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Veridical and False Memory Performance as a Function of the Timing of High-Intensity Acute Exercise

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By

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Abstract

Background: Our recent experimental work demonstrated that high-intensity acute exercise improved veridical (true) memories and also increased the rate of false memories. The present experiment was designed to re-evaluate these effects for replication purposes. We also extend this literature by evaluating whether these effects are influenced by the timing of acute exercise. **Methods**: The sample included young adults (N=37; M_{age} = 21.16 years). We employed a three-condition, within-group, counterbalanced controlled design, consisting of two exercise conditions and a control condition. The exercise conditions involved a 15-minute bout of high-intensity acute exercise. These conditions included the bout of exercise either *Before* or *During* the memory task. The control condition involved a time-matched seated task (video). Memory performance was evaluated from the DRM (Deese-Roediger-McDermott) paradigm, including an immediate and delayed (20-min post encoding) time period assessment. For veridical memory, we observed a significant main effect for condition, $F(1.98, 71.30) = 17.82$, $p < .001$, $\eta^2 = .13$, main effect for time period, $F(1.00, 36.00) = 74.83$, $p < .001$, $\eta^2 = .11$, but no condition by time period interaction, $F(1.97, 71.06) = .26$, $p = .77$, $\eta^2 = .0001$. Veridical memory was lower for the During condition when compared to the Before condition, $M_{diff} = -1.42$, SE = .32, $t = 4.32$, $p < .001$, and Control condition, $M_{diff} = -1.64$, SE = .29, $t = 5.52$, $p < .001$. For false memory, although not statistically significant, false memory rates were highest for the During (62.2%) vs. Before (48.6%) and Control (48.6%) conditions. **Conclusion**: High-intensity acute exercise prior to memory encoding did not affect veridical memory performance. However, we observed evidence to suggest that memory encoding during high-intensity

acute exercise reduces veridical memory performance and may, potentially, increase false memory rates.

Keywords: Activation-Monitoring Theory; Cognition; Cognitive Function; Fuzzy Trace theory

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BACKGROUND

False memory is a phenomenon in which a past event is recalled but actually never occurred. This section examines methods used to assess false memory, theoretical explanations of false memory, strategies to reduce false memory, brain structures involved, and neurophysiological mechanisms of false memory.

Table 1. Commonly used methods to assess false memory.

Assessment Name	**Example of How it is Assessed**	**Reference**
DRM (Deese-Roediger-McDermott)	Participants are presented with a list of semantically related words (e.g., candy, cake, sugar, etc.). During retrieval, if they indicate the non-presented critical lure (e.g., sweet), they are scored as having a false memory.	Roediger HL, McDermott, KB. Creating false memories: Remembering words not presented in lists. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1995;24(4): 803–814
Memory Conjunction Error Paradigm	Participants are presented with two "parent" stimulus items (e.g., blackmail and jailbird) that are later recombined to form a "conjunction lure" (e.g., blackbird)	Leding JK, Lampinen, JM, Edwards NW, Odegard TN. The memory conjunction error paradigm: Normative data for conjunction triplets. *Behavior Research Methods*. 2007;39(4): 920-925.
Category Associates Procedure	For example, the category four footed animal includes the ordered exemplars dog, cat, horse, cow, lion, tiger, elephant, pig, bear, mouse, and deer. During the study, the first and last exemplars from each category are removed and used as critical lures to determine if high- and low-frequency category exemplars would be	Seamon JG, Chun RL, Schlegal SE, Greene SE, Goldenberg AB. False memory for categorized pictures and words: The category associates procedure for studying memory errors in children and adults. *Journal of Memory and Language*. 1999;42(1):120-146.

	differentially recognized on a memory test.	

False memory can be assessed in a variety of ways. For example, early research of false memory included asking participants to recall a story at longer and longer intervals through a technique developed by Bartlett in 1932.[2] Other assessments of false memory include paradigms that used sentences or pictures. One of the most notable assessments of false memory is the Deese-Roediger-McDermott (DRM) paradigm. Roediger and McDermott expanded Deese's research by creating more list learning paradigms that included strong associates of a critical lure word. Roediger and McDermott were able to demonstrate that upon recall of these lists, there were high rates of accurate recall of listed associates as well as false recognition of the critical lure.[1]

Another way that converging associates are presented is through the memory conjunctive error paradigm. Leding et al. (2007) defines a memory conjunctive error as a false memory comprised of recombined pieces of items presented. The amount of conceptual overlap between the parent words within the memory conjunction triplet positively correlates with memory conjunction effects.[3]

The third method presented in Table 1 is the category associates procedure. This differs from the two methods aforementioned in that instead of semantically related words converging on a critical lure word, words within the list belong to a category. In terms of Underwood's (1965) implicit activation response hypothesis, subjects might activate non-studied category members when exposed to a series of exemplars from the same category based on their associative strength. This activation could be accomplished directly or indirectly based on the strength of associations between studied and non-studied exemplars. Furthermore, if subjects activate the category name from the studied exemplars, the activated category can lead to the activation of non-studied category members, again based on their associative strength.[4]

Table 2. Theoretical explanations of false memory.

Theoretical Name	**Explanation**	**Reference**
Fuzzy trace theory	For every event, two independent memory traces are encoded: gist and verbatim traces.	Reyna, Brainerd. Fuzzy-trace theory: An interim synthesis. *Learning and Individual Differences*. 1995;7:1-75.
Activation monitoring framework	Increased activation and inadequate monitoring of the source of that activation.	Roediger et al. Factors that determine false recall: A multiple regression analysis. *Psychonomic Bulletin & Review*. 2001;8: 385-407.
Spreading Activation	Related concepts are linked in memory so that when one item or concept is activated via encoding or retrieval, the activation spreads to other related concepts.	Meade et. al. The roles of spreading activation and retrieval mode in producing false recognition in the DRM paradigm. *Journal of Memory and Language*. 2007;56:305-320.

The first theoretical explanation of false memory in Table 2 was developed by Reyna and Brainerd in 1995. In the Fuzzy Trace Theory, verbatim traces are specific sensory properties of an object, place, or person. Gist traces are more vague than verbatim traces and include more general themes or meanings of an event. The Fuzzy Trace Theory states that gist and verbatim traces are independent of one another in that that they can be recalled separately and also decay at separate rates. In most cases, verbatim memory leads to true memories, however, overreliance on gist memories increases the likelihood of false memories.[2]

Activation Monitoring Framework involves two processes, notably the activation and the monitoring processes of encoding and retrieval of memories. Activation includes any processes that activates related lures or otherwise contributes to the retrieval of false information.[8] While encoding, people activate stimulus related information and the memory is encoded in terms of that person's own schema. During retrieval, the activation of critical lures may occur as the subject recalls more semantically related studied items.[5] Monitoring includes the memory editing and decision making processes. Monitoring can occur during encoding specifically during intentional learning, but is typically seen in retrieval when the primary goal is to distinguish information brought to consciousness in reference to perception of past events. A specific type of activation is spreading activation in which concepts are linked in memory. The Implicit Associative Response (IAR) theory states that the meaning of the studied item is also activated during encoding and the words associated to the studied item are also activated. This can be used to explain why false memories are created when implementing an assessment such as the DRM paradigm.[6]

Table 3. Strategies to reduce false memories.

Strategy Name	**Explanation**	**Reference**

Production Effect	Saying or speaking the material out loud (instead of reading it quietly) provides a basis for using a distinctive heuristic during the test because people expect to remember information about having said the word.	Dodson, Schacter. If I had said it I would have remembered it: Reducing false memories with distinctiveness heuristic. *Psychonomic Bulletin & Review*, 2001;8:155-161.
Distinctiveness Heuristic	The rejection of a memory based on the failure of recollection to conform to expectations	Gallo D, Bell D, Beier J, Schacter D. Two Types of Recollection Based Monitoring in Younger and Older Adults: Recall-to-Reject and the Distinctiveness Heuristic. *Memory*. 2006;14(6):730-741.
Recall-to-Reject	The subject recalls information that eliminated the questionable event as having occurred due to prior knowledge of the situation. This type of recall is dependent on the structure of the encoding context or task at hand.	Gallo DA. Using Recall to Reduce False Recognition: Diagnostic and Disqualifying Monitoring. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2004;30(1):120-128.

Much of reducing false memory involves the distinctiveness heuristic or the recall-to-reject strategy. However, behind these two concepts, are disqualifying and diagnostic monitoring. Disqualifying monitoring is the rejection of a memory based on the recall of logically inconsistent information. Gallo et al. (2006) uses the example “I couldn’t have studied basil, because I remember studying parsley, rosemary, and thyme, and only three words were studied per category.” Diagnostic monitoring, which includes the distinctiveness heuristic, is the rejection of a memory based on the failure of recollection to conform to expectations. For example, “I didn’t see this item, because I would remember seeing it.” The diagnostic monitoring process is reserved for instances where global recollective expectations are thought to influence memory decisions whereas the term “recall-to-reject” is used for those decisions in which the recollection of specific information is thought to disqualify a lure.[8]

Table 4. Brain structures involved in false memory

Brain Structure	**Explanation**	**Reference**
Cerebral cortex (various cortical areas)	Feature perception, distributed feature representation in memory	Johnson MK, Raye CL. Cognitive and brain mechanisms of false memories and beliefs. *Memory, brain, and belief*. 2000;35–86.
Medial temporal area (hippocampal formation)	Feature binding reactivation (nondeliberative)	Johnson MK, Raye CL. Cognitive and brain mechanisms of false memories and beliefs. *Memory, brain, and belief*. 2000;35–86.
Frontal regions	Reflective processing (e.g. self-generated cognition)	Johnson MK, Raye CL. Cognitive and brain mechanisms of false memories and beliefs. *Memory, brain, and belief*. 2000;35–86.
Right frontal cortex	Heuristic evaluation processes (heuristic source monitoring attributions)	Johnson MK, Raye CL. Cognitive and brain mechanisms of false memories and beliefs. *Memory, brain, and belief*. 2000;35–86.
Bilateral frontal cortex	Systematic processes (e.g. cue generation, strategic retrieval, evaluating consistency or plausibility)	Johnson MK, Raye CL. Cognitive and brain mechanisms of false memories and beliefs.

		Memory, brain, and belief. 2000;35–86.

Multiple brain regions work together in the encoding and retrieval of memories. The medial temporal lobe and the frontal regions typically work together but play different roles in memory. The medial temporal lobe is important in binding features into memories while the frontal region has the role of evaluation and systematic retrieval. The right frontal region is more specifically involved in monitoring during retrieval as well as the heuristic evaluation processes. There is interhemispheric cooperation as represented by the bilateral frontal effect. Subcortical regions encode information about the visual, auditory, spatial, and affective aspects of events. Together, the medial temporal and frontal regions through interaction with subcortical regions create complex memories.[10]

Table 5. Neurophysiological mechanisms of false memory.

Neurophysiological Parameter	**Explanation**	**Reference**
Prefrontal Hemodynamic Activity	Increases in oxygenation associated with higher rates of false recognition in left pre-frontal cortex	Kubota YA, Toichi ML, Shimizu MR, Mason R, Findling R. Yamamoto K. Calabrese, J. Prefrontal hemodynamic activity predicts false memory—A near-infrared spectroscopy study. *NeuroImage*. 2006;31(4):1783–1789.
Memory distortions	The use of Event Related Potentials (ERP) in studying the commitment and avoidance of false memories.	Cadavid S, Beato MS. Memory Distortion and Its Avoidance: An Event-Related Potentials Study on False Recognition and Correct Rejection. *Plos One*. 2016;11(10).

The prefrontal cortex plays an important role in the reconstructive processes of memory distortion. Kubota et. al. (2006) found that bilateral increases in the oxygenated hemoglobin were seen during false recognition in comparison to true recognition. Additionally, oxygenated hemoglobin increases were also seen in the left prefrontal cortex during encoding when subjects falsely recognized unstudied words.[11] Furthermore, the use of ERP in studies on recognition memory have shown that ERP's produced by correctly judged old stimuli usually show a more positive wave than the ERPs elicited by correctly judged new stimuli. Waveforms related to true and false recognition are indistinguishable from each other, but more positive than the correct rejection of new items.

The phenomenon of false memory can be explained using the Fuzzy Trace Theory and the Activation Monitoring Framework. The use of semantically or categorically related word lists is a common method of assessing false memory. Strategies used to reduce false memory include the production effect, recall-to-reject, and the distinctiveness heuristic, all of which rely on disqualifying or diagnostic monitoring. The majority of the brain structures involved in memory are located in the frontal region or the medial temporal lobe. Variations in brain oxygenation in the prefrontal cortex have been observed in false recognition compared to true recognition. Considerable research has been completed to result in theoretical explanations, methods of assessment, strategies to reduce, and brain structures involved in false memory. However, few studies have observed the effects of acute exercise on false memory and further, the potential temporal effects of acute exercise on false memory. The following study aimed to build on previous research and examine the effects of acute vigorous intensity exercise on false memory and potential temporal effects of vigorous intensity acute exercise on false memory.

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INTRODUCTION

Accumulating research demonstrates that an acute bout of exercise can enhance the accurate recall of past episodic memories,[1-4] or events that occur in a spatial-temporal context. We have thoroughly detailed potential mechanisms of this effect,[5,6] which likely occur through acute alterations in select proteins (e.g., brain-derived neurotrophic factor,[7,8] insulin-like growth factor-1,[9] cathepsin-B[10]) and supporting brain cells (e.g., astrocytes[11]), ultimately which help to facilitate long-term potentiation,[12] or the functional connectivity of communicating neurons.[13]

Much less research, however, has evaluated the effects of acute exercise on false episodic memories, or recalling an event or episode that never actually occurred. A common approach to evaluating false episodic memory is through the Deese-Roediger-McDermott (DRM) paradigm. This word-list model involves being exposed to a list of words, all of which are semantically related to a critical lure, and if the lure word is recalled, this serves as evidence for a false memory. For example, if hearing the words, "*bed, rest, awake*, and *tired*", and then the individual recalls the non-presented critical lure, "sleep", a false memory occurred.

Limited experiments have evaluated the effects of exercise on false memory.[14-16] In our first experiment (between-subject design),[15] young adult participants engaged in either an acute bout of moderate-intensity walking (15-min) or a time-matched seated task and then subsequently were evaluated on a false memory task (word-list task using the DRM paradigm). Results demonstrated that the control group recalled more false words and had a higher rate of false memory recognition. Following this study, we evaluated whether there were any time course effects of acute exercise on false memory, that is, whether acute exercise influences false memory depending on whether the bout of exercise occurs before or during the memory task. This is plausible as we have repeatedly demonstrated this temporal effect for veridical (accurate) episodic memories.[1-4,17] In our second false memory experiment (within-subject design),[16] utilizing the same DRM paradigm, we showed that the control visit, compared to the visit where moderate-intensity exercise (20-min) occurred before or during the DRM paradigm, resulted in a greater number of false memories. Thus, these two prior experiments demonstrate that acute moderate-intensity walking may help to reduce false memories. Our third false memory experiment (within-subject design) evaluated whether there was an intensity-specific effect of acute exercise on false memory.[14] This is plausible as our other work demonstrates that higher-intensity acute exercise may favor accurate recall of episodic memory.[17] In our third experiment,[14] which involved participants engaging in an acute (15-min) bout of moderate-intensity and vigorous-intensity exercise, as well as a time-matched seated task, we demonstrated that an acute bout of high-intensity exercise was more effective in enhancing the accurate recall of episodic memory, but interestingly, high-intensity exercise also increased false episodic memory.

As we discussed previously,[14] our surprising observation that acute high-intensity exercise increased false episodic memory may, in part, be attributed to aspects related to the Fuzzy Trace Theory.[18] Per this theoretical account, when memories are encoded, two distinct memory traces are created, including verbatim and gist traces. In the context of accurate, veridical memories (or verbatim traces), exercise has been shown to facilitate the consolidation of these memory traces.[5] It is plausible that high-intensity exercise may also help facilitate the consolidation of gist memory traces, which would help explain the findings from our third false memory experiment. Per the DRM model of false memory, another account for false memories may occur from the activation-monitoring hypothesis.[19,20] This model posits that the critical lure item is mentally generated at both encoding and potentially during retrieval, as a result of spreading activation, a process by which nodes that represent concepts in a semantic network are activated due to proximity and magnitude of activation of other nodes.[21] Faulty monitoring during encoding produces source confusion, and in turn, induces mistakenly recalling the critical item as having been presented. A critical brain region involved in source monitoring is the prefrontal cortex,[22] and higher-intensity acute exercise, via the transient hypofrontality hypothesis,[23,24] may reduce prefrontal cortex function, and in turn, impair source monitoring.[17] Thus, high-intensity acute exercise may, in theory, increase false memories from both the fuzzy trace and activation-monitoring theoretical frameworks.

The present experiment adds to the findings of our three previous experiments. Specifically, the aim of the present experiment is to re-examine (for replication purposes from experiment 3) whether high-intensity acute exercise is associated with greater false memory performance. Further, this experiment will also extend our second experiment (temporal effects for moderate-intensity exercise) by evaluating whether acute high-intensity exercise differentially influences false memory based on the timing of the acute bout of high-intensity exercise. We hypothesize that, similar to our third experiment, acute high-intensity exercise will increase accurate episodic memory and also increase false episodic memory, but this will occur only when the acute bout of exercise occurs prior to the memory task. However, we hypothesize that, when the acute bout of high-intensity exercise occurs during the memory task, accurate episodic memory performance will be reduced, whereas false episodic memory will increase. This latter hypothesis stems from theoretical insights regarding the exercise-memory interaction.[17] That is, during a bout of high-intensity acute exercise, metabolic resources are redistributed away from the prefrontal cortex,[23,24] theoretically impairing accurate episodic memory performance and increasing false episodic memory function. We repeatedly demonstrated this for veridical memories in a recent experiment.[25]

METHODS

Study Design

The present experiment was a three-visit, within-group, counterbalanced controlled 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). Primary outcomes for this experiment include veridical and false episodic memory measures (described below). See Table 1 for a schematic of the study procedures for each experimental condition.

Table 6. Experimental protocol of the three counterbalanced conditions.

Condition	**Start** → **Finish**						
Control	Consent/ Paperwork	20-min Video		Encode Words	Immediate Recall	20-min Video (rest)	Delayed Recall
Exercise Before Encoding	Consent/ Paperwork	15-min Exercise	5-min Video (rest)	Encode Words	Immediate Recall	20-min Video (rest)	Delayed Recall
Exercise During Encoding	Consent/ Paperwork	15-min Exercise – Start Encoding Words at Min 13 and Finish Encoding at Min 15			Immediate Recall	20-min	Delayed Recall

				Video (rest)	

Participants

The present experiment included 37 participants (10 males and 27 females). This is based from a power analysis 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), 1 group, 2 measurements, and an estimated effect size of η^2_p= 0.07 (derived from our previous work[14]). Participants were recruited through classroom announcements and word-of-mouth. Participants include male and females between the ages of 19 to 23 years.

Additionally, participants were excluded if they: 1) Self-reported as a daily smoker[26,27]; 2) Self-reported being pregnant[28]; 3) Exercised within 5 hours of testing[29]; 4) Consumed caffeine within 3 hours of testing[30]; 5) Took medications used to regulate emotion (e.g., SSRI's)[31]; 6) Had a concussion or head trauma within the past 30 days[32]; 7) Took marijuana or other illegal drugs within the past 30 days[33]; or 8) Were considered a daily alcohol user (> 30 drinks/month for women; > 60 drinks/month for men)[34]

Control and Experimental Conditions

The control condition involved watching a video (self-selected either The Office or Big Bang Theory) for 20-minutes. We have experimental evidence that this control task does not prime or enhance memory function.[35]

The two exercise conditions (exercise before encoding and during encoding) engaged in a 15-min bout of high-intensity treadmill 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-min (video).

The visit involving the acute bout of exercise during the memory task involved participants engaging in a 15-min bout of acute exercise at 80% of their HRR, and at the 13-min point into the bout of exercise, they encoded the words. After the participants completed the encoding of the words (i.e., at approximately the 15-min point into the bout of exercise), they stopped exercising and then immediately completed the free recall assessment. After this, they rested (video) for 20 min and then completed the delayed free recall.

The HRR equation used to evaluate exercise intensity was:

$$HRR = [(HR_{max} - HR_{rest}) * \%\ intensity] + HR_{rest}$$

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. HR_{max} was estimated from the 220-age formula. 80% of HRR represented vigorous-intensity exercise.[36]

Memory Assessment

The procedure for this false episodic memory task was modeled after Roediger and McDermott[37] and in alignment with our previous work on this topic.[15,16] For each visit, participants listened (via headphones) to a recording of a list of 15 words (recorded in a female voice); each word was read at a rate of 1 word per 2 seconds. After listening to the list once, there was a 10-second pause, and then they listened to the list a second time. After this, they completed an immediate free recall of the words. Following this immediate free recall, participants watched a video for 20-min and then performed a delayed free recall.

The three separate lists (one per visit) were matched for the proportion of false memories. Specifically, using prior normative research, each list has a false memory recall of 54%. We specifically used the “sweet”, “chair”, and “smoke” lure lists.[38] As an example, each list is composed of associates (e.g., sour, candy, sugar) of 1 non-presented word/lure (e.g., sweet). If, for example, they recall the word “sweet”, then this will be evidence of constructing a false episodic memory.

Statistical Analyses

All statistical analyses were computed in JASP (v. 0.9.1). For the number of words recalled, and the proportion of false memories, a 3 (condition; control, before exercise, and during exercise) x 2 (time point; immediate vs. delay) ANOVA was employed. Violations to sphericity were corrected with the Huynh-Feldt procedure. Statistical significance was set at a nominal alpha of 0.05. Partial eta-squared (η^2_p) are reported for effect size estimates.

RESULTS

Table 7 displays the characteristics of the sample.

Table 7. Sample characteristics

Variable	**Point Estimate**	**SD**
Age, mean years	21.16	0.95
Gender, % Female	73.0	
Race-Ethnicity, % White	94.6	
BMI, mean kg/m^2	24.35	6.05
MVPA, mean min/week	225.95	197.93

BMI, Body mass index

MVPA, Moderate to vigorous physical activity

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, $F(5.63, 174.49) = 293.79$, $p < .001$, $\eta^2 = .18$.

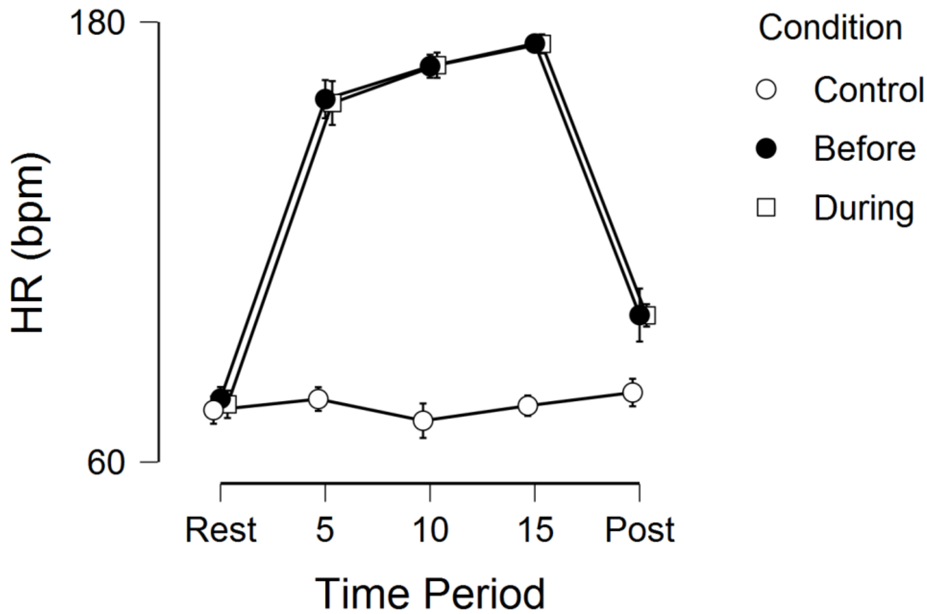

Figure 1. Heart rate responses to the three conditions. Error bars represent 95% CI.

Figure 2 displays the psychological (rating of perceived exertion) 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, $F(4.64, 167.30) = 199.85$, $p < .001$, $\eta^2 = .20$.

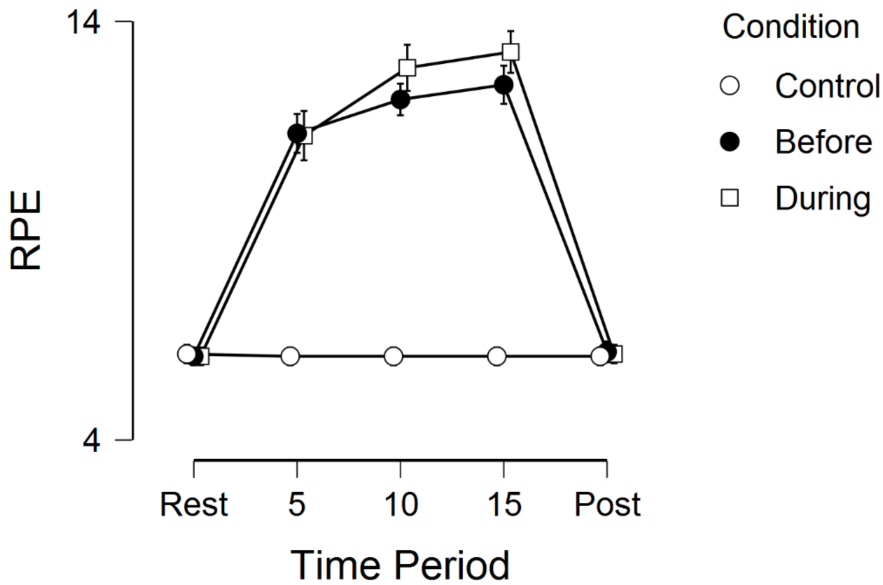

Figure 2. Rating of perceived exertion (RPE) responses to the three conditions. Error bars represent 95% CI. Due to minimal variation in the control group, error bars in the control group are not visible.

Figure 3 displays the veridical memory results across the three conditions. For the control, before, and during conditions, respectively, the number (SD) of veridical memories for the immediate recall period were 9.92 (1.81), 9.68 (1.58), and 8.18 (1.72). For the delay period, these respective estimates were 8.51 (1.72), 8.32 (1.93), and 6.97 (1.90). There was a significant main effect for condition, $F(1.98, 71.30) = 17.82$, $p < .001$, $\eta^2 = .13$, main effect for time period, $F(1.00, 36.00) = 74.83$, $p < .001$, $\eta^2 = .11$, but no condition by time period interaction, $F(1.97, 71.06) = .26$, $p = .77$, $\eta^2 = .0001$. Holm-corrected post-hoc tests indicated that the delay period had lower memory recall than the immediate time period, $M_{diff} = -1.32$, SE = .15, $t = 8.65$, $p < .001$. For the condition effects, Holm-corrected post-hoc tests indicated that Before was not different than

Control, M_{diff} = -.216, SE = .26, t = .82, p = .42. However, During was different than Before, M_{diff} = -1.42, SE = .32, t = 4.32, p < .001, and During was different than Control, M_{diff} = -1.64, SE = .29, t = 5.52, p < .001.

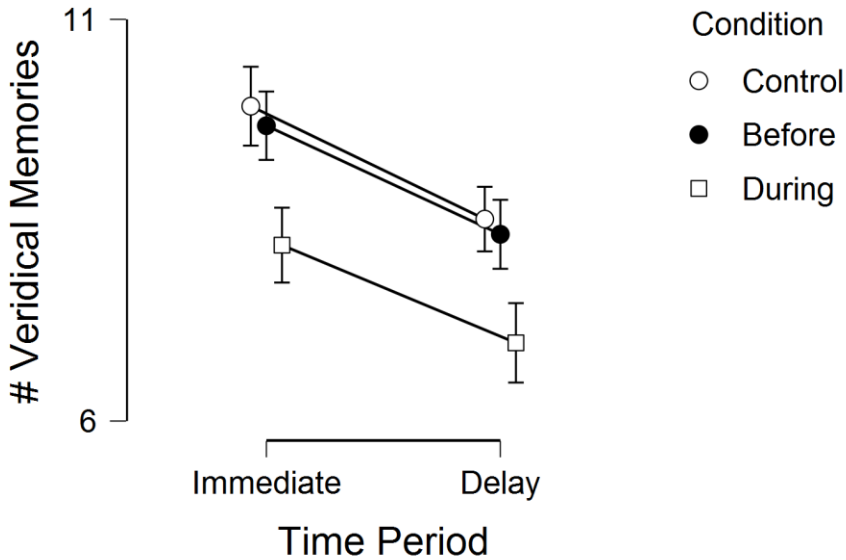

Figure 3. Veridical memory scores across the three conditions. Error bars represent 95% CI.

Figure 4 displays the false memory results across the three conditions. For the control, before, and during conditions, respectively, the proportion (SD) of false memories for the immediate recall period were 0.486 (0.50), 0.486 (0.50), and 0.622 (0.73). For the delay period, these respective estimates were 0.514 (0.50), 0.595 (0.49), and 0.730 (0.45). There was not a significant main effect for condition, F(1.86, 67.13) = 1.89, p = .16, η^2 =

.02, main effect for time period, $F(1.00, 36.00) = 2.26$, $p = .14$, $\eta^2 = .007$, or condition by time period interaction, $F(2.00, 72.00) = .35$, $p = .70$, $\eta^2 = .001$.

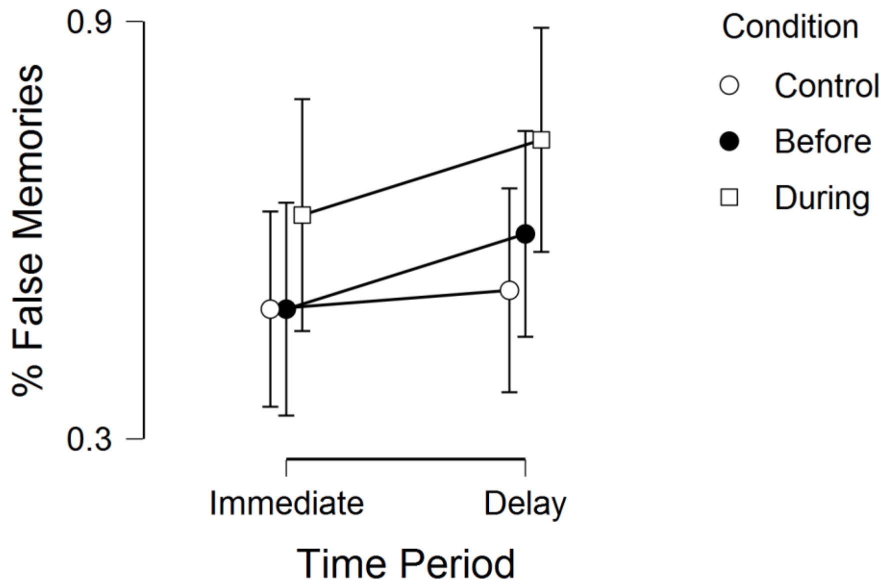

Figure 4. Proportion of false memories across the three conditions. Error bars represent 95% CI.

DISCUSSION

The present experiment was specifically designed to evaluate whether high-intensity exercise is associated with veridical and false memories and whether this is a function of the temporal coupling between the acute bout of exercise and memory encoding. We hypothesized that high-intensity acute exercise (vs. control) would be associated with greater veridical and false memories when the acute bout of exercise occurred prior to encoding. However, we hypothesized that when memory encoding occurred during the bout of exercise, veridical memory would be reduced whereas false memory would be heightened. Our results provide partial support for these hypotheses. When the acute bout of exercise occurred prior to memory encoding, exercise did not increase veridical memories. However, when the acute bout of exercise occurred during memory encoding, veridical memories were reduced. We observed no statistically significant effects for false memory.

For the present experiment, we were not able to replicate our previous experiment that provided suggestive evidence that high-intensity acute exercise increases false memories.[14] In the Before vs. Control conditions, false and veridical memory results were nearly identical. A potential explanation for this is the divergent methodology between our present and past experiment.[14] In the present experiment, we employed a single word list per condition, whereas in our past experiment, we utilized 6 word lists per condition. This was an intentional change in methodology, as we would have had to extend the duration of our During condition considerably, in order to complete all 6-word lists. Or, alternatively, we could have started memory encoding earlier on during the bout of exercise (e.g., starting a minute 5 instead of minute 13). However, we chose not to do this because we wanted participants to have achieved a greater exercise-induced physiological stimulus prior to encoding the words.

A notable observation of the present experiment was that veridical memories were reduced when memory encoding occurred during exercise. This aligns with other recent work demonstrating this effect for both episodic and working memory capacity.[25] Although not statistically significant, the present experiment also showed that the During exercise condition had higher false memory rates when compared to the other two conditions (see Figure 4). These findings align with the transient hypofrontality theoretical framework,[23,24] suggesting that high-intensity exercise may reduce prefrontal cortex function during the bout of exercise, and in turn, impair source monitoring.[17]

A limitation of this experiment is that we did not employ an initial bout of maximal exercise to appropriately guide the high-intensity bout of exercise. Despite this, the achieved heart rates for the high-intensity exercise were within the range of vigorous-intensity exercise. Another limitation is that we did not measure the participant's cardiorespiratory fitness which, in theory, could moderate the effects of high-intensity acute exercise on memory. We did, however, include the self-reported MVPA estimates in the analytical models and did not observe any (condition or time period) interaction effects with MVPA (results not shown).

In conclusion, high-intensity acute exercise prior to memory encoding did not affect veridical memory performance. However, we observed evidence to suggest that memory encoding during high-intensity acute exercise reduces veridical memory performance and may, potentially, increase false memory rates. Future work should further evaluate this latter observation within the context of the transient hypofrontality framework.

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