Article

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The Impact of Acute Exercise Timing on Memory Interference

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Abstract

This study evaluated whether the timing of acute exercise can attenuate a memory interference effect. Across two experiments, participants completed an AB/AC memory task. Participants studied eight word pairs; four denoted AB (e.g., Hero – Apple) and four control (DE) pairs. Following this List 1, participants studied eight additional word pairs (List 2); four denoted AC, re-using words from the AB pairs (e.g., Hero – Project) and four control (FG) pairs. Following their study of both lists, participants completed a cued recall assessment. In Experiment 1 ($N = 100$), an acute exercise bout occurred before the AB/AC memory interference task, and the participants' three lab visits (successive conditions) were control, moderate-intensity (50% HRR; heart rate reserve) exercise, and vigorous-intensity (80% HRR) exercise. In Experiment 2 ($N = 68$), the acute exercise occurred between List 1 and List 2, and the participants' two lab visits (successive conditions) were a (80% HRR) vigorous-intensity exercise visit and a control visit. Across both experiments, we observed evidence of both proactive and retroactive interference ($p < .05$), but acute exercise, regardless of intensity, did not attenuate this interference ($p > .05$). Acute moderate-intensity exercise was better than control or vigorous-intensity exercise in enhancing associative memory ($p < .05$), independent of interference. In Experiment 2, vigorous intensity exercise was associated with

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more pronounced interference ($p < .05$). Our results suggest that acute exercise can enhance associative memory performance, with no attenuation of interference by exercise.

Keywords
memory discrimination, memory similarity, mnemonic discrimination, associative interference, acute exercise

Introduction

Memory interference is a major cause of forgetting (Davis & Zhong, 2017). In proactive interference, previously learned information hinders recall of subsequently learned information. For example, after completing sequential tasks, learned experience from the first task may interfere with performance on the second task. Retroactive interference refers to forgetting previously learned information due to subsequently learned information. In this instance, recall of a first word list may be impaired by subsequent encoding of a second list (Darby & Sloutsky, 2015).

Meta-analytic work (Loprinzi et al., 2019; Roig et al., 2013) demonstrates that certain health-enhancing behaviors, such as acute exercise, can enhance post-exercise memory function; for details on how memory is influenced during exercise, see Tomporowski and Qazi (2020). Regarding post-exercise effects, Roig et al. (2013) demonstrated that acute exercise improved short- and long-term memory, respectively, in 48% and 58% of the evaluated studies. As thoroughly discussed elsewhere (Pontifex et al., 2019), various mechanisms may influence these exercise-induced effects, such as activation of the norepinephrine system, altered cerebral blood flow, and changes in catecholamines and neurotrophic factors.

An intriguing but minimally tested possibility is that the impact of acute exercise can enhance memory via attenuation of proactive and/or retroactive interference. As discussed in a recent, comprehensive review (Crawford et al., 2020), there are plausible mechanisms through which acute exercise may be involved in attenuating memory interference. For example, acute exercise might upregulate neural activity in the prefrontal cortex (Yanagisawa et al., 2010) and temporal lobe (Won et al., 2019), two critical structures involved in facilitating pattern separation.[1] Thus, an exercise-induced improvement in pattern separation of the stimuli to be recalled may be one mechanism linking exercise and attenuated memory interference (Suwabe, Hyodo, Byun, Ochi, Yassa, et al., 2017). However, as reported in a recent review (Li et al., 2020), very few studies have evaluated the effects of acute exercise on memory interference, and among those that have, findings have been mixed.

Wingate et al. (2018) evaluated the potential effects of acute exercise on memory interference. They used a between-subjects experimental design that comprised six groups, subdivided into two subgroups of three. Three of the groups were tested for proactive interference and the other three were tested for retroactive interference, utilizing the AB/AC paradigm. Each subgroup was divided into a control group (no interference and no exercise), an exercise group (with interference), and a no-exercise (with interference) group. Their results demonstrated that an acute bout of moderate-intensity treadmill exercise was not reliably associated with reduced memory interference.

A second study (Crawford & Loprinzi, 2019b) focused on the intensity-specific effect of acute exercise on memory interference by implementing a within-subject design, which comprised a control visit, a moderate-intensity exercise visit, and a vigorous-intensity exercise visit. Utilizing the AB/AC paradigm, participants studied non-repeating (DE and FG control word pairs) and repeating (AB and AC; e.g., Desk – Pants; Desk – Snow) items. In a cued recall test, poorer memory performance on the repeated-word pairs, relative to the control word pairs, is indicative of a memory interference effect. This experiment provided evidence of an intensity-specific effect of acute exercise (moderate-intensity was optimal) on associative memory performance, but acute exercise was not associated with memory interference (Crawford & Loprinzi, 2019).

Following up on these two studies (Crawford & Loprinzi, 2019b; Wingate et al., 2018), Loprinzi, Frith, et al. (2020) conducted a series of three randomized controlled trials in which participants were randomly placed into one of the following conditions: a self-paced brisk walk for 15-minutes (between subject), a moderate intensity jog for 15-minutes (within-subject), or a self-paced brisk walk for 15 minutes (within-subject). The Rey Auditory Verbal Learning Test (RAVLT) was utilized for each experiment to measure (item, not associative) retroactive interference in free recall. In this paradigm, participants encoded a series of words comprising List A. Following 5 trials of List A, participants encoded 15 new words comprising List B. Following List B recall, participants free-recalled List A again (trial 6 of List A). Retroactive interference was evaluated by comparing trial 6 (after List B) and trial 5 (before List B) of List A. For each experiment, there was suggestive evidence that exercise, compared to a resting condition, attenuated retroactive interference (Loprinzi et al., 2020). Using a similar paradigm, this effect has also been observed for proactive memory interference (Frith et al., 2018; Haynes & Loprinzi, 2019; Johnson et al., 2019). Collectively, these prior studies suggest that acute exercise may influence memory, but this may depend on the paradigm utilized (e.g., RAVLT or AB/AC) or the form of memory targeted (e.g., item-memory vs. associative memory interference).

The present study utilized two separate experiments to evaluate whether and how a bout of acute exercise can attenuate a memory interference effect.

We specifically utilized the AB/AC paradigm to evaluate memory interference, as it allows for both proactive and retroactive interference to be evaluated simultaneously. Across two experiments, we sought to manipulate the relative timing of the exercise in relation to the memory task. As thoroughly discussed elsewhere (Roig et al., 2016), acute exercise may influence memory in a time-dependent manner, priming different phases of memory depending on the placement of the exercise bout. In Experiment 1, the acute exercise bout occurred shortly before any aspect of the memory task (i.e., prior to studying both word-pair lists), permitting a test of whether acute exercise might influence an interference effect during any or all phases of the subsequent memory task, occurring during the few minutes immediately following the exercise. Our findings from Experiment 1 showed that acute exercise prior to memory encoding improved associative memory, but did not attenuate memory interference. In Experiment 2, we placed the acute exercise bout between a presentation of a first word-pair list to-be-recalled (List 1) and a second to-be-recalled list (List 2).

We intentionally altered the placement of the exercise bout, as recent meta-analytic work suggests that exercise during the early memory consolidation period may have a larger effect on memory when compared to other temporal periods (Loprinzi et al., 2019). This also aligns with a two-experiment study by McNerney and Radvansky (2015) showing that the beneficial effects of acute exercise on memory were due to exercise improving processes involved in maintaining information over time, as opposed to an increased arousal state at the time of encoding. In addition to exercise helping to maintain information from intentional instructions, recent work suggests that acute exercise may help to enhance subsequent memory performance after forgetting instructions. For example, using a non-interference paradigm, Loprinzi, Harper, et al. (2020) had participants learn a list of words (List 1), then were instructed to forget these List 1 words, then either engaged in high-intensity acute exercise or not (control), then learned a new list (List 2), and then, finally, recalled as many words as possible from both lists. Those who exercised between the two lists recalled more words from List 2 than those who did not exercise between the two lists. Further, and specific to memory interference, relative to Experiment 1, positioning the exercise bout between the two word-pair lists in Experiment 2 was expected to attenuate the proactive or retroactive memory interference effect associated with the two word-pair lists by increasing the amount of time between the two lists, and, thus, facilitating any exercise-induced pattern separation.

Couched within the context of these aforementioned studies, the present pair of experiments evaluated whether associative memory and memory interference would vary as a function of the timing of acute exercise. We also evaluated this phenomenon across multiple exercise intensities. A recent systematic review (Loprinzi, 2018) demonstrated that moderate-intensity acute exercise may favor improvements in performing post-exercise memory tasks that involve higher-order cognition (e.g., working memory), whereas higher-intensity acute exercise may favor memory systems that task fewer cognitive control processes (e.g., item memory performance). The effects of acute exercise intensity on memory interference, however, is, to date, unclear.

Methods

Participants

Undergraduate and graduate students of the University of Mississippi, aged 18 to 25, were recruited using convenience-based sampling and word of mouth. The study samples for these two experiments included 100 young adults (Experiment 1) and a separate set of 68 young adults (Experiment 2) who met the following eligibility requirements: (a) non-smoker (Jubelt et al., 2008), (b) not pregnant (Henry & Rendell, 2007), (c) had not exercised within 5 hours of testing (Labban & Etnier, 2011), (d) had not consumed caffeine within three hours of testing (Sherman et al., 2016), (e) had no concussion or head trauma within the past 30 days (Wammes et al., 2017), (f) were free of ADHD diagnoses (Ilieva et al., 2015), (g) had not used marijuana or other illegal drugs within the past 30 days (Hindocha et al., 2017), (h) were non-daily alcohol users (<30 drinks/month for women; <60 drinks/month for men) (Le Berre et al., 2017), and (i) responded "no" to all seven items of the Physical Activity Readiness Questionnaire (PAR-Q).

All participants provided written consent prior to participation, and both studies were approved by the Institutional Review Board at the University of Mississippi.

Experiment 1. **Study Design.** A counter-balanced, within-subject design was implemented with three laboratory visits (see Table 1).

Exercise Protocol. The exercise protocol always occurred prior to the memory task. During the cognitive engagement control condition, participants played a time-matched, medium-level, online administered, Sudoku puzzle for 20-minutes prior to the memory task (Blough & Loprinzi, 2019). For the two exercise conditions, participants exercised on a treadmill at 50% (moderate-intensity condition) and 80% (vigorous-intensity condition) of their heart rate reserve prior to completing the memory task. The exercise bouts were followed by 5-minutes of seated rest. The three laboratory visits were separated by at least 24-hours, but were completed within 10 days to reduce attrition rates.

Experiment 2. **Study Design.** A counter-balanced, within-subject design was also implemented, and included two laboratory visits (see Table 2).

Exercise Protocol. Participants completed the same control condition as Experiment 1, a time-matched seated session of online Sudoku for 20-minutes.

Table 1. Study Procedures for Experiment 1.

Experiment 1							
Control	20-min Sudoku		Learn List 1	Cued recall of List 1	Learn List 2	Cued recall of List 2	MMFR
Moderate exercise	15-min Treadmill	5-min Seated Rest	Learn List 1	Cued recall of List 1	Learn List 2	Cued recall of List 2	MMFR
Vigorous exercise	15-min Treadmill	5-min Seated Rest	Learn List 1	Cued recall of List 1	Learn List 2	Cued recall of List 2	MMFR

MMFR, Modified-Modified Free Recall.

Table 2. Study Procedures for Experiment 2.

Experiment 2							
Control	Learn List 1	Cued recall of List 1	20-min Sudoku		Learn List 2	Cued recall of List 2	MMFR
Vigorous exercise	Learn List 1	Cued recall of List 1	15-min Treadmill	5-min Seated Rest	Learn List 2	Cued recall of List 2	MMFR

MMFR, Modified-Modified Free Recall.

For the exercise condition, participants exercised at 80% of their heart rate reserve. For Experiment 2, we elected not to include both exercise intensities given that there was no memory interference difference between the conditions in Experiment 1. Further, we chose to focus on vigorous-intensity acute exercise because, when the exercise bout occurs after encoding, research suggests that higher intensity exercise (vs. control) improves memory to a greater extent than moderate-intensity acute exercise (vs. control) (Loprinzi et al., 2019). Similar to Experiment 1, the laboratory visits occurred at least 24-hours apart, but were completed in a timely manner.

Memory Protocol (Experiments 1 and 2)

The memory protocol for Experiments 1 and 2 were identical, with two exceptions. In Experiment 2, there was a 20-minute interval between Lists 1 and 2, whereas in Experiment 1, List 2 occurred shortly after List 1 (20-second distractor test between lists). Stimuli for Experiment 1 were words drawn from the Toronto Word Pool (Friendly et al., 1982) with an imageability score of 6 or higher. Words for Experiment 2 were drawn from the MRC Psycholinguistic Database, a database used to create the Toronto Word Pool, with imageability, familiarity and concreteness values ranging from 500–700. Separate word lists, matched on imageability, familiarity and concreteness, were created for each experimental condition within the experiments and were presented in a set order.

For this experiment, the AB/AC paradigm with control pairs (DE and FG, respectively) was utilized, which has been detailed elsewhere (Crawford & Loprinzi, 2019). This method was chosen due to its ability to create an interference effect and measure proactive interference and retroactive interference simultaneously. The AB-DE AC-FG method involves presentation of, and recall of, two individual lists of eight word-pairs containing semantically unrelated words. List 1 is comprised of AB and DE word-pairs while List 2 is comprised of AC and FG word-pairs. Each list includes eight word-pairs, half being interference pairs (AB, AC) and half being control pairs (DE, FG). The "A" words were the only words which repeat (e.g., AB = Hero – Apple, AC = Hero – Project), causing memory interference, while the remainder of the pairs (DE and FG) used non-repeating words.

Each list was presented on a computer screen in a set random order for all participants, and consisted of eight word-pairs displayed for 5-seconds each, followed by a 20-second distractor task (simple arithmetic) and then a cued-recall of the respective list. For cued-recall, participants were exposed to the cue words (left-hand words) from each word-pair, one at a time, and instructed to tell the researcher the corresponding response word (right-hand word) if they were able (e.g., Hero - _____). Each cue word was presented for 10 seconds. After cued-recall of List 2, and following a 20-second distractor task, participants completed a so-called "modified-modified free recall" (MMFR; Barnes &

Underwood, 1959), testing both Lists 1 and 2 together. During MMFR, participants were shown the cue words from each previously learned word-pair and were instructed to recall both responses (from List 1 and List 2), if possible (e.g., Hero - ____, _____), in any order. Thus, the MMFR setup was similar to the separate cued recall assessments of List 1 and List 2, except in the MMFR, there were 12 (A, D, and F cued words) cued words in the list (vs. 8 in the cued recall assessments of List 1 and List 2), four of which (from the A pairs) included two cued responses. The memory task procedure was: study List 1, cued recall of List 1, study List 2, cued recall of List 2, MMFR. See Table 3 for an illustration.

Evidence of proactive interference occurs when there is reduced accuracy in recall of AC word-pairs compared to FG, while retroactive interference would be represented by decreased accuracy in AB word-pairs compared to DE. Results presented here are from the MMFR assessment, as our cued-recall results were similar to our MMFR findings, which also aligns with past research (Burton et al., 2017).

Analyses

Frequentist and Bayesian repeated measures ANOVAs (RM-ANOVA) were conducted (JASP, v. 0.14.0, Amsterdam, The Netherlands). These analyses included the following factors: List (two levels: List 1 vs List 2), Interference/Non-Interference (two levels: Interference vs. Non-Interference), and Condition (three levels (Control, Moderate, Vigorous) for Experiment 1 and two levels (Control, Vigorous) for Experiment 2). The List 1 Interference cell was AB accuracy; List 1 Non-Interference, DE accuracy; List 2 Interference, AC accuracy; and List 2 Non-Interference, FG accuracy.

Table 3. Sample Illustration of the AB/AC Memory Interference Task.

List 1 **AB**, DE	Cued recall of List 1	List 2 **AC**, FG	Cued recall of List 2	MMFR A, D, and F cued words
Canoe – garden	Author –	Ocean – echo	Uncle –	**Coffee – anchor, jacket**
Hero – apple	Theater –	**Hero – project**	Model –	Detail – silver
Coffee – anchor	Hero –	Patent – orange	Ocean –	Ocean – echo
Detail – silver	Uncle –	**Uncle – climate**	Number –	**Uncle – triumph, climate**
Author – finger	Detail –	Number – fever	Author –	Patent – orange
Uncle – triumph	Coffee –	Model – hotel	Patent –	Insect – singer
Theater – baby	Insect –	**Coffee – jacket**	Hero –	**Author – finger, object**
Insect – singer	Canoe –	**Author – object**	Coffee –	Number – fever
				Canoe – garden
				Hero – apple, project
				Theater – baby
				Model – hotel

Bolded items represent AB/AC pairs, with the “A” items repeating.

Bayesian analyses were utilized to test the robustness of the examined effects. The inclusion Bayes factor (BFi) is reported, which represents the change from prior to posterior inclusion odds, a ratio reflecting support for the effect being included versus support for the effect being excluded. We follow the convention that a BF > 3 indicates moderate evidence in favor of the alternative hypothesis, whereas a BF$< 1/3$ indicates moderate evidence in favor of the null hypothesis (see Table 1 in Wagenmakers et al., 2018). Notably, herein, all Bayes factors > 1000 are reported as > 1000 since very large BF values should not be interpreted literally.

Sensitivity analyses evaluated whether self-reported physical activity interacted with any of the evaluated factors (List, Interference/Non-Interference, Condition). This assessment included two questions, asking the number of days and minutes per day engaged in moderate-to-vigorous physical activity (MVPA) over the past seven days. As evidence of concurrent validity, weekly MVPA from this instrument has been shown to correlate with weekly MVPA from a validated Modifiable Activity Questionnaire ($r = .71$, $p < .001$) (Ball et al., 2016).

Results

Table 4 displays the characteristics of the samples. Participants, on average, were 21 years of age, with both genders equally represented.

Table 4. Participant Characteristics.

	Experiment 1	Experiment 2
N	100	68
Age, mean (SD) years	21.25 (2.66)	20.79 (1.98)
Gender, % male	51.0	55.88
Race-ethnicity, % White	62.0	80.88
MVPA, mean min/week	234.30 (193.5)	163.30 (148.6)

MVPA, moderate-to-vigorous physical activity.

Table 5. Mean (*SD*) Heart Rates (Beats per Minute) for the Exercise Conditions.

	Experiment 1	Experiment 2
Moderate-intensity		
Rest	71.71 (12.6)	N/A
Mid-point	130.88 (15.75)	N/A
Endpoint	136.87 (10.75)	N/A
Vigorous-intensity		
Rest	73.84 (13.68)	79.50 (12.7)
Mid-point	163.14 (18.58)	162.48 (12.89)
Endpoint	175.57 (29.98)	167.50 (10.70)

Table 5 displays the physiological (heart rate) responses to the exercise stimuli.

Table 6 displays the memory outcomes. The general pattern of results included evidence of proactive interference for Experiment 1 and both proactive and retroactive interference for Experiment 2.[2] Moderate-intensity exercise, prior to encoding, was beneficial in improving associative memory performance relative to non-exercise and vigorous-intensity exercise (Experiment 1). Vigorous-intensity exercise, positioned between Lists 1 and 2, facilitated memory interference (Experiment 2).

Experiment 1

For Experiment 1, we computed a three-way RM-ANOVA. We observed a significant main effect of Condition, $F(2, 198) = 12.78$, $p < .001$, $\eta^2 = .03$, $BF_i > 1000$, with Control having worse associative memory performance than Moderate Exercise, $M_{diff} = -.05$ (95% CI: $-.07$, $-.03$), $BF_i > 1000$, and Vigorous Exercise, $M_{diff} = -.02$ (95% CI: $-.05$, $-.01$), $BF_i = 2.92$, but Moderate Exercise had better associative memory performance than Vigorous Exercise, $M_{diff} = .03$ (95% CI: .002, .05), $BF_i = 4.83$.

We also observed significant main effects of List, $F(1, 99) = 14.96$, $p < .001$, $\eta^2 = .02$, $BF_i = 717.2$, and Interference/Non-Interference, $F(1, 99) = 34.06$, $p < .001$, $\eta^2 = .03$, $BF_i > 1000$, which was qualified by a significant List x Interference/Non-Interference interaction, $F(1, 99) = 18.76$, $p < .001$, $\eta^2 = .01$, $BF_i = 37.48$. Neither the Interference/Non-Interference x Condition nor List x Interference/Non-Interference x Condition interactions reached statistical significance, $ps > .30$, $BF_i < .10$. The List x Condition interaction was also significant, $F(2, 198) = 5.40$, $p = .005$, $\eta^2 = .01$, $BF_i = 3.86$.

Collapsed across Condition, the List x Interference/Non-Interference interaction was investigated with separate Tukey corrected comparisons of List for each Interference/Non-Interference level. List 1 Interference (AB accuracy) was not different than List 1 Non-Interference (DE accuracy), $p = .20$, suggesting no evidence of retroactive interference. However, List 2 Interference (AC accuracy) was worse than List 2 Non-Interference (FG accuracy), $p < .001$ ($M_{diff} = -.07$; 95% CI: $-.09$, $-.04$), demonstrating evidence of proactive interference.

Collapsed across levels of Interference/Non-Interference, the List x Condition interaction was investigated with separate Tukey comparisons of List for each level of Condition. List 2 for Moderate Exercise was better than List 2 for Control, $p < .001$ ($M_{diff} = .08$; 95% CI: .04, .11), and List 2 for Vigorous Exercise, $p = .01$ ($M_{diff} = .05$; 95% CI: .005, .08). Regarding our sensitivity analyses, weekly engagement in MVPA did not interact with any of the factors (all $ps > 0.17$).

Table 6. Proportional Estimates for the MMFR Memory Outcomes (mean (*SD*)).

Experiment 1	AB	DE	AC	FG	PI	RI
Control	.24 (.16)	.25 (.18)	.22 (.15)	.28 (.16)	−.06 (.14)	−.01 (.15)
Moderate exercise	.26 (.17)	.27 (.17)	.29 (.13)	.36 (.13)	−.07 (.13)	−.01 (.13)
Vigorous exercise	.24 (.16)	.27 (.18)	.24 (.17)	.32 (.15)	−.08 (.15)	−.03 (.16)
Post-hoc						
Main effect condition						
Control v moderate[a]	$p < .001$					
Control v vigorous[a]	$p = .02$					
Moderate v vigorous[a]	$p = .02$					
List × Interference/Non-Interference interaction						
AB v DE[b]	$p = .20$					
AC v FG[b]	$p < .001$					
List × Condition interaction						
List 2 moderate v List 2 control[c]	$p < .001$					
List 2 moderate v List 2 vigorous[c]	$p = .01$					
Experiment 2						
Control	.35 (.30)	.58 (.32)	.62 (.32)	.65 (.28)	−.03 (.28)	−.23 (.30)
Vigorous exercise	.20 (.25)	.49 (.34)	.46 (.31)	.63 (.27)	−.17 (.32)	−.29 (.36)
Post-Hoc						
List × Interference/Non-Interference interaction						
AB v DE[b]	$p < .001$					
AC v FG[b]	$p < .001$					
Interference/Non-Interference × Condition interaction						
AB/AC Non-Exercise vs. AB/AC Vigorous Exercise[d]	$p < .001$					

PI, Proactive Interference; RI, Retroactive Interference.
[a]Collapsed across List and Interference/Non-Interference.
[b]Collapsed across Condition.
[c]Collapsed across Interference/Non-Interference.
[d]Collapsed across List.

Experiment 2

For Experiment 2, a three-way RM-ANOVA was computed, including the following factors: List (two levels: List 1 vs List 2), Interference/Non-Interference (two levels: Interference vs. Non-Interference), and Condition (two levels: Vigorous-Exercise vs. Control). We observed significant main effects of List, $F(1, 67) = 75.84$, $p < .001$, $\eta^2 = .12$, $BF_i > 1000$, Interference/Non-Interference, $F(1, 67) = 67.89$, $p < .001$, $\eta^2 = .11$, $BF_i > 1000$' and Condition, $F(1, 67) = 15.87$, $p < .001$, $\eta^2 = .04$, $BF_{10} = 1120.25$. There were no List x Condition or List x Interference/Non-Interference x Condition interactions, $ps > .32$, $BF_i < .36$.

The main effects of List and Interference/Non-Interference were qualified by a List x Interference/Non-Interference interaction, $F(1, 67) = 18.47$, $p < .001$, $\eta^2 = .02$, $BF_i = 125.4$. Collapsed across Condition, the List x Interference/Non-Interference interaction was investigated with separate Tukey corrected comparisons of List for each Interference/Non-Interference level. List 1 Interference (AB accuracy) was worse than List 1 Non-Interference (DE accuracy), $p < .001$ ($M_{diff} = -.26$; 95% CI: $-.34$, $-.18$), suggesting retroactive interference. Further, List 2 Interference (AC accuracy) was worse than List 2 Non-Interference (FG accuracy), $p < .001$ ($M_{diff} = -.10$; 95% CI: $-.17$, $-.02$), demonstrating proactive interference.

The main effects for Interference/Non-Interference and Condition was qualified by an Interference/Non-Interference x Condition interaction, $F(1, 67) = 6.65$, $p = .01$, $\eta^2 = .01$, $BF_i = .89$. Collapsed across List, Interference/Non-Interference x Condition interaction was investigated with separate Tukey corrected comparisons of Interference/Non-Interference for each Condition. Interference (AB and AC) scores were higher for the non-Exercise than Vigorous Exercise Condition, $p < .001$ ($M_{diff} = .15$; 95% CI: .06, .24). Non-Interference scores (DE and FG) were not different between non-Exercise and Vigorous Exercise, $p = .21$. Further, when comparing the difference (Interference – Non-Interference) of Interference scores (average of AB and AC) and Non-Interference scores (average of DE and FG) between the conditions, there was a greater difference for Vigorous Exercise ($M_{diff} = -.22$; 95% CI: $-.29$, $-.16$) than Control ($M_{diff} = -.13$; 95% CI: $-.18$, $-.08$), $p = .01$. Collectively, these results suggest that Vigorous Exercise, compared to Control, had a greater (worse) interference effect. Regarding our sensitivity analyses, weekly engagement MVPA did not interact with any of the factors (all $ps > 0.07$).

Discussion

Research evaluating the effects of acute exercise on memory is accumulating (Loprinzi et al., 2019; Roig et al., 2013), with mixed evidence of favorable effects of acute exercise on post-exercise memory. Less research, however, has evaluated whether acute exercise improves memory via attenuating memory interference. Experiment 1 demonstrated that acute moderate-intensity exercise was associated with improved associative memory performance, whereas exercise, regardless of intensity, was not associated with memory interference. However, in Experiment 2, vigorous-intensity exercise was not associated with either better or worse associative memory performance, but was associated with a more pronounced interference effect when it occurred between List 1 and List 2 of the paradigm. Our Bayesian analyses demonstrated moderate-to-strong evidence in support of these findings; Bayes factors either favored null interactions involving Condition and Interference, or in one case, supported a reverse effect (more interference in the vigorous-intensity exercise condition).

In Experiment 1, acute exercise, regardless of intensity, was not associated with memory interference. However, moderate-intensity acute exercise, relative to non-exercise and vigorous-intensity exercise, was superior in enhancing associative memory performance. This aligns with other work demonstrating that moderate-intensity acute exercise may be superior to higher-intensity exercise in enhancing memory from an image-word-pair task (Pyke et al., 2020). This finding also aligns with a meta-analysis by Roig et al. (2013) demonstrating that the effects of acute exercise on memory occurs 48–58% of the time. This variable response may, in part, relate to the timing of the exercise bout and memory assessment. In Experiment 1, memory encoding occurred five minutes after the exercise bout. This relatively short duration between exercise and memory encoding may create an ideal cognitive and neurophysiological arousal state to facilitate memory performance (for relevant reviews on potential mechanisms, see Loprinzi et al., 2017, 2018; Pontifex et al., 2019). The field would benefit from future research that identifies the specific window of opportunity for acute exercise to enhance memory. Further, our findings from Experiment 1 suggest that acute moderate-intensity exercise was associated with greater associative memory, even in the presence of memory interference. As such, it would be interesting for future research to manipulate the degree of interference to evaluate at what level of interference does acute exercise no longer have an effect on associative memory performance.

The main finding from Experiment 2 is that vigorous-intensity acute exercise was associated with worse interference when compared to the non-exercise control condition. Collectively, across our two experiments, we provide evidence that acute exercise may uniquely influence memory performance. As speculated in recent reviews (see Loprinzi et al., 2017, 2018), and demonstrated empirically (Won et al., 2019; Yanagisawa et al., 2010), acute exercise may increase neuronal excitability in key memory-related brain structures (e.g., prefrontal cortex and medial temporal lobe). Increased neural activity prior to encoding has been shown to predict both neural activity during encoding and subsequent item-memory performance (Urgolites et al., 2020). This may explain our results from Experiment 1 demonstrating that moderate-intensity exercise prior to encoding was advantageous in enhancing memory performance. It is possible that the high workload of vigorous-intensity exercise induced central fatigue, and subsequently, either impairs or nullifies the effects of acute exercise on memory (Roig et al., 2016). In contrast, we did not observe any enhancement effects of acute exercise on attenuating associative-memory interference. In a recent review by Li et al. (2020), chronic exercise, as opposed to acute exercise, was more robust in attenuating memory performance, likely as a result of chronic exercise-induced neurogenesis-facilitated pattern separation.

Although across both experiments we observed no beneficial effect of acute exercise on attenuating memory interference, an interesting observation was that vigorous-intensity exercise resulted in a greater (worse) memory interference effect in Experiment 2. This effect was not observed in Experiment 1, suggesting that the timing of high-intensity exercise may impart a unique effect on memory interference. Unlike Experiment 1, which included the exercise bout prior to List 1, in Experiment 2, vigorous exercise occurred between List 1 and List 2. In contrast to when the bout of exercise occurs prior to List 1 (Experiment 1), a centrally fatiguing stimulus (e.g., vigorous exercise) between the two lists may reduce the ability to resolve interference. The prefrontal cortex is a critical brain structure involved in memory interference resolution, and during high-intensity acute exercise, prefrontal cortex activation has been shown to drop below baseline levels (Ando et al., 2011; Guise & Shapiro, 2017). As such, after encoding the initial list, vigorous-intensity acute exercise may increase memory interference via a resource-limited cognitive mechanism. That is, at the time of similarity detection (i.e., encoding of List 2), high-intensity exercise-induced reduction in function of key brain structures (e.g., prefrontal cortex and dentate gyrus) involved in interference resolution may accentuate an interference effect. This effect also aligns with other research demonstrating that a high-interference task (e.g., working memory task with high interference trials) between two tasks reduces the ability to resolve memory interference (Persson et al., 2007). In addition to exercise reducing the ability of key brain regions to detect and resolve competing stimuli, with the bout of exercise occurring between the two lists, exercise may have increased the reactivation of the neural representation of List 1, and further, created a scenario (e.g., central fatigue, elevated catecholamines) that reduced the subsequent encoding and consolidation of List 2. These effects may have resulted in increased interference across the lists by increasing the degree of intrusion of List 1 into List 2, and ultimately, decreasing the distinction between the two lists.

From a cognitive perspective, one may have expected exercise in Experiment 2 to function much like a contextual boundary, protecting participants from confusing lists 1 and 2, thereby attenuating interference (our hypothesis). On the other hand, Burton et al. (2017) found that interference was more pronounced when participants were explicitly asked to avoid thinking of list 1 while studying list 2 (their "Separation-Imagery" group), whereas interference was reduced and even reversed when participants were asked to form combined images of the pairs from the two lists (their "Integration-Imagery" group). Although speculative, it could be that exercise in Experiment 2, in fact, reduced the likelihood of participants thinking about an AB pair while studying its corresponding AC pair, and missed out on the chance to resolve interference during study of list 2. This could be tested in a future study, by, for example, cross-manipulating exercise with Separation-Imagery versus Integration-Imagery instructions.

Further experimentation will be required to confirm that, indeed, the timing of exercise plays a unique role in influencing memory interference. If confirmed, additional critical reflection will be required to elucidate the unique reasons behind these time course effects. It is also important to suggest that perhaps our differential exercise-interference effects across the two experiments may be due to the more consistent and larger interference effects observed in Experiment 2 relative to Experiment 1; both proactive and retroactive interference were observed in Experiment 2, compared to just proactive interference in Experiment 1.

Overall, this collective and accumulating body of research suggests that acute exercise may help enhance item and associative memory performance, and the discrepant findings in the literature regarding the effects of acute exercise on memory interference may be a result of the paradigm utilized. Unlike the acute exercise RAVLT studies (Frith et al., 2018; Haynes & Loprinzi, 2019; Loprinzi, Frith, et al., 2020), the past acute exercise studies using versions of the AB/AC paradigm (Crawford & Loprinzi, 2019; Wingate et al., 2018), as well as the current set of experiments, did not demonstrate any effect of acute exercise on memory interference. For the RAVLT studies, perhaps the strengthened association for List A (i.e., five trials of List A) allowed for a greater exercise-induced attenuation of memory interference. Alternatively, perhaps the effects observed in these prior RAVLT studies are an overestimation, given that there was no memory interference control (i.e., no conditions in which List B was not present). In addition to these RAVLT and AB/AC studies, recent studies have utilized a recognition-based memory discrimination task of objects and showed that acute exercise (Suwabe, Hyodo, Byun, Ochi, Yassa, et al., 2017), fitness (Suwabe, Hyodo, Byun, Ochi, Fukuie, et al., 2017) and chronic exercise training (Heisz et al., 2017) were effective in attenuating high-interference memory lures. In the Suwabe, Hyodo, Byun, Ochi, Yassa, et al. (2017) study, memory encoding occurred shortly after acute exercise, with the recognition task occurring 45-minutes after encoding. A lengthy retention interval, such as that employed by Suwabe, Hyodo, Byun, Ochi, Yassa, et al. (2017), may be needed for exercise to sufficiently attenuate memory interference. It is possible that the very short retention interval employed in our two experiments was too short to observe any exercise memory interference attenuation effects.

Limitations and Future Research Directions

Strengths of this paper include evaluating intensity-specific effects of acute exercise on both associative memory and memory interference, evaluating whether the timing of exercise influences these effects, and including a relatively large sample. There are, however, several limitations of our studies. We prescribed exercise intensity from an estimate of maximal heart rate (vs. performing a maximal exercise test) and did not evaluate the participant's cardiorespiratory fitness. Further, we did not evaluate the extent to which the participants had experience exercising on a treadmill. Dislike, or aversion toward treadmill exercise, could, potentially, influence intra-exercise affect, which may influence cognitive processing. Additionally, participants were only required to refrain from caffeine use for three hours prior to the study. Caffeine's elimination half-life may range between 1.5 and 9.5 hours (Institute of Medicine, 2001), and thus, a three-hour abstinent period may have been insufficient. Thus, future work should consider overcoming these limitations. If confirmed by future work, these findings may have practical implications in that an acute bout of moderate-intensity exercise, prior to encoding, may help to improve memory performance. As such, individuals may wish to engage in, for example, a short brisk walk prior to learning. Further, and if our findings are confirmed by future experimentation, then individuals may wish to refrain from high-intensity acute exercise that occurs between learning two sets of interfering information.

Conclusion

In conclusion, our results suggest that acute moderate-intensity exercise, prior to encoding, may enhance associative memory, whereas high-intensity acute exercise, positioned between two sets of interfering stimuli, may facilitate memory interference. As such, the relationship between acute exercise and memory appears to be complex and may be influenced by the retention interval, exercise intensity, and timing of the exercise bout relative to the memory task.

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Notes

1. Pattern separation refers to minimizing the overlap of the two neuronal patterns that represent the conflicting stimuli (e.g., List 1 and 2).
2. To check whether multiple sessions might attenuate the effect of exercise on interference, we conducted the same analyses on session-1 data alone. Ruling out this possibility, the Exercise x Interference interaction was still non-significant (*p*s>.31).

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