Vigorous-Intensity Acute Exercise During Encoding Can Reduce Levels of Episodic and False Memory

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Abstract

The potential benefits (veridical memory) and, importantly, costs (false memory) of acute exercise on memory in conjunction with the timing and type of exercise have not been fully studied. In Experiment 1, we employed a three-condition (15-minute vigorous-intensity acute exercise Before or During, or a Control condition of watching a video), within-subjects, counterbalanced design. The procedures included an immediate and delayed (20-minute post encoding) free recall assessment. Veridical memory was determined by the number of studied words that were recalled, whereas false memory was determined by retrieving a non-presented, critical item. For veridical memory, Before was not different than Control (p=.42), however, During was worse than Before and Control (p's$<.001$). No differences occurred for false memory. Experiment 2 was conducted that included several additional exercise conditions (e.g., light-intensity exercise) during memory encoding, used a recognition task instead of a free recall task, and extended the long-term memory assessment out to 24-hours. Experiment 2 demonstrated that vigorous-intensity acute exercise during encoding reduced both veridical and false memory for related new items ($p<.05$). These findings demonstrate that the timing and intensity of exercise play an important role in influencing memory performance.

Keywords: memory accuracy; memory distortion; physical activity; physical exercise

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Effect of Acute Exercise on Memory Accuracy

Accumulating research demonstrates that an acute bout of exercise can enhance the accurate (veridical) recall of episodic memories (Chang, Labban, Gapin, & Etnier, 2012; Labban & Etnier, 2011, 2018; Loprinzi et al., 2019; Pyke et al., 2020; Roig, Nordbrandt, Geertsen, & Nielsen, 2013; Salas, Minakata, & Kelemen, 2011; Tomporowski, 2003; Zuniga, Mueller, Santana, & Kelemen, 2019), or events that occur in a spatial-temporal context (Loprinzi, Rigdon, Javadi, & Kelemen, 2021). A recent systematic review with meta-analysis by Loprinzi et al. (2019) also demonstrated facilitating effects of acute exercise on post-exercise episodic memory performance (Cohen's d = .18). This memory enhancement effect from acute exercise likely has a greater effect for long-term memory (e.g., assessed at least a few minutes after encoding), as opposed to short-term memory (Coles & Tomporowski, 2008). The potential mechanisms of this effect have been thoroughly detailed elsewhere (El-Sayes, Harasym, Turco, Locke, & Nelson, 2019; Loprinzi, Edwards, & Frith, 2017; Loprinzi, Ponce, & Frith, 2018), which may occur through acute alterations in select proteins (e.g., brain-derived neurotrophic factor, insulin-like growth factor-1, cathepsin-B), supporting brain cells (e.g., astrocytes, which help to facilitate long-term potentiation in the hippocampus) and/or the functional connectivity of communicating neurons (Moore, Jung, Hillman, Kang, & Loprinzi, 2022; Poo et al., 2016).

As highlighted recently (Loprinzi, Roig, Etnier, Tomporowski, & Voss, 2021), the timing of acute exercise plays a critical role in the effects of acute exercise on memory. When occurring either before or after memory encoding, acute exercise may improve memory. However, if the bout of exercise occurs during memory encoding, memory performance may be impaired (Jung, Ryu, Kang, Javadi, & Loprinzi, 2021).

False Memory

Unlike veridical episodic memory, much less research has evaluated the effects of acute exercise on false episodic memories, or recalling an event or episode that never occurred. We view this as an important area to consider, because, at this point, it is unclear as to whether the benefits of acute exercise on enhancing memory (increased veridical memory performance) may be annulled by potential increases in false memories from acute exercise. A common approach to evaluating false episodic memory is through the Deese/Roediger-McDermott (DRM) paradigm (Deese, 1959; Roediger & McDermott, 1995). This paradigm involves being exposed to a list of words, all of which are semantically related to a non-presented critical item, and if this critical item is retrieved, this serves as evidence of false memory. For example, when hearing the words, "*bed*, *rest*, *awake*, and *tired*", if an individual retrieves the non-presented critical item, "*sleep*", a false memory occurred.

Effect of Acute Exercise on False Memory

There are many contributing factors interacting with the effects of exercise on memory. For example, higher-intensity (v lower-intensity) acute exercise may favor veridical memory (Loprinzi, 2018). Additionally, meta-analyses have demonstrated that acute exercise prior to memory encoding may help to enhance memory performance (Chang, Labban, Gapin, & Etnier, 2012; Loprinzi et al., 2019). These effects on false memory, however, has not been investigated thoroughly.

A sequence of studies in Loprinzi's lab, as well as other labs (Marchant, Hampson, Finnigan, Marrin, & Thorley, 2020), evaluated the effects of acute exercise on false memory (Dilley, Zou, & Loprinzi, 2019; Green & Loprinzi, 2018; Siddiqui & Loprinzi, 2018). Acute vigorous-intensity exercise (v moderate-intensity or control) occurring before memory encoding has been shown to be more effective in enhancing veridical memory, and it also increased false memories (Dilley, Zou, & Loprinzi, 2019). The observation that acute vigorous-intensity exercise increased false episodic memory may, in part, be attributed to aspects related to the spreading activation theory of false memory (Howe, Wimmer, Gagnon, & Plumpton, 2009; Roediger III, Balota, & Watson, 2001). Per this theoretical account, related concepts (e.g., DRM list items) are embedded in an associative network and the presence of an item within that network may activate a corresponding concept. The effects of acute exercise on veridical memory may, in theory, activate corresponding concepts within the evaluated network, ultimately having a similar effect on false memory for related new (unstudied) items. This theory would also predict that unrelated new items would not be activated. Thus, per the spreading activation theory, exercise may have similar effects of veridical and false memories for related new items, but not unrelated new items. Additionally, prior work related to memory interference would suggest that acute exercise before encoding may not increase false memories for related items, but in contrast, may help to reduce rates of false memory as exercise has been shown to improve mnemonic discrimination in high similarity lures (Suwabe et al., 2017). These discrepant perspectives highlight the need for future work on this topic.

Timing of Exercise on Memory

The timing of the exercise bout with memory encoding plays an important role in influencing memory (Frith, Sng, & Loprinzi, 2017; Haynes, Frith, Sng, & Loprinzi, 2019; Labban & Etnier, 2011, 2018; Loprinzi et al., 2021; Sng, Frith, & Loprinzi, 2018). As stated, when exercise occurs before encoding or during the memory consolidation period, memory performance may be enhanced. In contrast, recent narrative (Roig et al., 2016; Tomporowski & Qazi, 2020) and meta-analytic (Jung, Ryu, Kang, Javadi, & Loprinzi, 2021) work demonstrates that when the bout of exercise occurs during memory encoding, memory performance may be reduced. This memory impairment effect when exercising during memory encoding may be due to various factors, such as reduced attention and prefrontal cortex oxygenation during high-intensity acute exercise. Per the transient hypofrontality theory, during vigorous-intensity exercise, blood flow and oxygenation may be redistributed away from the prefrontal cortex to the motor cortex to sustain movement (Jung, Ryu, Kang, Javadi, & Loprinzi, 2021). What has yet to be fully investigated, however, is how the timing and intensity of acute exercise influences both veridical and false memory.

Present Set of Experiments

In Experiment 1, we evaluate the effects of vigorous-intensity acute exercise prior to memory encoding and during memory encoding on immediate and 20-min delayed free-recall memory (veridical and false). Our findings demonstrated that vigorous-intensity exercise during memory encoding reduced veridical memory performance. To evaluate if this effect is exercise-intensity dependent, Experiment 2 incorporated a lower-intensity bout of exercise during encoding. In Experiment 2, we employed a recognition task to increase the rate of false memories and extended the delayed memory recognition task out to 24-hours. Experiment 2 provides some support for the findings from Experiment 1 in that vigorous-intensity exercise during encoding reduced veridical memory. Experiment 2 also demonstrated reductions in false memory when vigorous exercise occurs during memory encoding, an effect that did not occur for lower-intensity exercise. These experiments provide important insight on the effects of exercise timing and intensity on veridical and false memory performance.

Methods – Experiment 1

Participants

The first experiment included 37 participants (27 females, ages range 19-23 years, M_{age} = 21.16 years). This is based on a power analysis (G*Power, v 3.1.9.2; ANOVA: repeated measures, within factors), indicating a sample size of 37 would be needed for sufficient power (1-β error probability, 0.90), with inputs of 0.05 (α error probability), two time-points per condition, and an estimated effect size of $\eta_p^2 = 0.07$ (Dilley, Zou, & Loprinzi, 2019). Due to potential confounding effects on memory, participants were excluded if they: (1) were a daily smoker, (2) were pregnant, (3) engaged in exercise within 5 hours of testing, (4) consumed caffeine within 3 hours of testing, (5) took any medications to regulate emotion (e.g., SSRI's), (6) had a concussion or head trauma within the past 30 days, (7) used marijuana or other illegal drugs within the past 30 days, or (8) were a daily alcohol user (> 30 drinks/month for women; > 60 drinks/month for men). Experiment procedures were approved by the authors' institutional review board and participants provided written consent prior to participation. Data is available at XXX.

Study Design

The first experiment employed a three-visit, within-subjects, counterbalanced design, consisting of two exercise conditions and a control condition. The exercise visits involved an acute 15-minute bout of vigorous-intensity exercise. The control visit involved a time-matched seated task (video). The three visits for each participant occurred at approximately the same time of day, with each visit occurring within 24-72 hours of each other. Primary outcomes for this experiment included veridical and false memory measures (described below). See Figure 1 for a schematic of the experimental procedures for each experimental condition.

Control and Experimental Conditions

The control condition involved watching a video (self-selected either The Office or Big Bang Theory) for 20 minutes while seated. There is experimental evidence that this control task does not prime or enhance memory function (Blough & Loprinzi, 2019), and as such, may be a suitable control condition. This approach is also similar to other related experiments (McNerney & Radvansky, 2015).

The two exercise conditions (exercise before encoding and during encoding) engaged in a 15 minute bout of vigorous-intensity treadmill exercise. In the present study, the "*Before*" condition was defined as the acute bout of exercise occurring prior to encoding the memory stimuli, whereas the "*During*" condition was defined as the acute bout of exercise occurring while encoding the memory stimuli. Treadmill exercise was chosen based on a previous meta-analysis (Lambourne & Tomporowski, 2010) showing that treadmill exercise (vs. cycling) is more likely to support the predictions of the transient hypofrontality model (i.e., impaired cognition during exercise).

The visit involving the acute bout of exercise before the memory task involved participants exercising for 15 minutes at 80% of their heart rate reserve (HRR). Following this bout of exercise, participants rested for 5 minutes (video). The HRR equation used to evaluate exercise intensity was: $HRR = [(HR_{max} - HR_{rest}) * \% \text{ intensity}] + HR_{rest}$

To calculate HR_{rest}, at the beginning of the visit, participants sat quietly for 5 minutes, and HR was recorded from a Polar HR monitor (chest-mounted F1 model). HR_{max} was estimated from the 220-age formula; 80% of HRR represents vigorous-intensity exercise (Garber et al., 2011). We specifically implemented a vigorous-intensity bout of exercise for two reasons: (1) to attempt to replicate (conceptually) the findings of Dilley et al. (2019), and (2) to evaluate the transient hypofrontality theory in the context of false memory, as memory function is only impaired during vigorous-intensity exercise, not moderate-intensity exercise (Loprinzi, Day, & Deming, 2019).

The visit involving the acute bout of exercise during the memory task involved participants engaging in a 15 minute bout of acute exercise at 80% of their HRR, and at the 13 minute period into the bout of exercise, they encoded the words. After the participants encoded the words (i.e., at approximately the 15 minute point into the bout of exercise), they stopped exercising and then immediately completed the free recall assessment.

Memory Assessment

The procedure for both veridical and false episodic memory tasks were modeled after Roediger and McDermott (1995) and in alignment with previous work using this task with acute exercise (Green & Loprinzi, 2018; Siddiqui & Loprinzi, 2018). For each visit, participants listened (via headphones) to a computer-generated (using Balabolka software) recording of a list of 15 words all belonging to a single category (recorded in a female voice); each word was read at a rate of one word every two seconds and words were presented in the same order as displayed elsewhere (Stadler, Roediger, & McDermott, 1999). After listening to the list once, there was a 10-second pause, and then they listened to the same word list a second time; a second cycle of encoding was implemented in an effort to reduce a potential floor effect in memory recall among the condition that engaged in vigorous-intensity acute exercise during encoding. After this, they completed an immediate free recall (verbal responding) of the words. Following this immediate free recall, participants watched a video for 20 minutes and then performed a delayed verbal free recall.

The three separate English-based lists (one per visit) were matched for the proportion of expected false memories since the list per se did not contain false memories. Specifically, using prior normative research, each list has a false memory recall of 54%; that is, approximately 54% of participants in the normative studied recalled this non-presented, critical item. We specifically used the "sweet", "chair", and "smoke" critical item lists (Stadler, Roediger, & McDermott, 1999). As an example, each list was composed of associates (e.g., sour, candy, sugar) of one non-presented critical item (e.g., sweet). If, for example, they recalled the word "sweet", then this was evidence of having a false episodic memory.

Outcome. For veridical memory, the outcome was the number of words they recalled (out of 15) at the two time periods (immediate and delayed assessments). For false memory, and at each of the two time periods, they were given a score of 1 or 0 depending on whether they recalled the non-presented critical item. The present study did not evaluate other types of errors (e.g., non-critical intrusions; recalling a non-presented item that was not the critical item).

Statistical Analyses

All statistical analyses were computed in JASP (v. 0.16) or SPSS (v. 28.0.1.0). First, descriptive statistics were used to examine demographic characteristics of the sample. For the number of words recalled (veridical memories), a 3 (condition: control, before exercise, and during exercise) × 2 (time point: immediate vs. delay) repeated measures ANOVA (rmANOVA) was employed. When the Mauchly's test of sphericity was statistically significant ($p < .05$), indicating violations to sphericity, the degrees of freedom were corrected with the Huynh-Feldt procedure. When appropriate, Holm-corrected post-hoc tests were conducted to adjust for multiple comparison. For the repeated measures binary false memory data, generalized estimating equations (GEE) were employed. Statistical significance was set at 0.05. Eta-squared (η^2) was calculated as an effect size estimate for the ANOVA models. Sensitivity analyses and results are shown in the Appendix.

Results – Experiment 1

Table 1 displays the characteristics of the sample. The participants, on average, were 21.16 years of age and were predominately female (73.0%).

Memory Results

Table 2 displays the veridical memory results across the three conditions. Individual level data is presented in Figure 2. There was a significant main effect for condition, $F(2, 72) = 17.82$, $p < .001$, $\eta^2 = .21$, main effect for time period, $F(1, 36) = 74.83$, $p < .001$, $\eta^2 = .11$, but no condition by time period interaction, $F(2, 72) = .26$, $p = .77$, $\eta^2 = .0001$. For the condition effects, Before was not different from Control, $M_{diff} = -.216$, SE = .26, $t = .82$, $p = .42$. However, During was worse than Before, $M_{diff} = -1.42$, SE = .32, $t = 4.32$, $p < .001$, and During was also worse than Control, $M_{diff} = -1.64$, SE = .29, $t = 5.52$, $p < .001$. The delay period had lower veridical memory recall than the immediate time period, $M_{diff} = -1.32$, SE = .15, $t = 8.65$, $p < .001$.

Table 2 displays the false memory results across the three conditions. Individual level data is presented in Figure 3. There was no significant main effect for condition, df = 2, Wald $\chi^2 = 2.866$, $p = .24$, main effect for time, df = 1, Wald $\chi^2 = 2.309$, $p = .13$, or condition by time interaction, df = 5, Wald $\chi^2 = 5.2$, $p = .39$.

Discussion and Introduction to Experiment 2

Experiment 1 was specifically designed to evaluate whether acute vigorous-intensity exercise influences veridical and false memories and if so, whether this effect is a function of the temporal coupling between the acute bout of exercise and memory encoding. Our results provide partial support for our hypotheses. When the acute bout of exercise occurred prior to memory encoding, exercise did not increase veridical memory performance. However, when the acute bout of exercise occurred during memory encoding, veridical memory performance was reduced. Regarding false episodic memory, there was no statistically significant effect.

The reduced veridical memory performance during vigorous exercise aligns with other recent work demonstrating this effect for both episodic and working memory systems (Loprinzi, Day, & Deming, 2019). The potential mechanisms of this reduced memory accuracy during vigorous-intensity exercise have been highlighted elsewhere (Tomporowski & Qazi, 2020), which is consistent with arousal and attention theories. For example, maximal levels of arousal induced by acute vigorous-intensity exercise triggers a broad spectrum of metabolic and neurotransmitter changes, peripheral and central fatigue, and reduced perceived availability of attentional resources (McMorris & Hale, 2015). Under dual-task conditions, which include memorization while engaging in vigorous-intensity exercise, such physiological and psychological alterations may negatively affect encoding, and ultimately, impair memory retrieval.

Additionally, our reduced veridical memory performance during exercise aligns with the transient hypofrontality theoretical framework (Del Giorno, Hall, O'Leary, Bixby, & Miller, 2010; Dietrich, 2006), suggesting that vigorous-intensity exercise may reduce prefrontal cortex function during exercise, and in turn, impair higher-order cognition. This assertion is also supported by other research demonstrating that vigorous-intensity acute exercise decreases neural activity of the prefrontal cortex, which plays an important role in executive function and memory retrieval (Ando, Kokubu, Yamada, & Kimura, 2011).

A limitation of this experiment is that we did not employ an initial bout of maximal exercise to determine the participant’s maximal heart rate. Instead, we estimated maximal heart rate from an equation. Despite this, the achieved heart rates for the vigorous-intensity exercise were within the range of vigorous-intensity exercise. Our study would have also benefited with a longer follow-up period; it is possible that a 20-minute delay was not sufficient for memory consolidation to have occurred. We also see a benefit for including a condition that involves low velocity movement during encoding. In theory, higher velocities of movement may require greater focus and attention. Evaluating different intensities of movement may help disentangle the effects of physiological exertion and attention during exercise on memory function. For example, reduced memory performance during higher-intensity exercise could be attributed, in part, to increased physical exertion as well as reduced attention (e.g., focus on staying on the treadmill). Thus, at this point, since our Before and Control conditions did not engage in movement during encoding, it is unclear if our reduced veridical memory performance in the During condition is due to movement or physical exertion during encoding.

Additionally, we also see utility in separating the effects of exercise on encoding and retrieval-based mechanisms (Loprinzi et al., 2021). In the During condition, encoding occurred during exercise, but retrieval occurred immediately after exercise. Thus, it is difficult to know whether the reduced memory in the During condition is due to the influence of exercise on encoding or retrieval-based mechanisms. We address each of these limitations in Experiment 2.

Extending the findings from Experiment 1, we made six notable improvements in Experiment 2. First, instead of using an equation to determine vigorous-intensity exercise (Experiment 1), Experiment 2 uses a vigorous-intensity threshold determined from an initial maximal exercise visit. Second, to better tease out whether reduced memory performance during exercise is a result of altered attention or increased physical exertion, in Experiment 2, we included a lower-intensity (in addition to higher-intensity) exercise condition during memory encoding. Third, to better determine whether reduced memory performance during exercise is from altered mechanisms related to encoding or retrieval, we added two During conditions, one of which included the memory assessment immediately after exercise and the other implemented the memory assessment 30 minutes after exercise. If we were to observe memory impairments in both of these conditions, this would suggest that these memory impairments are likely due to encoding-based impairments. Fourth, to increase the reliability of our results, we extended the number of DRM lists from one (Experiment 1) to five (Experiment 2) in each condition. Fifth, we extended the delayed memory assessment out to 24-hours in Experiment 2. Lastly, another notable difference between Experiments 1 and 2 is that, for Experiment 2, we used a memory recognition, not a recall, assessment. This was done for several reasons. We were concerned that a recall assessment would produce relatively low levels of veridical and false memories when recall is to occur only after the final list, as opposed to other studies which implement recall assessments immediately after each list (Marchant, Hampson, Finnigan, Marrin, & Thorley, 2020). We did not want to implement separate recall assessments after each list because doing so would result in the recall occurring during exercise in the During condition, while occurring during rest in the Before and Control conditions. Our intent was to maintain the same retrieval context (rest) across conditions, while manipulating the encoding context across conditions. Importantly, we also note that recognition assessments, as opposed to recall assessments, result in higher false memories for non-presented critical items when using the DRM paradigm (Smith & Hunt, 1998).

Methods – Experiment 2

Participants

Recruitment and eligibility criteria for Experiment 2 was the same as Experiment 1. However, an independent set of participants were recruited for Experiment 2. Thirty-nine healthy young adults (mean age = 21 years, range = 19-24 years, 64% female) participated in Experiment

2. Written consent was obtained from all participants and ethical approval was obtained by the University of Mississippi. Data and study materials are available at XXX.

Study Design

Employing a within-subject design, participants completed five conditions (see Figure 4) in a counterbalanced order. Prior to the first condition, participants completed an initial visit involving a maximal treadmill exercise test. This was implemented to measure the participant's maximal heart rate during exercise, which was used to determine their vigorous-intensity (80% of HRR) and light-intensity (30% of HRR) exercise protocols for their subsequent visits. Participants took part in two laboratory testing sessions, one immediately following encoding and one 24-hours after that.

Control and Experimental Conditions

The initial visit was used to measure the participant's maximal heart rate. The specific assessment included an individualized protocol (Mier & Gibson, 2004). Participants warmed-up for 3-min by walking at 3.5 miles per hour. After the warm-up period, the speed was set, and remained, at 5.5 mph for the entire exercise protocol while the incline (starting at 0%) increased by 2% every 2-minutes. The maximal treadmill exercise bout ended when the participant reached exhaustion. During the maximal treadmill test, heart rate was monitored throughout the test. Rating of perceived exertion (RPE) was evaluated (6-20 scale) at the conclusion of the bout of exercise.

The control and exercise conditions (Figure 4) for Experiment 2 were similar to that of Experiment 1. Light- and vigorous-intensity exercise, respectively, occurred at 30% and 80% of HRR.

Memory Assessment

All stimuli were presented, and responses collected with a program created via E-Prime (v.3). Five sets of five DRM lists (15 items per list) were used (Stadler, Roediger, & McDermott, 1999). Set 1 included the lists with the lure items of *window*, *high*, *trash*, *pen*, and *mountain*; Set 2 included *sleep*, *shirt*, *anger*, *man*, and *cold*; Set 3 included *smell*, *flag*, *needle*, *music*, and *cup*; Set 4 included *doctor*, *thief*, *rough*, *river*, and *city*; and Set 5 included *sweet*, *girl*, *smoke*, *rubber* and *soft*. Using the normative results from Stadler et al. (1999), the respective proportion of participants with a false alarm to the critical target for these 5 sets was between 71% and 72%. These five DRM sets were randomized across the five experimental conditions.

Study List. In the study phase, participants listened (via headphones; computer-generated female voice) to a recording of five separate DRM lists, with each list including 15 items; each item was presented at a rate of one word every two seconds. Between the presentation of each list, there was a 5 second break. The five lists were presented in a random order, with the items in each list presented in the fixed order shown in Stadler et al. (1999).

Test List. In the test phase, participants viewed 160 words on a computer screen. For each item (self-paced), they were instructed to respond with "Yes" if the item was old (previously studied) or "No" if the item was new (not shown in the study phase). The test included 75 of the studied items, 5 critical target items and 80 new unrelated items. Items were pseudo-randomly ordered to ensure that there were no runs of four or more studied or new items.

Outcome. Hit rate was calculated as the proportion of old items (from the study phase) that were responded with a "Yes" keypress. Lure false alarms was calculated as the proportion of lure items (not presented in the study phase) that were responded with a "Yes" keypress.

Statistical Analyses

All statistical analyses were computed in JASP (v. 0.16). For hit rate and false alarm rates, a 5 (condition: Control, Light During Encoding, Vigorous Before Encoding, Vigorous During Encoding, and Vigorous During Encoding – Delayed) × 2 (time point: immediate vs. delay) repeated measures ANOVA (rmANOVA) was employed. When the Mauchly's test of sphericity was statistically significant ($p < .05$), indicating violations to sphericity, the degrees of freedom were corrected with the Huynh-Feldt procedure. Holm-corrected post-hoc tests were conducted when appropriate. Statistical significance was set at 0.05. Eta-squared (η^2) was calculated as an effect size estimate for the ANOVA models. Sensitivity analyses and results are shown in the Appendix.

Results – Experiment 2

Table 3 displays the characteristics of the sample. The participants, on average, were 21 years of age and were predominately female (64%).

Memory Recognition Results

Table 4 displays the memory recognition results across the five conditions. Individual level data is presented in Figure 5. With hit rate as the outcome, there was a significant main effect for condition, $F(4, 152) = 7.89$, $p < .001$, $\eta^2 = .12$, main effect for time period, $F(1, 38) = 53.32$, $p < .001$, $\eta^2 = .12$, but no condition by time period interaction, $F(4, 152) = 1.99$, $p = .10$, $\eta^2 = .005$. For the condition effects, Vigorous Before Encoding (b) had a higher hit rate than Vigorous During Encoding (d), $M_{diff} = .068$, SE = .02, $t = 3.06$, $p = .02$, and Vigorous During Encoding – Delayed Recognition (e), $M_{diff} = .115$, SE = .02, $t = 5.15$, $p < .001$. Light During Encoding (c) had a higher hit rate than Vigorous During Encoding – Delayed (e), $M_{diff} = .094$, SE = .02, $t = 4.185$, $p < .001$, and Control (a) had a higher hit rate than Vigorous During Encoding – Delayed (e), $M_{diff} = .065$, SE = .02, $t = 2.918$, $p = .02$. For the time period effects, hit rate was higher for the initial assessment when compared to the delayed assessment, M_{diff} = .079, SE = .01, t = 7.30, p < .001.

Table 4 displays the false memory data. Individual level data is presented in Figure 6. With the lure false alarm rate as the outcome, there was a main effect for condition, $F(4, 152)$ = 2.937, p = .02, η^2 = .04, and a main effect for time period, $F(1, 38)$ = 15.26, p < .001, η^2 = .03, but no condition by time period interaction, $F(4, 152)$ = .41, p = .80, η^2 = .003. For the condition effects, Vigorous Before Encoding (b) had a higher false alarm rate than Vigorous During Encoding – Delayed (e), M_{diff} = .128, SE = .03, t = 3.42, p = .008. No other comparisons were statistically significant. For the time period effects, false alarm rates were higher for the initial assessment when compared to the delayed assessment, M_{diff} = .063, SE = .01, t = 3.906, p < .001.

With the unrelated false alarm rate as the outcome, there was no main effect for condition, $F(3.13, 118.8)$ = .46, p = .72, η^2 = .008, but there was a main effect for time, $F(1, 38)$ = 33.04, p < .001, η^2 = .08, as well as a condition by time period interaction, $F(4, 152)$ = 3.71, p = .007, η^2 = .02. Unrelated false alarm rates were higher at the immediate time period for Vigorous During Encoding – Delayed (e) when compared to Light During Encoding (c), p = .049 (uncorrected p value). No other comparisons were statistically significant.

Discussion – Experiment 2

In Experiment 1, veridical memory performance was lower when encoding occurred during vigorous-intensity exercise when compared to no exercise or exercise before encoding. Similarly, in Experiment 2, hit rates were lower when encoding occurred during vigorous-intensity exercise when compared to encoding occurring after vigorous-intensity exercise. In Experiment 2, we added in a light-intensity exercise condition during encoding to better tease out whether the reduced memory performance during exercise is a result of altered attention or increased physical exertion. Experiment 2 demonstrated that hit rates were lower when encoding occurred during vigorous-intensity exercise when compared to light-intensity exercise. This finding suggests that reduced memory performance from encoding during vigorous-intensity exercise appears to be due to the exertion, not simply due to movement itself. This also aligns with other work showing that only vigorous-intensity acute exercise, and not lower-intensity exercise (including moderate-intensity exercise), impairs prefrontal-dependent cognitive function (Jung, Ryu, Kang, Javadi, & Loprinzi, 2021) and episodic memory (Loprinzi, Day, & Deming, 2019).

In Experiment 1, when encoding occurred during vigorous-intensity exercise, we had participants complete the memory recall task immediately after the cessation of exercise. Thus, it was not possible to determine if the reduced memory performance from encoding during exercise was due to impaired encoding or impaired retrieval-based mechanisms. To address this, in Experiment 2, we employed two conditions where after encoding the words during vigorous-intensity exercise, one condition involved an immediate recognition assessment whereas the other had a 30-minute break before the first recognition assessment. We observed evidence of reduced veridical memory for both scenarios as compared to the control condition, suggesting that the reduced memory performance is likely due to impaired encoding-based mechanisms. An important caveat, however, is that the reduced memory recognition after the 30-minute break may have simply been due to the passage of time, as opposed to impaired encoding during vigorous-intensity exercise. However, the memory recognition performance in this condition after 24-hours (i.e., our "delay" period) was the lowest of all conditions, suggesting that the reduced long-term memory performance in this condition was likely due to impaired encoding during vigorous-intensity exercise. Future work, however, may wish to replicate this paradigm but employ a time-matched control scenario (i.e., 30-min delayed assessment in the control condition).

As stated, in Experiment 2, vigorous-intensity exercise during encoding resulted in reduced veridical memory performance when compared to vigorous-intensity exercise before encoding. Experiment 2 also demonstrated a reduced lure false alarm rate during exercise when compared to exercise occurring before encoding. These findings provide suggestive evidence that memory may be influenced when encoding occurs during vigorous-intensity exercise. Within the context of the spreading activation theory, the reduced veridical memory performance resulting from encoding during vigorous-intensity exercise may have also had an effect on false memory via the reduced spread or activation of the non-presented critical item. The spreading activation theory, on the other hand, would predict that unrelated new items (as opposed to related new items) would be less activated when studying related items. Thus, the similar effects that exercise would have on veridical and false memory per the spreading activation theory would not be expected for unrelated new items. Our results partially support these theoretical predictions. That is, although engaging in vigorous-intensity exercise during encoding provided evidence of reduced veridical memory and false memory for related critical items, vigorous-intensity exercise during encoding increased false memory for unrelated new items.

Further work, however, is need to confirm the reliability of these findings. Neuroimaging methods can be used to study the brain areas involved in this process. For example, one can investigate the link between activity of different brain areas at the time of encoding based on the participants' performance at the time of retrieval (Paller & Wagner, 2002; Wagner, Koutstaal, & Schacter, 1999). Identification of these brain areas can highlight potential modulatory mechanisms of exercise on different traces of memory.

General Discussion

The purpose of these experiments was to evaluate the effects of acute exercise on veridical and false memory performance. Our general findings were that (1) acute vigorous-intensity exercise prior to encoding did not influence veridical memory when compared to a non-exercise control, (2) vigorous-intensity acute exercise during encoding reduced veridical performance when compared to exercise prior to encoding (Experiment 1) and a non-exercise control (Experiments 1 and 2), (3) vigorous-intensity, but not light-intensity, acute exercise during encoding reduced false memory for related new items when compared to exercise prior to encoding (Experiment 2), and (4) we observed some evidence to suggest that vigorous-intensity acute exercise during encoding increased false memory for unrelated new items when compared to light-intensity exercise during encoding. Thus, these findings demonstrate reduced veridical and false memory (for related new items) during exercise, an effect that appears to be intensity-dependent (only for higher-intensity exercise).

Unlike some prior studies which demonstrate that acute exercise can enhance veridical memory when the bout of exercise occurs prior to encoding (Labban & Etnier, 2011, 2018), the results of the present set of experiments did not support these findings. However, our null findings for the Before condition are not entirely surprising. Early work (Tomporowski, Ellis, & Stephens, 1987) demonstrates that vigorous-intensity acute exercise before memory encoding did not enhance memory when compared to a non-exercise control. Further, other studies demonstrate that exercising during the consolidation period can improve long-term memory performance (Pyke et al., 2020; van Dongen, Kersten, Wagner, Morris, & Fernandez, 2016). In addition to the timing of the acute exercise and memory task, there may be other moderators to consider. As discussed elsewhere (Loprinzi, Roig, Etnier, Tomporowski, & Voss, 2021), there is a need for future research to identify potential individual differences (e.g., working memory capacity) that may help to explain this variable response.

As discussed elsewhere (Tomporowski, Albrecht, & Pendleton, 2017), when coupling the acute bout of exercise with memory encoding, this may require the individual to switch attention between the two tasks. Ultimately, this dual-task situation may reduce efficient encoding, and in turn, impair episodic memory function. Although there is accumulating research demonstrating that veridical memory may be impaired during higher-intensity acute exercise (Loprinzi, Day, & Deming, 2019), limited research has evaluated this for false memory. Herein, we provide some evidence that vigorous-intensity acute exercise may also reduce false memory performance for related new items. If replicated, a worthwhile follow-up step may be to evaluate potential mechanisms of this effect. As speculated elsewhere (Jung, Ryu, Kang, Javadi, & Loprinzi, 2021), vigorous-intensity acute exercise during encoding may reduce veridical memory performance through various psychological and neurophysiological mechanisms. As an example, vigorous-intensity acute exercise during encoding may reduce the degree of attentional resources devoted toward encoding, which ultimately may impair memory retrieval. Vigorous-intensity acute exercise during encoding may also impair memory by reducing cerebral oxygenation in the prefrontal cortex. Another speculated mechanism is that vigorous-intensity acute exercise may induce excessive release of dopamine and norepinephrine, acting on D_1-receptors and β-adrenoreceptors, and in turn, inducing cAMP activation and increasing the noise-to-signal ratio (Jung, Ryu, Kang, Javadi, & Loprinzi, 2021). Whether these postulated mechanisms also explain the reductions in false memory from exercise during encoding are unknown, and thus, this is an area in need of future research.

Relatedly, it would worth investigating these relationships with an even higher intensity of exercise (i.e., maximal exercise). Per the tenets of hypofrontality theory (Audiffren, 2016), very high exercise intensity (above the respiratory compensation point) should reduce levels of neural activation in the prefrontal cortex, a brain structure involved in veridical and false memory formation and retrieval (Kim & Cabeza, 2007). This reduction in prefrontal cortex function may reduce source monitoring accuracy, and in turn, increase the rate of false memories. Thus, future work should carefully consider these intensity-specific effects of acute exercise on veridical and false memory while concurrently monitoring the degree of prefrontal cortex activation (e.g., via fNIR technology). It is plausible that our imposed vigorous-intensity exercise was intense enough to impair source monitoring, as demonstrated by the increased rate of false memories for unrelated new items when vigorous-intensity acute exercise occurred during encoding. Perhaps, however, maximal-intensity exercise may profoundly disrupt source monitoring, ultimately reducing the spread of activation to the related, non-presented critical item. Or perhaps such an intensity of exercise will further strengthen the predictions of the spreading activation theory. Future work is needed to better disentangle the theoretical mechanisms through which exercising during encoding influences false memory.

The present set of experiments also provide interesting insight on the effects of arousal during encoding on subsequent memory performance. Within the context of eyewitness testimony research, prior work demonstrates that medium levels of emotional arousal, elicited by viewing videos, improved recall of both central and peripheral details, whereas high levels of video-induced arousal impaired recall of central events (Dutton & Carroll, 2001). Our findings also demonstrate evidence of impaired veridical memory, but due to physiological arousal (exercise) as opposed to emotional arousal per se. It would be worthwhile for future work to compare the effects and mechanisms of emotional *and* physiological arousal during encoding on subsequent memory performance. It may also be worthwhile to evaluate how other factors (e.g., age, fitness) influence these effects. For example, lesser fit older individuals, compared to their counterparts, whom may have deficits in source monitoring, may have a differential emotional and physiological response during encoding, ultimately influencing the effects of arousal on subsequent veridical and false memory performance.

In conclusion, although vigorous-intensity acute exercise prior to memory encoding did not affect veridical memory performance, we observed some evidence to suggest that memory encoding during vigorous-intensity acute exercise may influence veridical and false memory performance. However, additional follow-up work is needed to evaluate the reliability of this effect. One practical consequence of our findings that could be applied to daily life settings is that exercising at higher intensity during school or workplace activities may impair memory retention, while at the same time, may not increase false memories. Future work should evaluate if other exercise intensities and modalities have the most optimal gains in memory performance, i.e., increasing veridical memory while concurrently reducing false memory. Such work should carefully consider various other factors (e.g., stimulants prior to experimentation, native language of the participant) that may confound the exercise-memory relationship.

References

Ando, S., Kokubu, M., Yamada, Y., & Kimura, M. (2011). Does cerebral oxygenation affect cognitive function during exercise? *Eur J Appl Physiol, 111*(9), 1973-1982. doi: 10.1007/s00421-011-1827-1

Audiffren, M. (2016). The reticular-activating hypofrontality (RAH) model of acute exercise: Current data and future perspectives. In T. McMorris (Ed.), *Exercise-cognition interaction: Neuroscience perspectives* (pp. 147-166): Elsevier Academic Press.

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

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

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Med Sci Sports Exerc, 14*(5), 377-381.

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

Coles, K., & Tomporowski, P. D. (2008). Effects of acute exercise on executive processing, short-term and long-term memory. *J Sports Sci, 26*(3), 333-344. doi: 10.1080/02640410701591417

Deese, J. (1959). On the prediction of occurrence of particular verbal intrusions in immediate recall. *J Exp Psychol, 58*(1), 17-22.

Del Giorno, J. M., Hall, E. E., O'Leary, K. C., Bixby, W. R., & Miller, P. C. (2010). Cognitive function during acute exercise: a test of the transient hypofrontality theory. *J Sport Exerc Psychol, 32*(3), 312-323.

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Res, 145*(1), 79-83. doi: 10.1016/j.psychres.2005.07.033

Dilley, E. K., Zou, L., & Loprinzi, P. D. (2019). The effects of acute exercise intensity on episodic and false memory among young adult college students. *Health Promot Perspect, 9*(2), 143-149. doi: 10.15171/hpp.2019.20

Dutton, A., & Carroll, M. (2001). Eyewitness testimony: Effects of source of arousal on memory, source-monitoring, and metamemory judgments. *Australian Journal of Psychology, 53*(2), 83-91.

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

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

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

Green, D., & Loprinzi, P. D. (2018). Experimental Effects of Acute Exercise on Prospective Memory and False Memory. *Psychol Rep*, 33294118782466. doi: 10.1177/0033294118782466

Haynes, J. T. t., Frith, E., Sng, E., & Loprinzi, P. D. (2019). Experimental Effects of Acute Exercise on Episodic Memory Function: Considerations for the Timing of Exercise. *Psychol Rep, 122*(5), 1744-1754. doi: 10.1177/0033294118786688

Howe, M. L., Wimmer, M. C., Gagnon, N., & Plumpton, S. (2009). An associative activation theory of children's and adults' memory illusions. *Journal of Memory and Language, 60*, 229-251.

Jung, M., Ryu, S., Kang, M., Javadi, A. H., & Loprinzi, P. D. (2021). Evaluation of the transient hypofrontality theory in the context of exercise: A systematic review with meta-analysis. *Q J Exp Psychol (Hove)*, 17470218211048807. doi: 10.1177/17470218211048807

Kim, H., & Cabeza, R. (2007). Differential contributions of prefrontal, medial temporal, and sensory-perceptual regions to true and false memory formation. *Cereb Cortex, 17*(9), 2143-2150. doi: 10.1093/cercor/bhl122

Labban, J. D., & Etnier, J. L. (2011). Effects of acute exercise on long-term memory. *Res Q Exerc Sport, 82*(4), 712-721. doi: 10.1080/02701367.2011.10599808

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

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

Loprinzi, P. D. (2018). Intensity-specific effects of acute exercise on human memory function: Considerations for the timing of exercise and the type of memory. *Health Promot Perspect, 8*(4), 255-262.

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

Loprinzi, P. D., Day, S., & Deming, R. (2019). Acute Exercise Intensity and Memory Function: Evaluation of the Transient Hypofrontality Hypothesis. *Medicina (Kaunas), 55*(8). doi: 10.3390/medicina55080445

Loprinzi, P. D., Day, S., Hendry, R., Hoffman, S., Love, A., Marable, S., . . . Gilliland, B. (2021). The Effects of Acute Exercise on Short- and Long-Term Memory: Considerations for the Timing of Exercise and Phases of Memory. *Eur J Psychol, 17*(1), 85-103. doi: 10.5964/ejop.2955

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

Loprinzi, P. D., Ponce, P., & Frith, E. (2018). Hypothesized mechanisms through which acute exercise influences episodic memory. *Physiol Int, 105*, 1-13. doi: 10.1556/2060.105.2018.4.28

Loprinzi, P. D., Rigdon, B., Javadi, A. H., & Kelemen, W. L. (2021). Effects of acute exercise intensity on source episodic memory and metamemory accuracy. *Q J Exp Psychol*.

Loprinzi, P. D., Roig, M., Etnier, J. L., Tomporowski, P. D., & Voss, M. (2021). Acute and Chronic Exercise Effects on Human Memory: What We Know and Where to Go from Here. *J Clin Med, 10*(21). doi: 10.3390/jcm10214812

Marchant, D., Hampson, S., Finnigan, L., Marrin, K., & Thorley, C. (2020). The Effects of Acute Moderate and High Intensity Exercise on Memory. *Front Psychol, 11*, 1716. doi: 10.3389/fpsyg.2020.01716

McMorris, T., & Hale, B. J. (2015). Is there an acute exercise-induced physiological/biochemical threshold which triggers increased speed of cognitive functioning. *J Sport Health Sci, 4*(1), 4-13.

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

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

Moore, D., Jung, M., Hillman, C. H., Kang, M., & Loprinzi, P. D. (2022). Interrelationships between exercise, functional connectivity, and cognition among healthy adults: A systematic review. *Psychophysiology*, e14014. doi: 10.1111/psyp.14014

Paller, K. A., & Wagner, A. D. (2002). Observing the transformation of experience into memory. *Trends Cogn Sci, 6*(2), 93-102. doi: 10.1016/s1364-6613(00)01845-3

Poo, M. M., Pignatelli, M., Ryan, T. J., Tonegawa, S., Bonhoeffer, T., Martin, K. C., . . . Stevens, C. (2016). What is memory? The present state of the engram. *BMC Biol, 14*, 40. doi: 10.1186/s12915-016-0261-6

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

Roediger, H. L., & McDermott, K. B. (1995). Creating false memories: Remebering words not presented in lists. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*(4), 803-814.

Roediger III, H. L., Balota, D. A., & Watson, J. M. (2001). Spreading activation and arousal of false memories. In H. L. Roediger III, J. S. Nairne, I. Neath & A. M. Surprenant (Eds.), *The nature of remembering: Essays in honor of Robert G. Crowder* (pp. 95-115): American Psychological Association.

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

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

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

Siddiqui, A., & Loprinzi, P. D. (2018). Experimental Investigation of the Time Course Effects of Acute Exercise on False Episodic Memory. *J Clin Med, 7*(7). doi: 10.3390/jcm7070157

Smith, R. E., & Hunt, R. R. (1998). Presentation modality affects false memory. *Psychonomic Bulletin and Review, 5*(4), 710-715. doi: 10.3758/BF03208850

Sng, E., Frith, E., & Loprinzi, P. D. (2018). Temporal Effects of Acute Walking Exercise on Learning and Memory Function. *Am J Health Promot, 32*(7), 1518-1525. doi: 10.1177/0890117117749476

Stadler, M. A., Roediger, H. L., & McDermott, K. B. (1999). Norms for word lists that create false memories. *Mem Cognit, 27*(3), 494-500.

Suwabe, K., Hyodo, K., Byun, K., Ochi, G., Yassa, M. A., & Soya, H. (2017). Acute moderate exercise improves mnemonic discrimination in young adults. *Hippocampus, 27*(3), 229-234. doi: 10.1002/hipo.22695

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

Tomporowski, P. D., Albrecht, C., & Pendleton, D. M. (2017). Effects of Isometric Hand-Grip Muscle Contraction on Young Adults' Free Recall and Recognition Memory. *Res Q Exerc Sport, 88*(1), 95-100. doi: 10.1080/02701367.2016.1264567

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

Tomporowski, P. D., & Qazi, A. S. (2020). Cognitive-Motor Dual Task Interference Effects on Declarative Memory: A Theory-Based Review. *Front Psychol, 11*, 1015. doi: 10.3389/fpsyg.2020.01015

van Dongen, E. V., Kersten, I. H., Wagner, I. C., Morris, R. G., & Fernandez, G. (2016). Physical Exercise Performed Four Hours after Learning Improves Memory Retention and Increases Hippocampal Pattern Similarity during Retrieval. *Curr Biol, 26*(13), 1722-1727. doi: 10.1016/j.cub.2016.04.071

Wagner, A. D., Koutstaal, W., & Schacter, D. L. (1999). When encoding yields remembering: insights from event-related neuroimaging. *Philos Trans R Soc Lond B Biol Sci, 354*(1387), 1307-1324. doi: 10.1098/rstb.1999.0481

Zuniga, K. E., Mueller, M., Santana, A. R., & Kelemen, W. L. (2019). Acute aerobic exercise improves memory across intensity and fitness levels. *Memory, 27*(5), 628-636. doi: 10.1080/09658211.2018.1546875

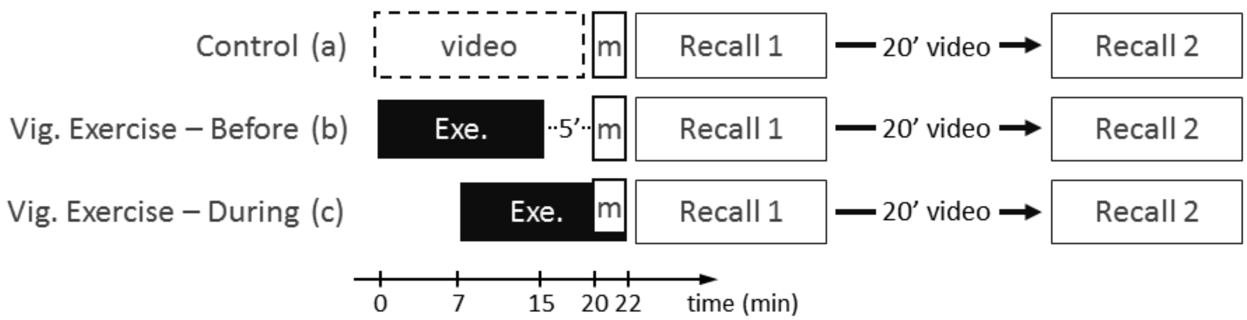


Figure 1

Experimental protocol of the three counterbalanced conditions.

(a) Control; (b) Before, and (c) During; m: memory encoding

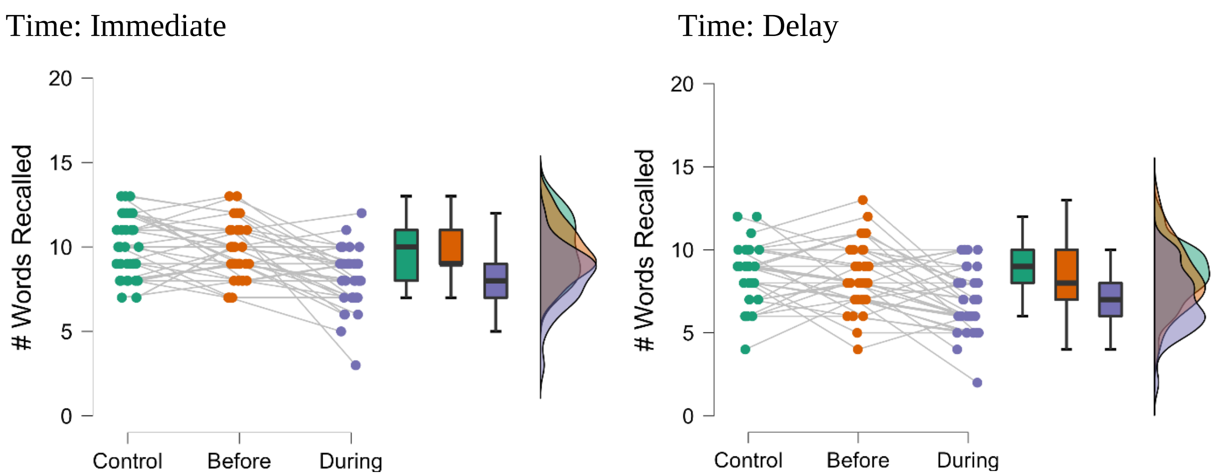


Figure 2

Raincloud plots depicting individual and group-level veridical memory performance across conditions and time.

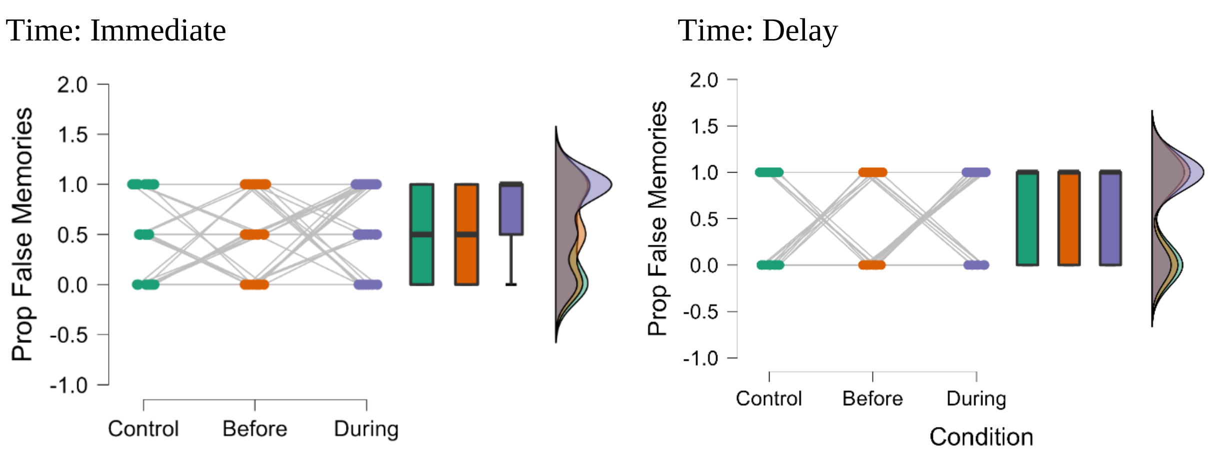


Figure 3

Raincloud plot depicting individual and group-level false memory performance across conditions and time. Prop = proportion.

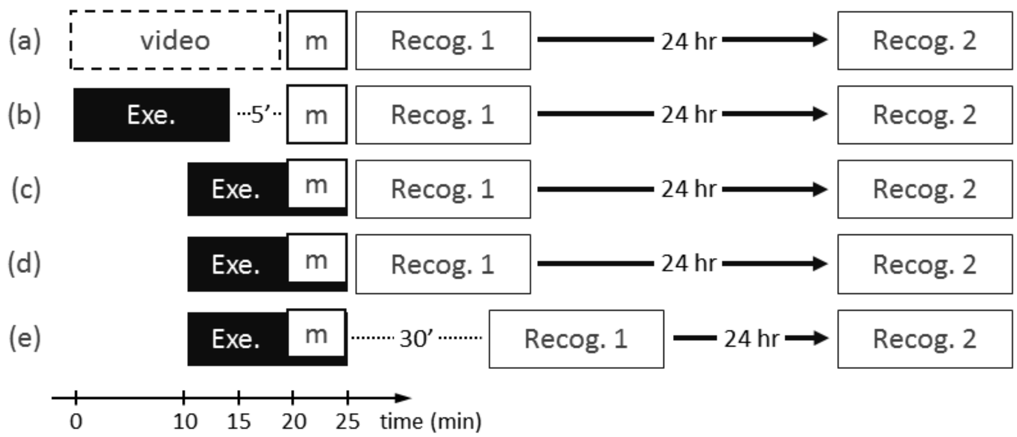


Figure 4

(a) Control, (b) Vigorous Exercise – Before, (c) Light Exercise During Encoding, (d) Vigorous Exercise During Encoding, and (e) Vigorous Exercise During Encoding – Delayed Recognition. Exe.: Exercise; Recog.: recognition

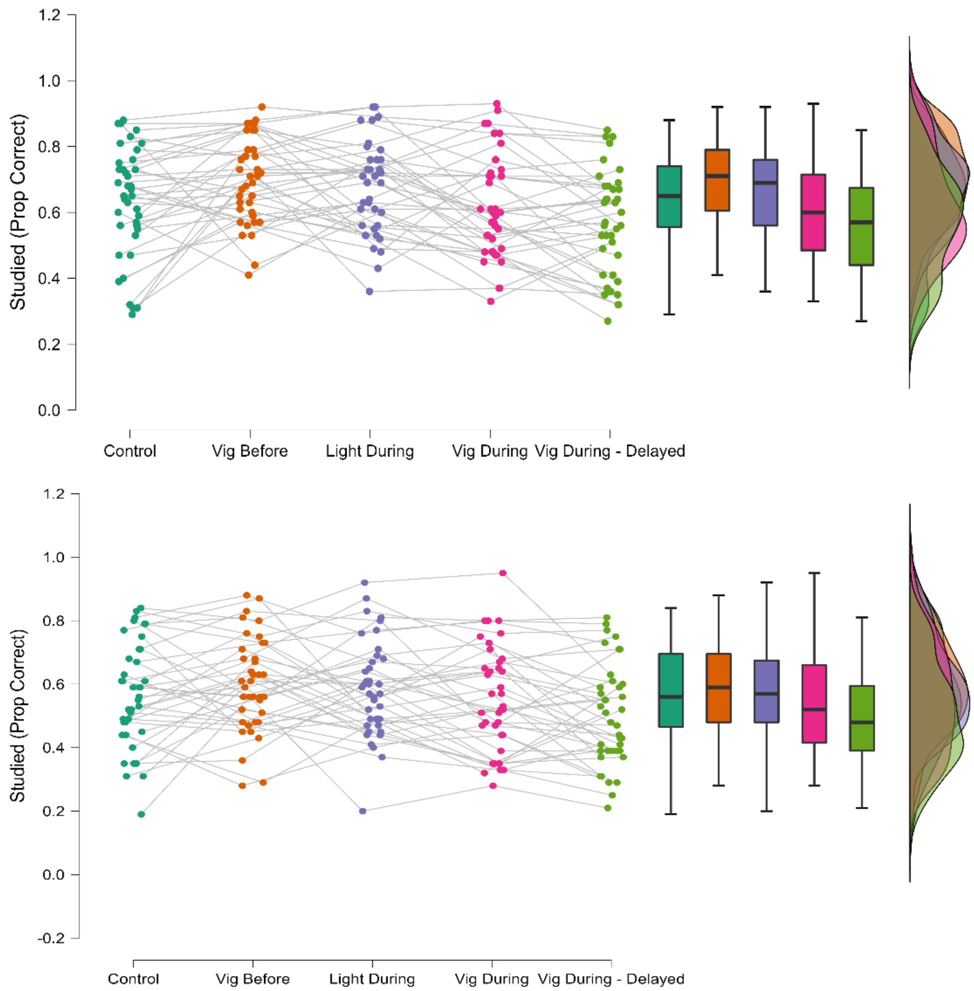


Figure 5

Raincloud plot depicting individual and group-level veridical memory performance across conditions for the immediate (top) and delayed (bottom) assessments.

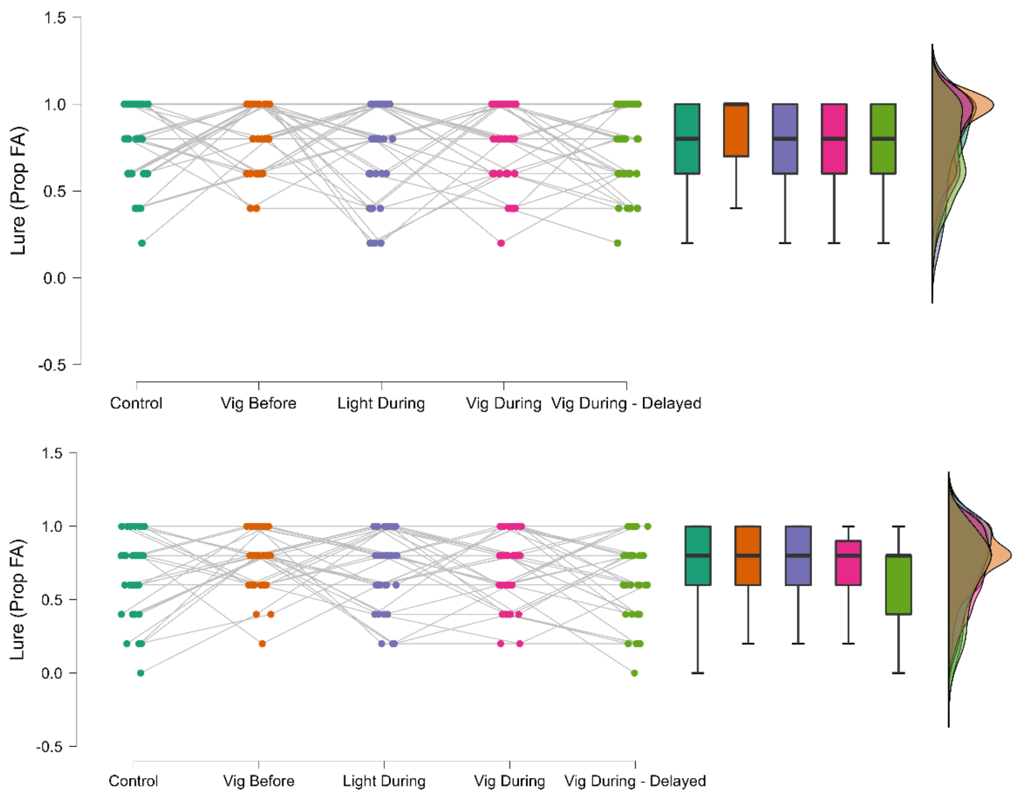


Figure 6

Raincloud plot depicting individual and group-level false memory performance across conditions for the immediate (top) and delayed (bottom) assessments.

Table 1

Sample characteristics

Variable	Point Estimate	SD
Age, mean years	21.16	0.95
Gender, % Female	73.0	
BMI, mean kg/m^2	24.35	6.05
MVPA, mean min/week	225.95	197.93

Notes: BMI: body mass index; MVPA: moderate to vigorous physical activity

Table 2

Memory results across the experimental conditions (mean (SD)).

Memory	Time	Control	Before	During	Total
Veridical Memory*	Immediate	9.92 (1.81)	9.68 (1.58)	8.18 (1.72)	9.26 (1.24)
	Delayed	8.51 (1.72)	8.32 (1.93)	6.97 (1.90)	7.98 (1.48)
	Total	9.22 (1.57)	9.00 (1.68)	7.58 (1.70)	
False Memory†	Immediate	0.49 (0.50)	0.49 (0.50)	0.62 (0.73)	0.53 (0.32)
	Delayed	0.51 (0.50)	0.60 (0.49)	0.73 (0.45)	0.61 (0.30)
	Total	0.50 (0.44)	0.54 (0.41)	0.68 (0.41)	

Notes: * mean number of words recalled (range 0-15). † mean proportion of false memory recall (range 0-1). Total refers to the averages across time/condition.

Table 3

Sample characteristics

Variable	Point Estimate	SD
Age, mean years	20.7	1.0
Gender, % Female	64.1	
BMI, mean kg/m^2	24.6	3.7
MVPA, mean min/week	195.6	156.3

Notes: BMI: body mass index; MVPA: moderate to vigorous physical activity

Table 4

Memory recognition results (proportion, SD) across the conditions.

	Studied (Proportion Correct)			Critical Item (Proportion FA)			Unrelated Item (Proportion FA)		
Condition	Immediate	Delayed	Total	Immediate	Delayed	Total	Immediate	Delayed	Total
(a)	.63 (.16)	.57 (.17)	.60 (.16)	.79 (.21)	.70 (.28)	.75 (.22)	.11 (.11)	.19 (.17)	.15 (.13)
(b)	.70 (.13)	.60 (.14)	.65 (.13)	.85 (.19)	.78 (.19)	.81 (.16)	.11 (.12)	.16 (.14)	.13 (.12)
(c)	.67 (.13)	.58 (.15)	.63 (.13)	.76 (.26)	.74 (.25)	.75 (.23)	.11 (.10)	.16 (.14)	.13 (.12)
(d)	.62 (.15)	.55 (.16)	.58 (.15)	.77 (.23)	.71 (.24)	.74 (.20)	.12 (.12)	.15 (.12)	.13 (.11)
(e)	.57 (.16)	.50 (.16)	.53 (.15)	.72 (.22)	.65 (.28)	.69 (.22)	.14 (.11)	.16 (.12)	.15 (.11)

Notes: Total refers to the averages across time/condition.

(a) Control, (b) Vigorous Exercise – Before, (c) Light Exercise During Encoding, (d) Vigorous Exercise During Encoding, and (e) Vigorous Exercise During Encoding – Delayed Recognition.

Appendix

Experiments 1 and 2

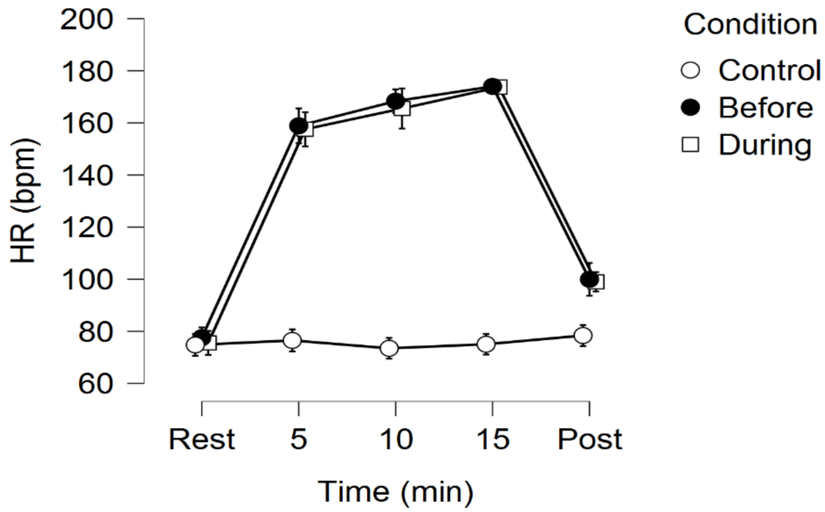
Additional Assessments

Body mass index (BMI) was estimated from measured weight in kilometers divided by measured height in meters squared. Habitual engagement in moderate-to-vigorous physical activity (MVPA) was assessed from the Physical Activity Vitals Sign questionnaire. This instrument includes two questions: (1) How many days did you engage in moderate-to-vigorous physical activity in the past 7 days? (2) On average, how many minutes did you engage in physical activity at the level? The product of these two items was obtained for a weekly estimate of MVPA. As evidence of concurrent validity, MVPA from this instrument has been shown to moderately correlate with MVPA from a validated Modifiable Activity Questionnaire (r = .71, p < .001) (Ball, Joy, Gren, & Shaw, 2016). The RPE scale was used as a measure of whole-body ratings of perceived exertion during exercise, which is a 15-point scale ranging from 6 (no exertion at all) to 20 (maximal exertion) (Borg, 1982). The odd numbered categories have verbal anchors (e.g., 11 = *light*, 13 = *somewhat hard*, 15 = *hard*, 17 = *very hard*, 19 = *extremely hard*).

Experiment 1

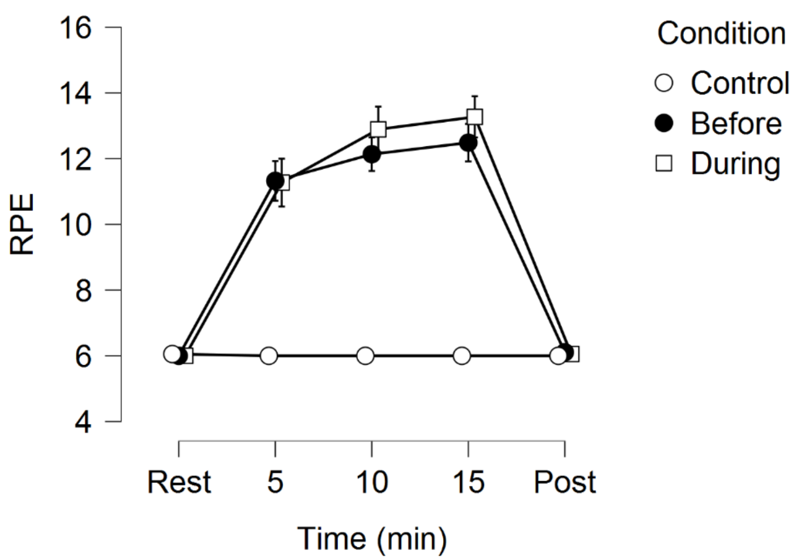
Manipulation Checks

Supplementary Figure 1 displays the physiological (heart rate) responses to the three conditions. There was a significant main effect for condition, $F(1.85, 57.35) = 734.63$, $p < .001$, $\eta^2 = .40$, main effect for time period, $F(2.94, 90.63) = 480.31$, $p < .001$, $\eta^2 = .34$, and a condition by time period interaction, $F(5.63, 174.49) = 293.79$, $p < .001$, $\eta^2 = .18$. With the exception of rest, Control was different than Before and During across all other time periods, p's < .001. Before and During did not differ at any time period, ps > .37.



Supplementary Figure 1. Heart rate responses to the three conditions. The post assessment occurred 5-minutes after the bout of exercise ended. Error bars represent 95% CI.

Supplementary Figure 2 displays the psychological (RPE) responses to the three conditions. There was a significant main effect for condition, $F(1.70, 61.41) = 430.31$, $p < .001$, $\eta^2 = .28$, main effect for time period, $F(2.06, 74.25) = 396.74$, $p < .001$, $\eta^2 = .38$, and a condition by time period interaction, $F(4.64, 167.30) = 199.85$, $p < .001$, $\eta^2 = .20$. Control was different than Before and During across all other time periods, *p*s < .001. Before and During differed at minute 10, $p = .01$, and at minute 15, $p = .001$, but not differ at the other time periods, *p*s > .16.



Supplementary Figure 2. Rating of perceived exertion (RPE) responses to the three conditions. The post assessment occurred 5-minutes after the bout of exercise ended. Error bars (minimally visible) represent 95% CI.

Memory Results

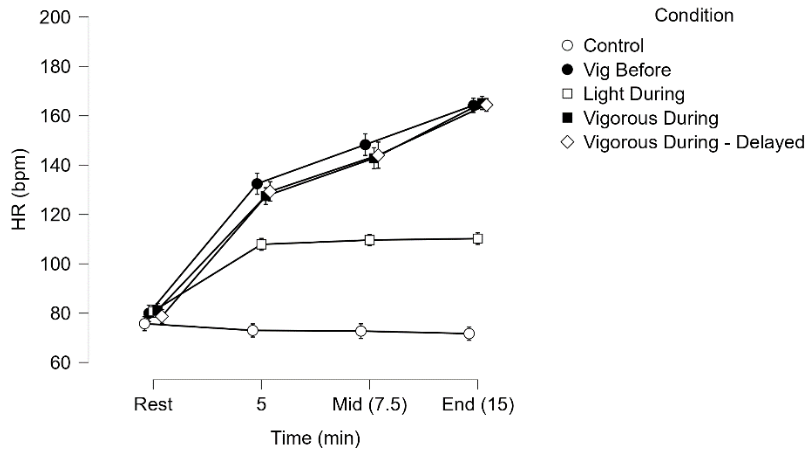
To investigate *** we ran ***. This analysis showed that self-reported MVPA did not interact with condition or time to influence veridical or false memory, all *p*s > .05.

Experiment 2

Manipulation Checks

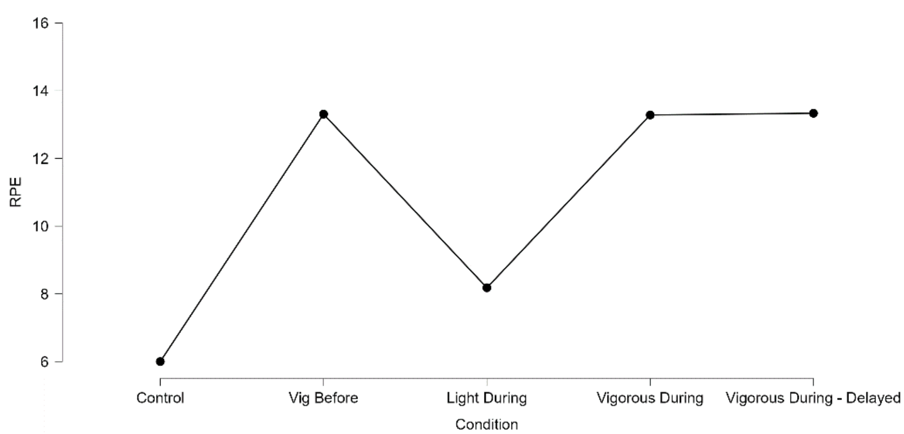
For the maximal treadmill test on the first visit, participants lasted a mean (SD) duration of 531.7 (155.8) seconds. At the end of the maximal treadmill test, mean (SD) heart rate (bpm) and RPE, respectively, were 185.6 (13.8) and 16.0 (2.0).

Supplementary Figure 3 displays the physiological (heart rate) responses to the five conditions. There was a significant main effect for condition, $F(2.98, 113.3) = 551.5$, $p < .001$, $\eta^2 = .42$, main effect for time period, $F(2.12, 80.7) = 593.3$, $p < .001$, $\eta^2 = .36$, and a condition by time period interaction, $F(5.77, 219.4) = 234.2$, $p < .001$, $\eta^2 = .15$. No differences were observed at rest, *p*s > .05. Control and Light During Encoding differed from all groups across all time periods, *p*s < .05. Vigorous Before Encoding, Vigorous During Encoding – IR, and Vigorous During Encoding – DR did not differ at any time period, *p*s > .05.



Supplementary Figure 3. Heart rate responses across time and condition. Error bars (minimally visible) represent 95% confidence interval.

Supplementary Figure 4 shows the rating of perceived exertion responses (at the end of exercise) to the five conditions A rmANOVA demonstrated a significant main effect for condition, $F(3.35, 127.3) = 276.4$, $p < .01$, $\eta^2 = .88$. Control and Light During Encoding were different than all groups, *p*s < .001. Vigorous Before Encoding, Vigorous During Encoding, and Vigorous During Encoding – Delayed did not differ between each other, *p*s > .83.



Supplementary Figure 4. Rating of perceived exertion responses across time and condition. Error bars (minimally visible) represent 95% confidence interval.

Memory Results

Similar to Experiment 1, we ran ***. This analysis showed that self-reported MVPA did not interact with condition or time to influence veridical or false memory, all *p*s > .05.