1-1-2021

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Recommended Citation

Rigdon, Brandon Thomas, "EFFECTS OF ACUTE EXERCISE INTENSITY ON SOURCE EPISODIC MEMORY: CONSIDERATIONS BY CARDIORESPIRATORY FITNESS" (2021). *Electronic Theses and Dissertations*. 2049.
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EFFECTS OF ACUTE EXERCISE INTENSITY ON SOURCE EPISODIC MEMORY: CONSIDERATIONS BY CARDIORESPIRATORY FITNESS

A Thesis

presented in partial fulfillment of requirements

for the degree of Master of Exercise Science

in the Department of Health, Exercise Science, and Recreation Management

The University of Mississippi

by

Brandon Rigdon

May 2021

ABSTRACT

Prior research suggests that behavioral (e.g., acute 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 primary 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. A secondary objective was to evaluate if cardiorespiratory fitness moderates this potential relationship. 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 and this effect was not influenced by cardiorespiratory fitness. 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

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CHAPTER 1

LITERATURE REVIEW OF THE ASSOCIATION BETWEEN CARDIORESPIRATORY FITNESS AND MEMORY FUNCTION

Unquestionably, memory function is critical for daily functioning. Memory is a complex neuropsychological system, involving various memory subsystems, including various processes and streams of information subserving its respective system. Working memory capacity, a short-term memory system, involves the transient storage of information with concomitant interfering stimuli. The declarative long-term memory system involves explicit and implicit sub-streams, with the former involving conscious retrieval of material, whereas the latter involves subconscious retrieval of information. Further, within the explicit declarative memory system, episodic memory refers to retrospective memories that are bound contextually, whereas semantic memory involves non-contextually bound retrospective memories.[1-3]

Of interest to our research group is the effects of exercise on episodic memory function. In various reviews,[1,4] and empirical experiments,[5-8] we have provided suggestive evidence that both acute and chronic engagement in exercise may, potentially, subserve various memory systems, particularly episodic memory function. The focus of this chapter is to evaluate the potential unique effects (i.e., independent of exercise) of cardiorespiratory fitness (CRF) on memory function. We address this inquiry as an important component of this thesis is to evaluate if CRF can moderate the effects of exercise on memory function.

Cardiorespiratory fitness is defined as the ability of the circulatory and respiratory systems to transport and supply oxygen to skeletal muscles. As determined from the Fick equation, CRF is influenced from central and peripheral factors. Specifically, CRF is a function of cardiac output (central) and arterio-venous difference (peripheral). Enhanced transport of oxygenated blood and enhanced extraction of oxygen at the muscle cell level, corresponds with higher CRF.

Emerging research demonstrates that, independent of exercise, CRF is associated with various health-related outcomes,[9] including mortality risk.[10,11] We have also demonstrated that, independent of exercise and sedentary behavior, CRF is positively associated with cognitive function.[12] Importantly, though, objective measures of CRF should be considered, as our recent work demonstrates that estimates of CRF, in young adults, is not associated with memory function.[13]

Future work on this topic is needed, and as such, the purpose of this chapter was to systematically review the literature to evaluate the extent to which objectively-determined CRF is associated with memory function. A particular interest of this chapter was to evaluate whether this potential relationship is independent of exercise engagement. Such an effect is plausible, as CRF and exercise may include distinct components of cardiovascular health.[14] As an example, the association between exercise engagement and CRF is weak-to-modest at best (r = 0.30 to 0.60).[15,16] Further, CRF may not only be influenced by exercise engagement, but may also be influenced by subclinical disease and genetic predisposition.[17]

Methods

Data Sources and Search Strategy. The following databases were used for our computerized searches: Embase/PubMed, Web of Science, Google Scholar, Sports Discus, and PsychInfo.[18]

Articles were retrieved from inception to March 14, 2019. The search terms, including their combinations, were: fitness, maximum oxygen consumption, aerobic fitness, aerobic capacity, cardiorespiratory fitness, cognition, memory, and episodic memory. Each independent variable (e.g., cardiorespiratory fitness, aerobic fitness) was searched with each outcome variable (cognition, episodic memory). An example search strategy is shown below: ("cardiorespiratory fitness"[MeSH Terms] OR ("cardiorespiratory"[All Fields] AND "fitness"[All Fields]) OR "cardiorespiratory fitness"[All Fields]) AND ("memory"[MeSH Terms] OR "memory"[All Fields])

Study Selection. The literature searches were performed independently by two separate individuals and comparisons were made to determine the number of eligible studies. Consensus was reached from these two independent reviews. Upon performing the computerized searches, the article titles and abstracts were reviewed to identify potentially relevant articles. Articles appearing to meet the inclusionary criteria were retrieved and reviewed at the full text level.

Inclusionary Criteria. Studies were included if they: (1) were conducted among adult humans (18+ years), (2) evaluated cardiorespiratory fitness as the independent variable, (3), measured cardiorespiratory fitness with an objective device (e.g., indirect calorimetry), (4) evaluated memory function (any type) as the outcome measure, and (5) included either a cross-sectional, prospective, or experimental study design.

Data Extraction of Included Studies. Detailed information from each of the included studies were extracted, including the following information: author, study design, population characteristics, cardiorespiratory fitness assessment, memory type, whether the study statistically controlled for physical activity behavior, and study results. Notably, a qualitative [systematic] review was employed, as opposed to a quantitative [meta-analysis] review, because of study design heterogeneity, population heterogeneity, and variability in the reported outcome metrics (e.g., F-values, correlation coefficients, beta coefficients, relative risk estimates).

Results

Retrieved Articles. Figure 1 displays the flow chart of the article retrieval process. The computerized searches identified 1,007 articles. Among the 1,007 articles, 977 were excluded and 30 full text articles were reviewed. Among these 30 articles, 13 were ineligible as they did not meet our study criteria. Thus, in total, 17 articles met our inclusionary criteria and were evaluated herein.

Article Synthesis. Details on the study characteristics are displayed in Table 1 (extraction table). As shown in Table 1, 17 studies evaluated the association between CRF and memory. Of these 17, there were 2 prospective cohort studies (6-year follow-up and 18-year follow periods) and 15 cross-sectional studies. Among the 17 studies, only 5 focused on young adults (<35 years),[19-23] with the remaining studies focused on middle-age or older adults.

All 17 studies employed an objective measure of cardiorespiratory fitness, which involved a maximal exercise test (as opposed to VO_{2max} estimated from a submaximal test). Among the 17 studies, various memory systems were evaluated, including, working memory, spatial memory, episodic memory, and source memory.

Among the 17 studies, none statistically controlled for physical activity when evaluating the relationship between CRF and memory function. Among the 17 studies, 12 did not mention anything about physical activity level being an inclusionary/exclusionary criterion, and thus, the level of physical activity behavior among the majority of these studies (12/17; 70.6%) is uncertain. However, 1 of these studies (5.9%) sampled both sedentary and endurance athletes at baseline, and 4 of the 17 studies (23.5%) only sampled relatively inactive individuals. Regarding these 4 latter studies, however, the criteria for being inactive varied, including being “inactive”, “low active”, “not very physically active (< 2 days per week of physical activity in past 6 months)”, and “inactive as defined by < 30 min each week of physical activity within the past 6 months.” Thus, even among these few studies (i.e., 4) that, by study design, only included “inactive” individuals, there likely was considerable variability in their physical activity levels (not only at moderate-to-vigorous physical activity intensity, but also at light-intensity physical activity).

Among the 2 prospective cohort studies,[24,25] one study employed a 6-year follow-up period among older adults and showed that baseline CRF was positively and prospectively associated verbal memory and verbal fluency ($p < 0.01$). The other prospective cohort,[25] which employed an 18-year follow-up period among adults 19-94 years, showed that lower levels of CRF were associated with a greater decline in learning and memory function.

Among the 15 cross-sectional studies,[19-23,26-35] 13 demonstrated a statistically significant positive association between CRF and memory function, whereas two studies[30,32] demonstrated no statistically significant association between CRF and memory. Thus, the majority of these cross-sectional studies (86.7%; 13/15) demonstrated a positive relationship between CRF and memory. Importantly, though, among the 13 studies demonstrating a positive association between CRF and memory, not all of the analyses within each study demonstrated a positive association. For example, Oberlin et al. (2015)[31] demonstrated a positive association between CRF and memory in their second cohort ($\beta = 0.237$, $p = 0.006$), but not their first cohort ($\beta = 0.17$, $p = 0.15$). Tarumi et al. (2015)[29] showed that CRF (expressed in mL/kg/min) was not associated with CRF, but when expressed as a percentile, was statistically significantly associated with memory. Hayes et al. (2016)[21] demonstrated that CRF was not associated with memory in young adults, but was statistically significantly positively associated with memory in older adults ($p < 0.05$). Further, when examined across the entire sample, Dougherty et al.[28] demonstrated no overall statistically significant association between CRF and memory, but CRF was positively and statistically significantly associated with memory among men. Lastly, Brown et al.[26] did not observe an association between CRF and verbal memory, but did observe a statistically significant positive association between CRF and paired associative memory.

Discussion

The emerging field of exercise neurophysiology has accumulated evidence suggesting that acute and chronic exercise may subserve memory function. Less work, however, has focused on the effects of CRF on memory function. Further, it is uncertain as to whether the potential relationship between CRF and memory is independent of exercise behavior or is mediated by exercise levels. As a result, the purpose of this chapter was to evaluate the literature to determine the association between CRF and memory and evaluate the extent to which exercise has been considered in this relationship. The main findings of this review are twofold: (1) across the 17 evaluated studies, 15 (88.2%) studies demonstrated some evidence of a positive association between CRF and memory function, and (2) none of these 17 studies statistically controlled for exercise behavior.

Previous work suggests that CRF and exercise may have distinct effects on health.[14] This stems from several observations. First, exercise behavior and CRF are only modestly correlated.[15,16] Second, CRF has been shown to be a stronger predictor of cardiovascular health when compared to exercise behavior.[14] Thirdly, approximately 40-50% of an individual's CRF has been suggested to be influenced by their genetic profile.[36] Collectively, this suggests that both CRF and exercise may play distinct roles in cardiovascular health, and by extension, cognitive health.[37] However, this needs to be carefully and critically evaluated. The modest correlation between CRF and exercise may, in part, be influenced by measurement error associated with the assessment of exercise behavior. This may also explain the relatively stronger associations between CRF (vs. exercise) and CVD health. Lastly, considerable work still needs to be conducted to determine the extent to which specific genes and combinations of genetic factors contribute to inter-individual variability in CRF and CRF adaptations to exercise training interventions.[38]

Strengths of this chapter include the comprehensive approach taken, and evaluating whether physical activity was considered in the CRF-memory relationship. A limitation, however, is that we were unable to quantitatively evaluate the results, as a meta-analysis was not appropriate given the considerable heterogeneity across multiple study parameters (e.g., study design).

In conclusion, the present chapter demonstrates a consistent association between CRF and memory function, occurring across various populations and memory systems. Thus, efforts to maximize and preserve CRF during aging should be a high public health priority. Future work that carefully evaluates the potential independent and/or synergistic effects of CRF and exercise on memory is needed. If such work demonstrates a unique role of CRF on memory, then candidate mechanisms will need to be identified. Relatedly, we recently demonstrated that higher CRF was associated with greater interhemispheric parahippocampal connectivity,[39] which likely plays an important role in subserving episodic memory function. Future work should also evaluate whether CRF moderates the intensity-specific effects of acute exercise on memory function.[40] This latter point is the main focus of this thesis.

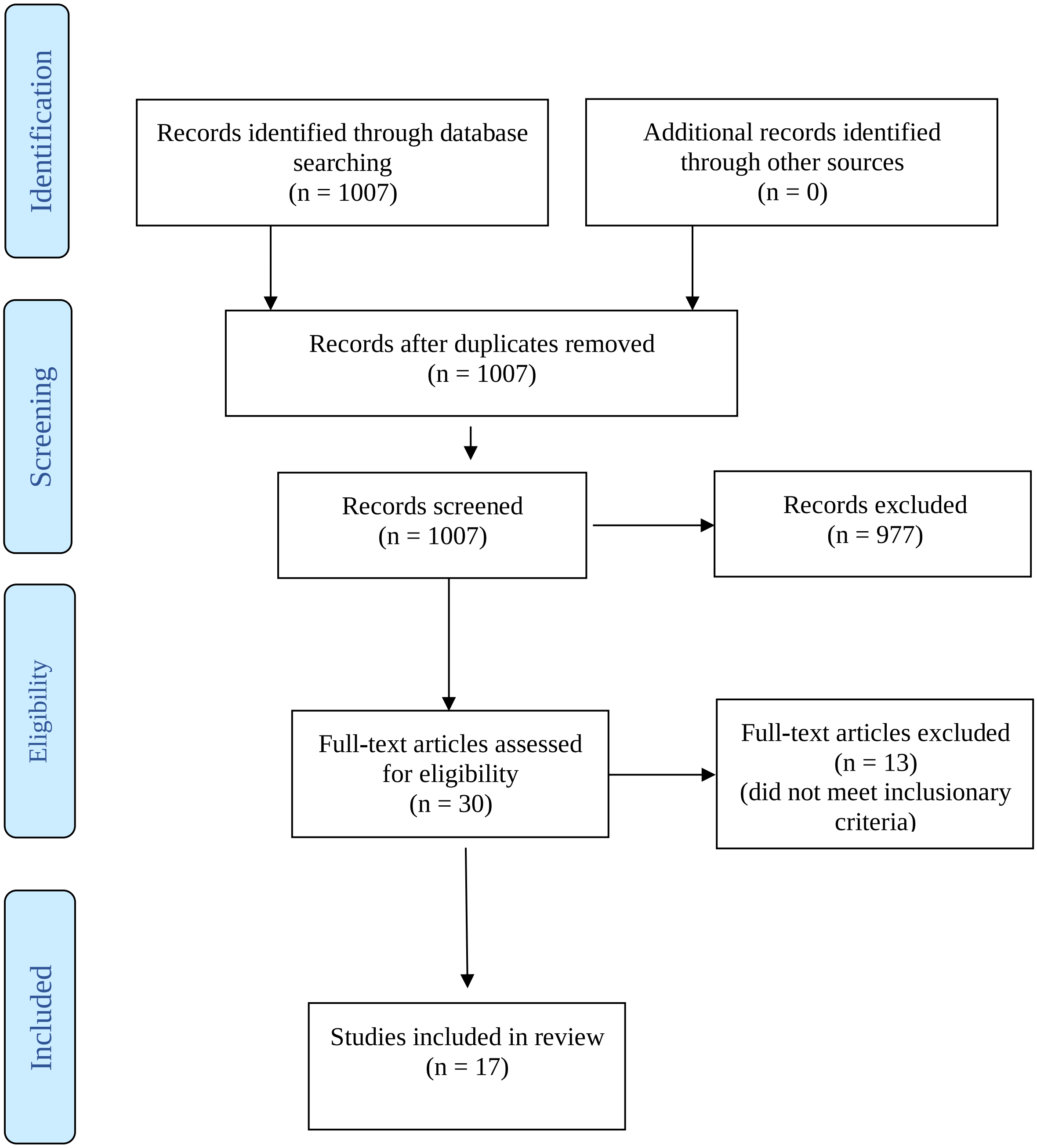

Figure 1. Flow chart of article retrieval

Table 1. Extraction table of the evaluated studies.

Author	**Design**	**Population**	**Cardiorespiratory fitness assessment**	**Memory type**	**Excluded Active Individuals at Baseline?**	**Statically Control for PA?**	**Results**
Barnes et al. (2003)[24]	6-year prospective cohort study	N=349 older adults (59-88 y); M_{age} = 69 y; 97% white	Indirect calorimetry; max test	Verbal memory and verbal fluency	Not mentioned	No	Baseline CRF was positively and prospectively associated verbal memory and verbal fluency ($P<0.01$).
Burns et al. (2008)[35]	Cross-sectional	N=64 non-demented; N = 57 Alzheimer's Disease; 52.3% female non-demented; 47.7% female Alzheimer's Disease	Indirect calorimetry; max test	Working memory; logical memory;	Not mentioned	No	In early AD, CRF was positively associated with delayed memory ($r=0.30$, $P=0.02$) and digit symbol memory ($r=0.37$, $P=0.05$). In non-demented controls, CRF was positively

							associated with delayed memory (r=0.26, P=0.04).
Voss et al. (2010)[19]	Cross-sectional	N=32 young adult; Mage= 24.1 y; 85% female; N=120 elderly participants; Mage=66.5 y; 71% female;	Indirect calorimetry; max test	*Spatial memory and working memory*	Not mentioned	No	CRF was associated with fewer perseverative errors on the working memory task, $r = -.19$, p<.05. CRF was associated with better average accuracy and mean response time across all levels of the spatial memory task (Accuracy: $r = .33$, p<.05; RT: $r = -.31$, p<.05).
Szabo et al. (2011)[34]	Cross-sectional study	N=158 older adults; Mage=66.49 y; 65.4 % female;	Indirect calorimetry; max test	Spatial working memory	Yes, excluded “active” individuals.	No	CRF was inversely associated with working

		VO_{2max} = 20.92 ml/kg					memory reaction time (r=-0.33) and positively associated with working memory accuracy (r=0.309)
Weinstein et al. (2011)[33]	Cross-sectional	N=139; M_{age} = 66.6 y	Indirect calorimetry; max test	Spatial working memory	Yes, only included “low active” individuals.	No	CRF was positively associated with greater working memory performance (F=13.91, P<0.01).
Erickson et al. (2012)[32]	Cross-sectional	N =137; M_{age} = 66.08 y; 65.7% female; $V0_{2max}$ = 21.32 ml/kg/min	Indirect calorimetry; max test	Digit span task and spatial memory task.	Yes, only included individuals “not very physically active as defined by participation in physical activity on two or fewer days of the week in the past six months.	No	Aerobic fitness levels were not correlated with backward digit span lengths (*r*= 0.107; *P*= 0.23); or with forward digit span lengths (*r*= 0.124; *P*= 0.16).

Wendell et al. (2013)[25]	Prospective cohort, with follow-up to 18-years	N=14,000 ages 19-94; 115 participants died and 46 withdrew; VO_{2max} = 28.6 ml O_2/kg/min	Indirect calorimetry; max test	Visual and verbal memory	Not mentioned	No	Lower levels of CRF were associated with a greater decline in learning and memory function.
Oberlin et al. (2015)[31]	Cross-sectional	Study 1, N=113; 36.3% male Study 2, N=154; 31.20% male; M_{age} = 66.6 y	Indirect calorimetry; max test	Spatial working memory	Yes, only included physically inactive individuals, defined by engaging in 30 min or less each week of physical activity within the past 6 months.	No	CRF was not associated with spatial working memory (β=0.17, P=0.15) for Experiment 1, but was positively associated with spatial working memory for Study 2 (β=0.237, P=0.006).
Schultz et al. (2015)[30]	Cross-sectional	N=69; late middle-aged adults between the ages of 40-65; VO_2peak was 25.95 ± 5.50 mL/kg/min	Indirect calorimetry; max test	Working memory, immediate memory, verbal and learning memory	Not mentioned.	No	No significant main effect associations between CRF and memory.

Tarumi et al. (2015)[29]	Cross-sectional	N=55 community dwelling adults, aged 43-65; M_{age} = 54 y for sedentary; M_{age} = 52 y for endurance trained; VO_{2max} = 26 ml/min/kg sedentary; VO_{2max} = 43 ml/kg/min	Indirect calorimetry; max test	Episodic memory (CAVLT)	Evaluated both sedentary and endurance athletes.	No	Aerobic fitness percentile was positively associated with memory ($r=0.36$).
Scott et al. (2016)[20]	Cross-sectional	120 healthy women aged 18-35 yrs	Indirect calorimetry; max test	Working memory	Not mentioned.	No	Positive association between CRF and working memory (accuracy) ($\beta=0.15$, $P=0.006$).
Hayes et al. (2016)[21]	Cross-sectional	N= 33 Young adults (age 18–31 years) and N=28 Older Adults (age 55–82 years); sample mean $\dot{V}O_{2peak}$ of $44.6\ mL\cdot min^{-1}\cdot kg^{-1}$	Indirect calorimetry; max test	Episodic memory	Not mentioned.	No	CRF was not associated with memory in young adults ($F<1$), but was positively associated with memory in older adults ($F=5.40$, $P<0.05$).

Dougherty et al. (2017)[28]	Cross-sectional	N=1500; 86 cognitive healthy, M_{age}=63.6 y, 57 analytic sample, Mage=62.6 y, 65 for CRF & episodic memory analysis, M_{age}=62.9 y	Indirect calorimetry; max test	Episodic memory (RAVLT)	Not mentioned. But participants were not enrolled in any exercise trials at the start of the study.	No	No overall significant association between CRF and memory, but CRF was positively and significantly associated with memory among men; delayed recall score (R^2=0.23, P=0.026) and composite memory score (R^2=0.19, P=0.049).
Hayes et al. (2017)[23]	Cross-sectional	N= 26 Older Adults (55-74 y), 31 Younger Adults (18-31 y) Mage = 29.3 & 63.6 y; VO_{2max} = 25.9 mL/kg/min	Indirect calorimetry; max test	Source memory (face-name recognition)	Not mentioned.	No	Peak CRF accounted for 43.7% of the variance in source memory (F=18.64, P<0.001)
Hwang et al. (2017)[22]	Cross-sectional	N=87 young adults (18-29); M_{age} = 23.22; 57 % female; 43% male; VO2max = 37.78 ml/kg/min	Indirect calorimetry; max test	Working memory	Not mentioned.	No	Higher CRF was associated with higher correct trials (F=4.70,

							P=0.03) and shorter memory retrieval latency (F=7.00, P<0.01).
Schwarb et al. (2017)[27]	Cross-sectional	N=63; Mage = 22.9 y; Relative VO_{2max} = 42.1 ml/kg/min	Indirect calorimetry; max test	Relational memory	Not mentioned.	No	CRF was positively associated with relationship memory (r=0.29, P=0.04).
Brown et al. (2019)[26]	Cross-sectional	N=99 aged 60-80; M_{age} = 69 y; VO_{2peak} = 23 ml $*kg^{-1}$ $*min^{-1;}$ M_{age} = 67 y for higher fit group; M_{age} = 71.5 y for lower fit group	Indirect calorimetry; max test	Verbal, visuospatial memory, and paired associative memory	Not mentioned.	No	No difference between the lower-fit and higher-fit groups were observed on the CVALT delayed recall (F=0.73, P=0.40) and BVMT delayed recall (F=0.05, P=0.83). However, the higher-fit group performed

							better than the lower-fit group (in terms of errors) on the paired associative task (F=7.94, P=0.006).

CHAPTER 2

Episodic memory, or the remembrance of one's own previous experience,[41] often in a spatial-temporal context, plays a critical role in optimal daily functioning. Deficiencies in episodic memory may impair activities of daily living[42] and increase the risk of premature mortality.[37,43] Per the context binding theory,[44] the hippocampus plays a critical role in binding the target memory with important contextual information that is processed from various neocortical areas.

Episodic memory involves integrating the context of the memory.[41] Source memory, in particular, is an important aspect of episodic memory and includes the ability to remember the context of the memory.[45] 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 remembering which parent (mother/father) scolded you for staying out late with your first partner (e.g., girlfriend/boyfriend).

The effects of acute exercise on cognition have been of great interest over the last several decades.[46-51] Generally, these studies provide evidence that moderate-intensity acute exercise may improve global levels of post-exercise higher-order cognition,[46] with high-intensity acute exercise improving post-exercise lower-order cognitions.[52] Research evaluating the specific effects of acute exercise on post-exercise episodic memory, however, has recently started to accumulate.[53,54] This body of research demonstrates that, among young adults, acute exercise may improve post-exercise episodic memory function.[55] 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.[56] had participants engage in different acute exercise intensities, then encoded words from 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. Follow-up work 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;[57] no significant differences were observed between exercise and control conditions. 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 color and the other half in red color.[58] 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[56-58] suggest that there may be an intensity-specific effect of exercise on source memory. However, additional work is needed to confirm this. In a recent systematic review, Loprinzi[40] demonstrated that moderate-intensity exercise was optimal for enhancing working memory, whereas higher-intensity exercise was optimal for enhancing episodic memory. A recent meta-analysis also confirmed that high-intensity exercise was the most optimal intensity to improve episodic memory.[55] These intensity-specific findings also align with past research focusing on global cognition, with moderate-intensity exercise being optimal for higher-order cognitions.[46,52] However, unlike simple recall memory tasks, which may require fewer cognitive resources, source memory tasks require integration of multiple aspects of episodic memory (e.g., spatial information, semantic information). As such, it is less clear as to whether the previous findings demonstrating that high-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,[59,60] despite observations showing metamemory tracks memory performance in verbal learning tasks.[61] It is plausible that metamemory judgements (e.g., confidence) may be influenced by exercise as related judgements (exercise confidence) have been associated with exercise in other non-memory domains.[62] It is reasonable to hypothesize that acute exercise may enhance perceptions of memory performance, which in turn, may associate with actual memory performance.

In addition to evaluating intensity-specific effects of acute exercise on source memory and metamemory judgements, another novel aspect of the present experiment is integrating the potential moderational effects of cardiorespiratory fitness on the relationship between acute exercise and source episodic memory. To our knowledge, no study, to date, has evaluated whether cardiorespiratory fitness moderates the potential intensity-specific effects of acute exercise on episodic memory. Such a moderational effect is plausible for several reasons. For example, a prior review demonstrates that cardiorespiratory fitness is positively associated with episodic memory.[63] Relatedly, longitudinal work demonstrates that changes in cardiorespiratory fitness is associated with improvements in cognition among young adults.[64]

However, the extent to which cardiorespiratory fitness moderates the effects of acute exercise on post-exercise memory is uncertain and requires additional investigation. It is possible that an individual's cardiorespiratory fitness may moderate the physiological demands and/or perceptions of the exercise, ultimately predisposing the individual to a greater acquisition of the memory stimuli;[65] however, a recent evaluation of this demonstrated that cardiorespiratory fitness was not related to spatial relational memory in young adults.[66] Further, a higher-intensity bout of acute exercise may, in theory, induce greater cognitive fatigue and physiological perturbation among individuals with lower cardiorespiratory fitness. This assertion is partially supported by a recent meta-analysis demonstrating that older adults (who presumably have a lower fitness level), when compared to younger adults, had an unfavorable acute exercise-induced memory effect.[55] A meta-analysis,[53] with few studies directly evaluating multiple cardiorespiratory fitness levels, provided inconclusive results regarding this potential moderational role of cardiorespiratory fitness. The meta-analytic findings showed that while cardiorespiratory fitness did not influence the effects of acute exercise on short-term memory, individuals with average cardiorespiratory fitness showed greater effects on long-term memory. Collectively, these mixed findings underscore the need for additional research to evaluate whether cardiorespiratory fitness moderates the effects of acute exercise on memory. For this experiment, the implemented bout of acute exercise occurred prior to memory encoding, as previous work suggests that this placement of exercise in reference to the memory stimulus may be optimal in enhancing memory;[6,67,68] however, we recognize that acute exercise can still enhance memory when occurring during the memory consolidation period.[69]

To address these gaps in the literature, the aims of the present study are as follows: (1) evaluate whether there is an intensity-specific effect of acute exercise on source episodic memory and metamemory accuracy, and (2) evaluate whether cardiorespiratory fitness moderates this potential intensity-specific effect of acute exercise on source episodic memory. We hypothesized that high-intensity acute exercise would be optimal in enhancing source memory and metamemory. We, however, made no directional hypothesis for the potential moderational role of cardiorespiratory fitness, given the aforementioned mixed findings in the literature.

CHAPTER 3

Participants

Recruitment. Participants were recruited from undergraduate and graduate courses at the University of Mississippi.

Sample Size. Thirty participants (18 female) comprised the sample (see Table 1 for demographics).

Eligibility Criteria. Participants were excluded if they (1) self-reported as a daily smoker;[70,71] (2) self-reported being pregnant;[72] (3) exercised within 5 hours of testing;[67] (4) consumed caffeine within 3 hours of testing;[73] (5) took medications used to regulate emotion (e.g., SSRI's);[74] (6) had a concussion or head trauma within the past 30 days;[75] (7) took marijuana or other mind-altering drugs within the past 2 days;[76] or (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.[77] 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 who came to the laboratory after being recruited were excluded, as the specific exclusionary criteria were explicitly discussed during recruitment.

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 happened 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 they would complete until arriving in the lab.

In each experimental session (Visits 2-4), participants completed 25 minutes of the randomly selected stimuli, 25 minutes of 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.[78] 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.[79]

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) 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. 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.

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-min) 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[80] and has also been used in other related experiments.[69]

The Moderate and Vigorous-intensity conditions consisted of 20-minutes of moderate or vigorous-intensity exercise followed by 5-minutes of seated rest, respectively. In the Moderate and Vigorous exercise condition, participants exercised at 64-76% and 77-95% of their HR_{max} (based on the measurements in Visit 1), respectively.[81] The target heart rate was the mid-point of the range (i.e., 70% and 86% of their HR_{max} for the two conditions). The treadmill speed and incline were adjusted to achieve the target heart rate.

At baseline, every 5 minutes during the 20 minute 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.[79]

Source Episodic Memory Assessment.

Protocol. See Figure 1 for a schematic of the source episodic memory protocol. An identical protocol of the source episodic memory assessment was administered across the three experimental conditions. Different stimuli were used for each session. 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 other related experiments.[82] 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. The image was placed in either quadrant 1, 2, 3, or 4 (counterbalanced). Participants were instructed to try and 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 *(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) question.[60] 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 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 minute video clip (either The Office or The Big Bang Theory). 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?*"

The dependent measures were (1) immediate and delayed free recall, (2) immediate and delayed attribution true positive, (3) immediate and delayed attribution true negative, (4) immediate and delayed recognition percent correct, (5) JOL magnitude, and (6) metamemory accuracy. The recall scores were expressed as proportion correct. Attribution true positive was calculated as the proportion of correctly attributed old images; that is, the participant recognized the old image as old and got the quadrant correct. Attribution true negative was calculated as the proportion of correctly attributed new images; that is, if the participant indicates the image was new and it was indeed new. Recognition percent correct was calculated as: (True Positive + True Negative / 32). Judgement of learning (JOL) magnitude was calculated as the mean proportion from the JOL assessment. Metamemory accuracy for free recall was calculated as: (JOL mean %

- free recall %); bias scores greater than zero reflect over-confidence, whereas bias scores less than zero reflect under-confidence. Metamemory accuracy for recognition was calculated as: (JOL mean % - Recognition Percent Correct %).

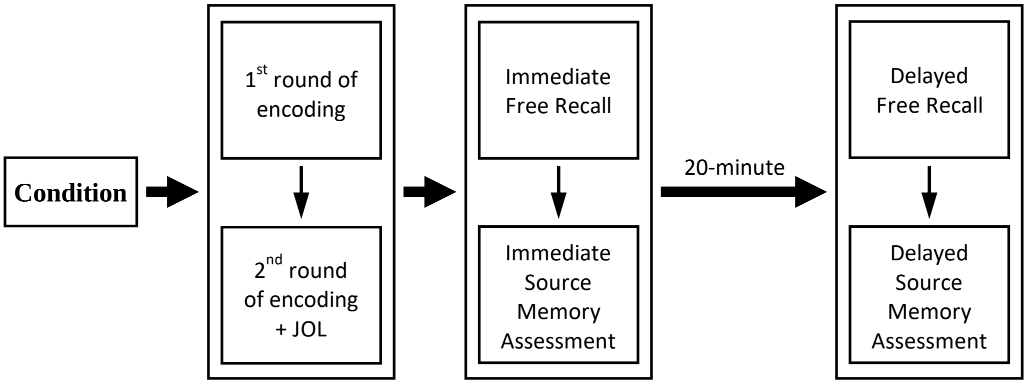

Figure 1. Schematic of the source episodic memory protocol. The conditions included Control, Moderate or Vigorous-intensity exercise. In the free recall task, participants recalled as many pictures as they could remember. In the source memory task, participant indicated whether the image was old or new, and if old, what quadrant the picture was in.

Potential Moderators

The primary moderator of interest was the participants cardiorespiratory fitness, expressed relative to their body weight (mL O_2/kg/min). 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 in order to comply by mandates. Masks were used during the exercise protocols and participants were screened for COVID-19 as well. Based on their potential to influence the exercise-memory relationship,[46] other 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, and (7) self-reported levels of mental fatigue. Regarding self-reported moderate-to-vigorous physical activity (minutes/week), this was assessed at the beginning of the first visit and evaluated using the Physical Activity Vital Signs survey.[83] At the beginning of the first visit, working memory was assessed via the Brown Peterson memory task. 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 seconds), 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[84] 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).

CHAPTER 4

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

Table 1. Demographic and behavioral characteristics of the sample.

Variable	**Point Estimate**	**SD**
Age, mean years	22.1	2.6
Gender, % Female	60.0	
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	

Notes: CRF: Cardiorespiratory fitness; fitness classification based on age- and gender-thresholds from the American College of Sports Medicine.
MVPA: Moderate to vigorous physical activity

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 interaction effect, F (8, 224) = 99.9, $p < .001$, $\eta^2 = .12$. Heart rates were significantly higher for vigorous, compared to moderate, which were also higher compared to control. The results were similar for ratings of perceived exertion.

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)
RPE, mean				
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)

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

Source Episodic Memory

Table 3 displays the source episodic memory results. In a 2 (Time: Immediate and Delay) × 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, $F(1, 29) = .18$, $p = .68$, $\eta^2 = .0001$, or interaction effect, $F(2, 58) = 1.14$, $p = .33$, $\eta^2 = .01$. Collapsed across time, Control was not significantly different than Moderate-Intensity, $M_{diff} = -.016$, $p = .49$, and Moderate-Intensity was not different than Vigorous-Intensity, $M_{diff} = -.042$, $p = .14$, but Control was significantly worse than Vigorous-Intensity, $M_{diff} = -.057$, $p = .04$.

In a 2 (Time: Immediate and Delay) × 3 (Condition: Control, Moderate, Vigorous-intensity) rANOVA with attribution true positive as the outcome, we observed a significant main effect for Condition, *F*(2, 58) = 3.50, *p* = .03, η^2 = .09, but no significant main effect for Time, *F*(1, 29) = 1.93, *p* = .18, η^2 = .005, or interaction effect, *F*(2, 58) = 2.12, *p* = .13, η^2 = .01. Collapsed across time, Control was not significantly different than Moderate-Intensity, M_{diff} = -.059, *p* = .09, and Moderate-Intensity was not different than Vigorous-Intensity, M_{diff} = -.014, *p* = .64, but Control was significantly worse than Vigorous-Intensity, M_{diff} = -.073, *p* = .04.

In a 2 (Time: Immediate and Delay) × 3 (Condition: Control, Moderate, Vigorous-intensity) rANOVA with attribution true negative as the outcome, there was no significant main effect for Condition, *F*(2, 58) = 1.34, *p* = .26, η^2 = .03, no significant main effect for Time, *F*(1, 29) = .61, *p* = .44, η^2 = .003, or significant interaction effect, *F*(2, 58) = .09, *p* = .91, η^2 = .001.

In a 2 (Time: Immediate and Delay) × 3 (Condition: Control, Moderate, Vigorous-intensity) rANOVA with recognition percent correct as the outcome, there was no significant main effect for Condition, *F*(2, 58) = 1.27, *p* = .28, η^2 = .03, no significant main effect for Time, *F*(1, 29) = 2.35, *p* = .13, η^2 = .005, or significant interaction effect, *F*(2, 58) = 1.52, *p* = .22, η^2 = .003.

Sensitivity Results. Baseline levels of mental fatigue at the start of the visit were not associated with any of the memory outcomes for the Control and Moderate-intensity conditions (all *p*'s > .10). However, for the Vigorous-intensity condition, baseline mental fatigue at the start of the visit was inversely associated with Immediate (*r* = -.45, *p* = .02) and Delayed (*r* = -.41, *p* = .04) attribution true positive, as well as Immediate (*r* = -.41, *p* = .03) and Delayed (*r* = -.47, *p* = .01) attribution true negative. Given these findings, we conducted a series of multilevel linear mixed models evaluating condition, fatigue, and condition × fatigue effects. For attribution true positive at the immediate assessment, there was an effect for condition, *F*(2, 50.4) = 3.99, *p* = .02, but no effect for fatigue, *F*(1, 38.84) = .18, *p* = .67, or condition × fatigue effect, *F*(2, 51.66)

= 2.47, *p* = .09. For attribution true positive at the delayed assessment, there was an effect for condition, *F*(2, 49.80) = 4.09, *p* = .02, but no effect for fatigue, *F*(1, 48.41) = 1.65, *p* = .20, or condition × fatigue effect, *F*(2, 50.85) = .78, *p* = .46. For attribution true negative at the immediate assessment, there was no effect for condition, *F*(2, 62.31) = 1.37, *p* = .26, fatigue, *F*(1, 18.69) = .16, *p* = .69, or condition × fatigue effect, *F*(2, 62.89) = .28, *p* = .75. Similarly, for attribution true negative at the delayed assessment, there was no effect for condition, *F*(2, 58.85) = 1.90, *p* = .15, fatigue, *F*(1, 16.23) = .02, *p* = .89, or condition × fatigue effect, *F*(2, 62.16) = 1.12, *p* = .33. Collectively, these findings suggest that levels of mental fatigue at the beginning of the laboratory visits did not interaction with condition to influence source memory.

Potential Moderators. In a 2 (Time: Immediate and Delay) × 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, fitness, self-reported moderate-to-vigorous physical activity, working memory capacity, verbal/picture processing, or time of day of the assessments) interacted with Condition or 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 Delay) and Condition (Control, Moderate, Vigorous), there was a statistically significant positive association between working memory capacity and free recall, *r* = .67, *p* < .001.

We also did not observe any interaction effects of the evaluated moderators for the other memory outcomes. However, 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, $r = .38$, $p = .03$.

Metamemory

Table 4 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 Delay) × 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, $F(1, 29) = .17$, $p = 2.35$, $\eta^2 = .002$, 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 4, across all conditions, recall bias scores differed from zero for at least one of the time periods (i.e., immediate or delay). Relatedly, all recognition bias scores differed from zero across all conditions and time periods.

Table 3. Mean source episodic proportions (SD) across the experimental conditions.

Memory Metric	**Control**	**Moderate**	**Vigorous**
Free Recall			
Immediate	.69 (.16)	.69 (.15)	.73 (.16)
Delay	.67 (.17)	.71 (.19)	.75 (.20)
Attribution True Positive			
Immediate	.78 (.19)	.81 (.15)	.83 (.13)
Delay	.74 (.19)	.82 (.15)	.82 (.16)
Attribution True Negative			
Immediate	.97 (.07)	.98 (.03)	.99 (.03)
Delay	.97 (.07)	.98 (.05)	.98 (.04)
RPC			
Immediate	.87 (.10)	.90 (.08)	.89 (.13)
Delay	.85 (.12)	.90 (.09)	.88 (.14)
JOL Magnitude	.59 (.18)	.58 (.20)	.64 (.19)
Recall Bias			
Immediate	-.10 (.23)	-.11 (.24)	-.09 (.26)
Delay	-.08 (.23)	-.13 (.27)	-.11 (.29)
Recognition Bias			
Immediate	-.28 (.19)	-.32 (.20)	-.25 (.22)
Delay	-.26 (.19)	-.32 (.20)	-.24 (.23)

Notes: TN: True Negative;
TP: True Positive;
RPC: Recognition Percent Correct

Table 4. Mean (95% CI) judgement of learning scores across experimental conditions.

Memory Metric	**Control**	**Moderate**	**Vigorous**
JOL Magnitude	.59 (.53-.66)	.58 (.50-.65)	.64 (.56-.71)
Recall Bias			
Immediate	-.10 (-.18, -.01)	-.11 (-.20, .02)	-.09 (-.19, .01)
Delay	-.08 (-.16, .01)	-.13 (-.23, -.02)	-.11 (-.22, -.002)
Recognition Bias			
Immediate	-.28 (-.34, -.21)	-.32 (-.40, -.24)	-.25 (-.34, -.17)
Delay	-.26 (-.33, -.19)	-.32 (-.39, -.24)	-.24 (-.33, -.15)

CHAPTER 5

The aims of the present experiment were to: (1) evaluate whether there is an intensity-specific effect of acute exercise on source episodic memory and metamemory accuracy, and (2) evaluate whether cardiorespiratory fitness moderates the potential intensity-specific effect of acute exercise on source episodic memory. 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 and the cardiorespiratory fitness of the individual did not moderate these effects.

Several previous reviews have evaluated the effects of acute exercise on cognition.[46,48,50,52,65,85] Regarding global cognition, Chang et al.[46] 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,[52] lower-level cognitive tasks may benefit more from high-intensity exercise. Importantly, as pointed out by Pontifex et al.,[65] 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.

Regarding the accuracy of the intensity of the activity, and rather than employing a prediction equation to estimate exercise intensity, our utilized intensity-thresholds were based on maximal heart rates observed during the initial cardiorespiratory fitness test. Related to the cognitive task type potentially moderating the effects of exercise intensity on cognition, as stated, prior research suggests that higher-intensity acute exercise may benefit lower-level cognitions. In contrast, higher cognitions, such as interference or inhibitory control, may benefit from low- to moderate-intensity acute exercise. Relatedly, according to a qualitative review by Loprinzi,[40] when acute exercise occurs before the memory task, high-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.[55] showing that high-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[86] showing that high-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 high-intensity acute exercise.[56] 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.[67,68,87,88] Couched within the above, the present experiment extends prior work by also showing that high-intensity exercise favors source memory.

The mechanisms through which high-intensity acute exercise may favor episodic memory is unclear.[1,89,90] However, Winter et al.[91] demonstrated that high-intensity acute exercise improved learning, which was mediated by exercise-induced increases in brain-derived neurotrophic factor (for opposing results, see Etnier et al.[56] and Loprinzi[92]), dopamine and epinephrine. Alterations in these proteins and catecholamines may help facilitate encoding and consolidation mechanisms of memory.[93] Further, and as discussed by Brisswalter et al.,[50] high levels of adrenaline are associated with an improvement in memory capacity or information processing efficacy.[94] Couched within the above, 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[52] and Pontifex et al.[65] However, the complexity of the cognitive task my 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, with source memory requiring 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.[95] As such, our findings suggest that even higher-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. For example, unlike the present study, which implemented a five-minute recovery period after exercise, altering this post-exercise recovery period prior to memory encoding may impact the effect of high-intensity acute exercise on source memory. Additionally, it is possible that a more complex source memory task may benefit less from higher-intensity exercise. 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.[96]

We did not observe any exercise-related effect on metamemory. That is, judgement of learning perceptions did not differ across the conditions. Similarly, changes in 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 high-intensity exercise on memory were not driven by judgements of learning. Our findings are similar to those of Salas et al.[60] 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.

The second aim of our experiment was to evaluate if cardiorespiratory fitness moderated the effects of acute exercise intensity on source memory. We did not observe reliable evidence that it did. Chang et al.[46] demonstrated that, when cognitive performance occurred after a delay following acute exercise, greater global cognitive performance occurred among those with moderate- and high-levels of fitness. However, more related to our evaluated outcome (i.e., memory), the meta-analysis by Roig et al.[53] demonstrated that cardiorespiratory fitness did not influence the effects of acute exercise on short-term memory, but individuals with an average fitness level showed the greatest effects on long-term memory. Our finding that cardiorespiratory fitness did not moderate the effects of acute exercise intensity on source memory could have been a result of several factors. First, as suggested by Pontifex et al.,[65] it would seem reasonable that cardiorespiratory fitness may play a large role for longer exercise durations. It is possible that our relatively short acute exercise duration (i.e., 20 minutes) may not have been of sufficient duration to observe a moderation effect of cardiorespiratory fitness. Interestingly, however, a recent experiment showed that those low in cardiorespiratory fitness, but not those high in cardiorespiratory fitness, showed improvements in Stroop cognitive performance following 30 minutes of moderate-intensity exercise.[97] Second, given that those with a greater cardiorespiratory fitness may recovery faster than their counterparts, cardiorespiratory fitness may play a greater moderational role if memory encoding occurs immediately (or shortly thereafter) after exercise.

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. For example, and as stated, altering the post-exercise recovery period may allow for cardiorespiratory fitness moderation effects to be observed. Additionally, it is possible that the timing of our judgement of learning 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.[98,99]

In conclusion, our findings provide suggestive evidence that high-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. Our findings also suggest that the effects of acute exercise on memory were not moderated by the cardiorespiratory fitness level of the individual.

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