However, there was a significant main effect for overall working memory capacity, $F(1, 28) = 22.67$, $p < .001$. With free recall collapsed across Time (Immediate and Delayed) and Condition (Control, Moderate, Vigorous), there was a statistically significant positive association between working memory capacity and free recall, $r = .67$, $p < .001$. Similar to when free recall was the outcome, there was a significant main effect of working memory capacity on recognition percent correct, $F(1, 28) = 4.78$, $p = .03$. With recognition percent correct collapsed across Time (Immediate and Delay) and Condition (Control, Moderate, Vigorous), there was a statistically significant positive association between working memory capacity and recognition percent correct, $r = .38$, $p = .03$.

Relative Metacognitive Accuracy. Goodman-Kruskal Gamma correlations (*G*) were calculated between JOLs and recall. For immediate recall, *G*s were moderate (*M*s ranging from 0.22 - .044), and all three conditions were significantly non-zero using one-sample *t*-tests (*p*s <

.05). *G*s for delayed recall ranged from 0.07 - 0.36, with control and moderate conditions again producing significantly non-zero *G*s ($ps < .05$) whereas *G* in the vigorous condition was not significantly different than 0 ($p = .54$). No statistically significant differences between the 3 conditions emerged using rANOVAs. For recognition, the *G*s were expected to be lower due to correct guessing, which reduces resolution. In the immediate recognition test, *G*s ranged from -0.02 – 0.27, with only the control condition being significantly non-zero using a one-sample *t*-test. Similarly, *G*s ranged from -0.04 – 0.25 in the delayed condition and in this case none were significantly non-zero. As with recall, no statistically significant differences between the 3 conditions emerged using rANOVAs for recognition.