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Acute Exercise on Memory Function: Open vs. Closed Skilled Exercise

By

Justin Ray Cantrelle

A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College

Oxford

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Abstract

Justin Ray Cantrelle: Acute Exercise on Memory Function: Open vs. Closed Skilled Exercise

(Under the direction of Dr. Paul Loprinzi)

Accumulating research suggests that acute exercise may enhance memory function. Limited research, however, has evaluated whether the movement patterns of acute exercise may have a differential effect on memory. Such an effect is plausible, as research demonstrates that open-skilled exercise (e.g., racquetball) may have a greater effect on memory-related neurotrophins (e.g., brain-derived neurotrophic factors) when compared to closed-skilled exercise (e.g. treadmill exercise). A key distinction between open- and closed-skilled exercise is that open-skilled exercises are those that require an individual to react in a dynamic way to a changing, unpredictable environment. The purpose of this study was to evaluate whether retrospective is differentially influenced from open- and closed-skilled acute exercise. A within-subject design was employed. Participants (M_{age} = 20.6 yrs; 69% female) completed two visits, in a counterbalanced order. The two experimental conditions included open-skilled acute exercise (racquetball) and closed-skilled acute exercise (treadmill exercise), each lasting 30-min at 60% of heart rate reserve. During both experimental conditions, retrospective memory was evaluated across multiple word-list trials (e.g., Trials 1-6, 20-min delay, 24-hr delay). For retrospective memory, there was a significant main effect for condition, $F(1, 57) = 5.33$, $p = .02$, $\eta^2 = .004$, main effect for trial, $F(4.12, 234.9) = 227.85$, $p < .001$, $\eta^2 = .46$, but no condition by trial interaction, $F(4.63, 264.08) = 1.022$, $p = .40$, $\eta^2 = .002$. Retrospective memory was greater after closed-skilled exercise (treadmill) when compared to open-skilled exercise (racquetball).

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BMI, Body mass index

MVPA, Moderate to vigorous physical activity

HRR, Heart Rate Reserve

RAVLT, Rey Auditory Verbal Learning Test

1. **Background**

The following background was summarized from the article The Episodic Memory System: Neurocircuitry and Disorders by Eichenbaum and Dickerson (2010).

A. Brain regions associated with memory

Memory has been a long studied aspect as it is essential for everyday life. Memory exists in many different forms, as discovered by many different studies involving memory. The two main categories for memory involve declarative (explicit) and non-declarative memory. Explicit memory must contain conscious processing of information with one form of explicit memory, called episodic memory being seen as relatively new in the evolutionary existence. Non-declarative memory mostly contains behavioral and physiological responses that are primitive in the evolution timeline.

Non-declarative memory includes forms of learning during various tasks and are especially seen during changes in behaviors or quick behavior performances. The two main aspects of non-declarative memory are procedural memory and emotional memory. Procedural memory involves learning repetition of a specific movement pattern such as learning a baseball swing, driving a car, or riding a bike. This type of learning is used to make repetitive tasks easier and is refined over time. The other type, emotional memory, centered around interactions with the amygdala is used in situations to set up preferences to otherwise neutral stimuli. This involves creating preferences towards foods or avoiding objects that one has had a very negative exposure to. It involves both cortical and subcortical interactions and changes the approach an individual has towards an object or stimulus.

Declarative memory contains both working memory and long term memory. Working memory is the short-term maintenance of information and processing of the information to achieve an immediate goal. Working memory is also involved in multitasking and holding in a string of new information. The long term declarative memory is split into semantic memory and episodic memory. Semantic memory encompasses factual knowledge but which one does not does not remember the original time and place the information was learned. Episodic memory differs in the sense that it involves personal experiences including daily life as well as factual knowledge that have a specific time and place associated with the memory. Episodic memory is involved in several areas of the brain. This large network consists of neocortical association areas, the medial-temporal lobe, and the parahippocampal cortical area and hippocampus. There is an extensive network connecting these areas, that has been found to be largely conserved in mammalian species. The system is organized to where the neocortical association areas all converge onto the parahippocampal area, which then project onto a specific subdivision of the hippocampus. Each subdivision of the hippocampus are interconnected through unidirectional pathways starting at the debate gyrus, passing through CA3 and CA1, and ending in the subiculum. As the hippocampus processes information, outlet signals are formed in the subiculum and the CA1, which are then sent back into the parahippocampal area and then projected back into the neocortical association areas in the medial temporal lobe in which the input originated.

There are several neocortical ares that have been shown to contribute to episodic memory including the prefrontal cortex and many other areas used for retrieval, source monitoring, and conscious recall of memories. There are also areas in the parietal and temporal cortices that are responsible for processing the information that will be essential for the recollection of a memory. The organization of these neocortical areas are very different across mammalian species, yet the pathways for the projections of these areas onto the medial temporal lobe are similar across mammalian species. As the neocortical areas project their signals, the signals all converge onto the hippocampus through the parahippocampal region, which consists of the perirhinal, parahippocampal, and entorhinal cortices. There are two distinct yet parallel pathways that terminate in the hippocampus from the perirhinal and parahippocampal cortices. Though these two pathways take similar routes, the perirhinal cortex sends information about the non-spatial aspects of the stimuli to the hippocampus after receiving that information from the appropriate neocortical association areas. The parahippocampal cortex is different in that it sends information about the spatial aspects of the stimuli after receiving the information from the appropriate neocortical association areas. A good example of this process can be seen in monkeys when presented with an object in motion. Data shows that the information from the ventral visual pathway, in charge of object recognition, inputs the information to the perirhinal cortex, which then sends it to the hippocampus while the dorsal visual pathway, in charge of visually guided actions, inputs the information to the parahippocampal cortex which is then sent to the hippocampus. As the information is sent into the perirhinal and parahippocampal cortices, both streams of information are send into the entorhinal cortex though the information still says separate as the perirhinal projects onto the lateral area while the parahippocampal cortex projects onto the medial area of the entorhinal cortex before entering the hippocampus (Burwell et al, 1995; Suzuki and Amaral, 1994). As the information enters the hippocampus, each stream of information from the medial and lateral entorhinal cortex project into the four subregions of the hippocampus, but with different neuronal patterns. The information stream is combined as it enters the dentate gyrus and CA3, but the information pattern differs as the signal enters the subiculum and CA1, allowing the hippocampus to distinguish both the event and context in which the event appears.

Multiple studies have been conducted to draw the above conclusions for the organization of the neocortical association areas, parahippocampal region, and hippocampus and its role in memory function. As some of the studies looked at the connection between the perirhinal and lateral entorhinal cortex, several conclusions were drawn. Suzuki and Eichenbaum concluded in their studies on rats and monkeys that many of the cells in the perirhinal cortex had advanced or suppressed responses to stimuli in recognition tests (2000). This combined with studies from Otto and Eichenbaum, 1992, and Suzuki et al, 1993, have led to the conclusion that the perirhinal cortex has developed to identify the strength of a memory for each single stimuli. This leads to the conclusion that these areas are responsible for object recognition and memory of the object through the unipolar sensory information that it processes. As more studies started to look at the parahippocampal and medical entorhinal cortices, conclusions were drawn largely due to lesions developing in the perirhinal cortex and the observed ability to still distinguish the context for which the object was presented (Alvarado and Bachevalier, 2005). Several studies, including Alvarado and Bachevalier's, produced damage in the parahippocampal cortex with an inability for the location in which an object was recognized (Gaffan et al, 2004). Additionally, a study was conducted showing neurons within the parahippocampal cortex have excellent special coding ability compared to the perirhinal cortex (Hargreaves et al, 2005). This led to the conclusion that the neurons in the parahippocampal and medial entorhinal cortex are responsible for special context for an individual object.

Although the studies have looked at the roles that the perirhinal, parahippocampal and entorhinal cortices have played in memory function, studies on the hippocampus itself have shown how important a role the hippocampus has on memory function. Several studies by Eichenbaum have shown that the hippocampus is essential for combining the two events of "what" and "where" in studies using rats and different odors in different locations. It was the neuron within the hippocampus that fired only when the certain combination of the odor and location was received, indicating a match for the initial stimuli. Findings from the studies looking at the functional characteristics combined with the anatomical knowledge of these brain areas have established a possible mechanism for episodic recollection. The pathway includes the perirhinal and lateral entorhinal areas creating a memory cue for stimulus that can signal if the stimulus has been received before , but with no context of where or when. This can lead to a sense of familiarity without the signal needed to enter the hippocampus. As the to-be remembered stimulus is processed by the perirhinal and lateral entorhinal cortices, the spatial information is simultaneously processed by the parahippocampal and medical entorhinal cortices which then converge in the hippocampus. During the retrieval of this stimulus, the activation of neurons within the hippocampus back produce a back projection going all the way to the neocortical association areas that originally processed the item with the contextual information (Eichenbaum et al, 2007). The retrieval of the stimulus can be strengthen by increased connections of the neurons that are involved in the reactivation loop, supporting consolidation of the memory.

B. Differing neurocircuitry for episodic memory

The Human medial temporal lobe episodic memory system uses positron emission technology and functional magnetic resonance imaging (fMRI) to locate the different areas involved in episodic memory tasks. This technology showed increased functional performance in the medial temporal lobe and hippocampus during episodic memory recall tasks when compared to the baseline activation of these areas. As technology advanced in the late 1990's, researchers viewed an even larger increase in the areas for information was was successfully recalled later then information that was presented but was unable to be later recalled (Burock et al, 1998). There has been some argument over the validity of these studies mostly due to the fact that the medial temporal lobe has different levels of activation during encoding and retrieval, leading to concern over the organization of the medial temporal lobe and hippocampus with some studies finding the rostral hippocampus is activated during encoding while the casual is activated during retrieval (Zeineh at al, 2003), but studies have conflicted this finding (Gabreieli et al, 1997). Another topic of challenge has to do with the gap in resolution between animal and human studies testing episodic memory function and interference in the signal-to-noise ratio that can cause false findings. Although some studies have produced conflicting results in the order of certain memory processes, there has been agreement for specific medical temporal lobe regions for specific content. Preston et al, 2009, showed that there was a higher level of activation for the perirhinal and rostral hippocampal region with memory for faces while the caudal hippocampus was more involved with object recognition. More neuroimaging has developed that researchers can view the ability for the medical temporal lobe to create associations without complete information yet still being able to distinguish between distinct objects. Additionally, the research has shown the medical temporal lobe's ability to use episodic information in inferential reasoning and generalizations.

The human isocortical episodic memory system has only recently been researched for the true extent that the ventrolateral temporal, medial and lateral parietal, and medial and lateral frontal regions support the processes of encoding and retrieval tasks, but other high level tasks involved in memory. Each of these regions are activated during a specific coding or retrieval cue. Some examples of this are the ventral temporal cortex being activated when pictures of visual objects are presented, and the lateral temporal cortex being activated during auditory stimuli. Similar to the medial temporal cortex, these isocortical regions are activated during recall of a stimuli, indicating their role in memory function (Wheeler et al, 2000). In addition to the above regions of the brain, the frontal lobe has recently shown that it plays a primary role in memory function. This has been discovered largely from studies on patients with frontal lobe lesions have multiple problems with memory impairment, including source memory (Janowsky et al, 1989; Shimamura et al, 1990). Several areas have been shown to have a specific lateralization for different memory stimuli. This includes the ventrolateral cortex, which displays left sided preference for semantic information. This research led to the development of the ‘hemispheric encoding/retrieval asymmetry’ (HERA) model of memory, with the left activation during encoding and right activation during retrieval (Habib at al, 2003; Tulving at al, 1994). This model of memory is observed in the several prefrontal regions that are involved in episodic memory. In order to understand how this occurs, there are several cognitive processes to take into account. First, preretrieval processing is a support for the attempt to retrieve information and includes retrieval mode and orientation. Several neuroimaging studies have shown that the retrieval effort and orientation favor the left prefrontal cortex, while the retrieval mode is involved in the frontopolar cortex in a right-lateralized position. Postretrieval involves the monitoring and evaluation of retrieved information, contributing to a retrieval decision. Studies have shown that the right dorsolateral prefrontal cortex is involved in the postretrieval processing. Lastly, fMRI studies show the right frontopolar cortex is involved in retrieval mode and the left frontopolar cortex is individual retrieval attempts when looking at sustained contributions to memory retrieval. There are an increasing number of studies revealing many functionally distinct subregions in the lateral parietal cortex and many connections between the parietal cortical and medial temporal lobe. These studies have brought attention to the increased roles of the frontoparietal and parietotemporal interactions (Kobayashi and Amaral, 2003,2007; Mesulam et al, 1977; Van Hossein et al, 1972).

The large-scale distributed episodic memory network largely consists of prefrontal-temporal interactions as it has become widely known that many task performance abilities require large scale interactions in the brain. The current theory for the prefrontal-temporal cortices interactions for episodic memory have been created using human and monkey lesion analysis. Additionally, there has been a systems-level analytic approach that show the interactions between these brain regions that make up the episodic memory network. Multiple models created have shown the interactions between the prefrontal-medial temporal-ventrolateral temporal cortex during episodic encoding that occur during successful recall of said information (Dickerson et al, 2007). fMRI studies have reveal a ‘default mode’ system within the brain that is active during many performance directed tasks including memory encoding and retrieval tasks. This has led to a theory that one certain activity may be occurring but the activation of the rest of these brain regions engage the episodic memory system. Data to support this hypothesis comes from the development of functional connectivity MRI studies, which show the activation of brain regions. This technique has not only shown the hippocampal-parietal system, but the presence of the rostral hippocampal-perirhinal and caudal hippocampal-parahippocampal-retrosplenial subnetworks. This process will further link the data between animal and human studies which will only enhance our knowledge on the spatial localization for the episodic memory system.

C. Exercise’s effect on memory

Numerous studies have looked into the effect that acute exercise has on various memory functions. A study by Sng et al looked into the effects of acute walking on memory function. This study was particularly concerned about the timing of exercise and exposure to the learning protocol, with which they found that exercising before learning provides the most benefit to memory function when compared to exercise during learning or exercise after learning (2017). This benefit is likely seen through a few possible modalities. Some possible modalities include the enhancement of neuronal excitability or growth of dendritic spines from exercise. One modality that has been explored is the increase in brain derived neurotrophic factor (BDNF) which has been shown to improve memory function in multiple studies (Loprinzi et al. 2018). With Griffin et al. showing that acute exercise increases serum BDNF, the possible connect between exercise and increased episodic memory function is apparent.

2. Introduction

Emerging research demonstrates that acute exercise is associated with enhanced memory performance, typically assessed from word-list paradigms. Mechanisms of this potential effect are multifold, including, for example, exercise-induced neuronal excitability, transcription factor expression, and growth factor production. Regarding the latter, a key growth factor that may mediate the effects of acute exercise on memory is brain-derived growth factor production (BDNF). This key protein plays a critical role in synaptic plasticity, as well as long-term potentiation, a key cellular correlate of memory function. Notably, acute exercise can upregulate BDNF levels. We have previously discussed the synthesis and regulation of BDNF, as well as the potential role through which BDNF may mediate the effects of acute exercise on memory. Although it is conceivable, from a mechanistic perspective, that BDNF may mediate this effect, actual experimental studies in humans have provided mixed findings regarding whether BDNF causally mediates the effects of acute exercise on memory.

As recently suggested and demonstrated, the type of acute exercise, notably whether it is an open vs. closed skilled exercise, may have a differential role on cognitive function. Open-skill exercises are those that require an individual to react in a dynamic way to a changing, unpredictable environment (e.g., badminton, racquetball). Exercises such as walking and running would be considered “closed-skill” exercises as the environment is relatively stable, predictable, and self-paced. Recent research demonstrates that, at the same given intensity (60% of heart rate reserve), open-skilled acute exercise (30-min bout) was more effective in enhancing BDNF and executive function when compared to closed-skill acute exercise. The present study extends this emerging line of inquiry by examining whether open vs. closed-skilled acute exercise has a differential effect on memory function, which, to date, has yet to be examined in the literature. For a comprehensive assessment of memory, herein we assess both retrospective (recall of past events). Notably, limited research has evaluated the effects of acute exercise on prospective memory and no study has compared the potential differential effects of open vs. closed skilled exercises on prospective memory.

3. Methods

A. Study Design

A within-subject design was employed. Participants completed two visits, in a counterbalanced order. The two experimental arms included open-skilled acute exercise (racquetball) and closed-skilled acute exercise (treadmill exercise). During both experimental conditions, participants completed shortand long-term assessments of memory function (both retrospective and prospective memory).

B. Participants

Recruitment occurred via a convenience-based, non-probability sampling approach (classroom announcement and word-of-mouth). Participants included undergraduate and graduate students between the ages of 18 and 25 yrs.

Additionally, participants were excluded if they:

Self-reported as a daily smoker[17,18]
Self-reported being pregnant[19]
Exercised within 5 hours of testing[20]
Consumed caffeine within 3 hours of testing[21]
Had a concussion or head trauma within the past 30 days[22]
Took marijuana or other illegal drugs within the past 30 days[23]
Were considered a daily alcohol user (>30/month for women; >60/month for men)[24]

C. Exercise Assessment

In a counterbalanced order, on separate visits, participants were instructed to engage in either a 30-min bout of treadmill exercise or a 30-min bout of racquetball. Both bouts of exercise lasted for 30-minutes and occurred at 60% of their heart rate reserve (HRR). Heart rate was monitored continuously (Polar heart rate monitor) and recorded every 5-minutes. Based on the achieved heart rate, participants were instructed to either increase or decrease the speed/intensity of the bout of exercise.

Following the 30-minute bout of exercise at 60% of HRR, participants walked slowly (self-selected pace) for 5-minutes. Following this 5-minute cool-down period, participants rested (sit) quietly for 5-minutes before commencing the memory assessment.

D. Memory Assessment

1. **Retrospective Memory**. Short-term and long-term memory (retrospective memory) was assessed using the standardized Rey Auditory Verbal Learning Test (RAVLT).[25] Participants were asked to view and immediately recall a list of 15 words (List A) five times in a row (Trials 1-5). Each word, one at a time, was presented on a computer screen for 3-seconds. Participants then were asked to listen to and immediately recall a list of 15 new words (List B). Immediately following the recall of List B, participants were asked to recall the words from List A (Trial 6).

Following Trial 6, there was a 20-minute delay, involving watching a video (self-selected either The Office of Big Bang Theory). Following this 20-min delay, participants recalled as many words as possible from List A. Following this, participants returned to the laboratory for a 24-hr follow-up assessment of List A.

E. Protocol for Visits

As stated, participants completed two main protocols, including 1) racquetball (open-skilled) exercise before the memory task, and 2) treadmill (closed-skilled) exercise before the memory task. These two main protocols occurred in a counterbalanced order. Details for these are as follows.

Racquetball (Open-Skilled Exercise)

Session 1

- 30-minutes of racquetball exercise at 60% of HRR
- 5-minutes of self-selected walking pace for cool-down
- 5-minute seated rest
- Commence memory task (RAVLT)
- Seated rest for 20 minutes
- Delayed recall of RAVLT

Session 2

- Long-term (24-hr) recall of episodic memory

Treadmill (Closed-Skilled Exercise)

Session 1

- 30-minutes of treadmill exercise at 60% of HRR
- 5-minutes of self-selected walking pace for cool-down
- 5-minute seated rest
- Commence memory task (RAVLT)
- Seated rest for 20 minutes
- Delayed recall of RAVLT

Session 2

- Long-term (24-hr) recall of episodic memory

F. Statistical Analysis

All statistical analyses were computed in JASP (v. .10). A 2 (condition) x 8 (trials) repeated measures ANOVA was computed for the retrospective memory task. When violations to sphericity were violated, the Huynh-Feldt correction was applied. Paired samples t-tests were computed for the prospective memory task (short- and long-term memory and time- and event-based). Effect size estimates (eta-squared for ANOVA or Cohen's for t-tests) were calculated. Statistical significance was set at an alpha of 0.05.

4. **Results**

Table 1 displays the characteristics of the sample. The sample included 58 participants (M_{age} = 20.6 yrs; 69% female).

Table 1. Sample characteristics.

Variable	**Point Estimate**	**SD**
Age, mean years	20.67	1.38
Gender, % Female	69.5	
Race-Ethnicity, % White	84.7	
BMI, mean kg/m^2	25.33	5.02
MVPA, mean min/week	178.81	171.1

Figure 1 displays the physiological (heart rate) response to the exercise stimuli. There was a significant main effect for time, $F(5.07, 289.3) = 1261.6$, $p < .001$, $\eta^2 = .86$, but no main effect for condition, $F(1, 57) = 1.46$, $p = .23$, $\eta^2 = .0001$, or time by condition interaction, $F(4.63, 263.7) = 1.27$, $p = .28$, $\eta^2 = .001$.

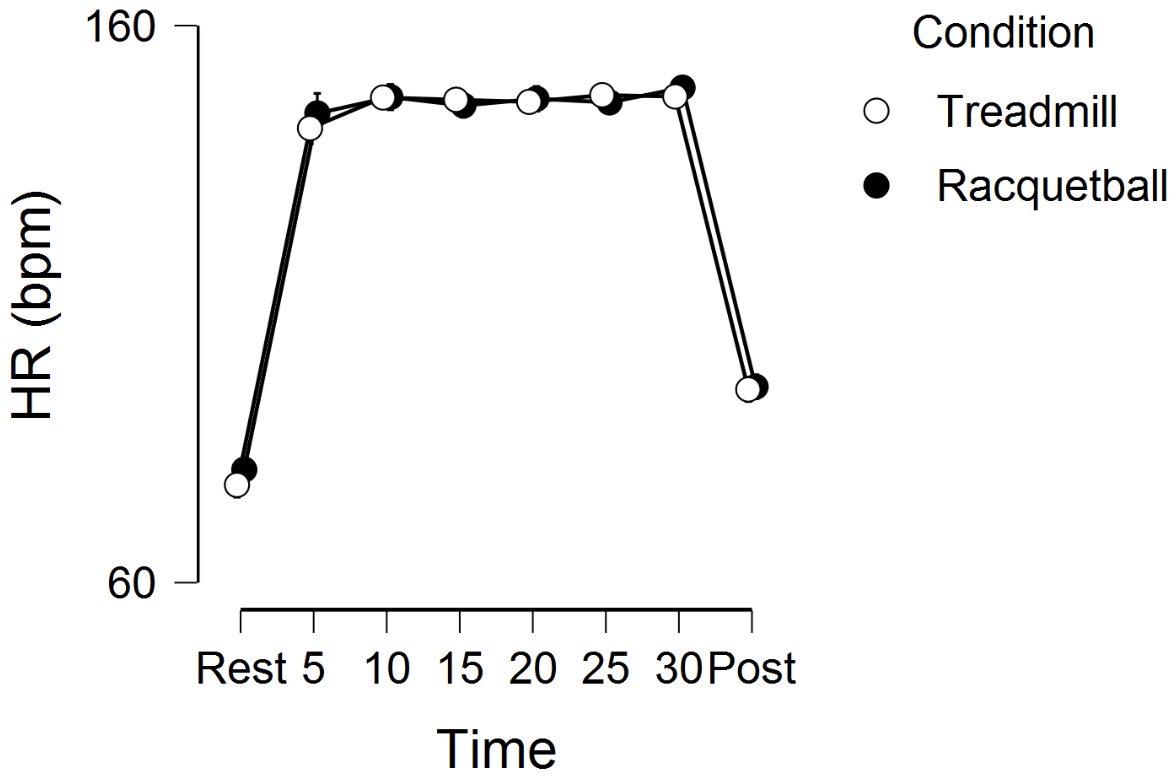

Figure 1. Heart rate responses across the 8 time periods (rest, 5-min, 10-min, etc.) for the two experimental conditions. Error bars (minimally visible) represent 95% CI.

Figure 2 displays the word-list results across the experimental conditions. There was a significant main effect for condition, *F*(1, 57) = 5.33, *p* = .02, η^2 = .004, main effect for trial, *F*(4.12, 234.9) = 227.85, *p* < .001, η^2 = .46, but no condition by trial interaction, *F*(4.63, 264.08) = 1.022, *p* = .40, η^2 = .002. The main effect for condition appeared to be, in part, driven by differences occurring for Trials 5 (t(57) = 2.13, p = .03, d = .28, M_{diff} = .49), 20-min delay (t(57) = 1.93, p = .05, d = .25, M_{diff} = .58), and the 24-hr delay (t(57) = 1.94, p = .05, d = .26, M_{diff} = .88), as there were no other differences for the other trials (p’s > .10).

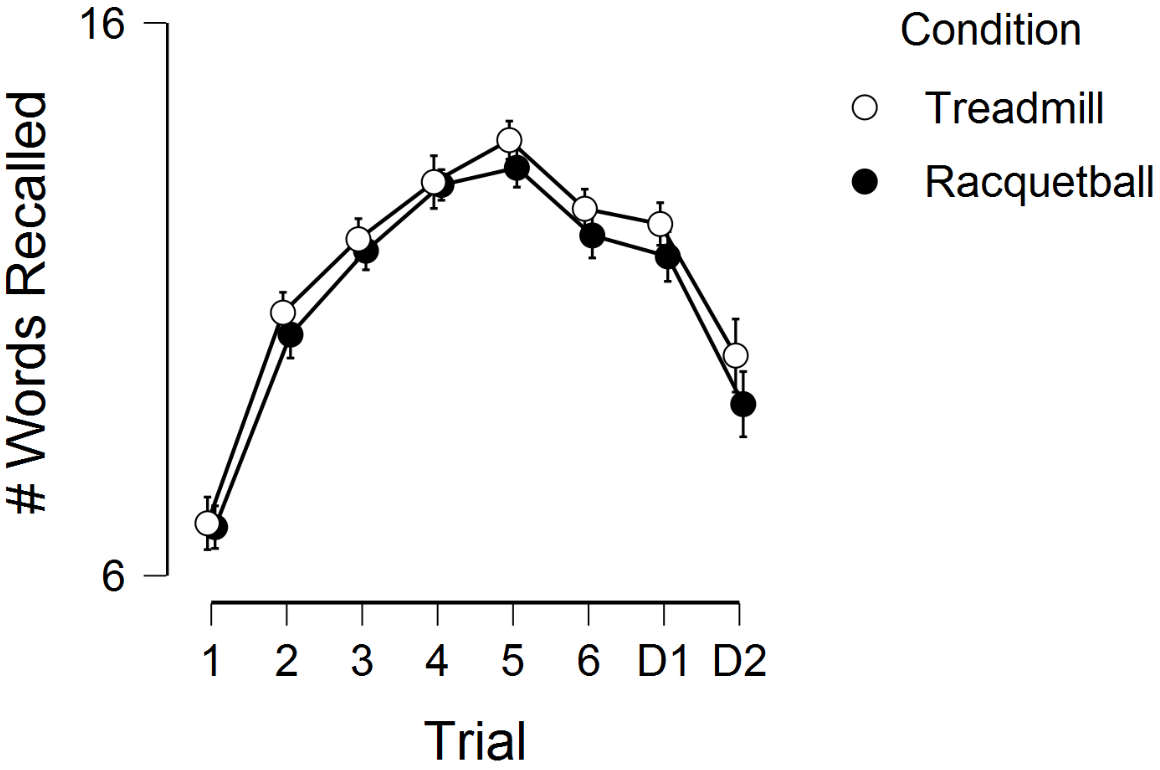

Figure 2. Word-list results across the experimental conditions. D1 and D2, respectively, represent the 20-min and 24-hr delay assessments. Error bars represent 95% CI.

2. Discussion

Accumulating research demonstrates that acute exercise may, potentially, enhance retrospective memory. We,[28,29] along with others,[30,31] have summarized this effect elsewhere. Recently, we have also demonstrated that cognitive function may also be influenced by the mode of exercise.[12] In a systematic review,[12] we demonstrated that open-skilled exercise was superior in enhancing cognitive function when compared to closed-skill exercise. This was observed for observational and intervention studies, as well as for several cognitive outcomes, including memory. Notably, however, few experimental acute exercise studies were conducted.[14] This served as the motivation for the present experiment, which was to evaluate whether acute open- or closed-skill exercise has a differential effect on memory function. Our two main findings are as follows, 1) closed-skilled exercise was more effective in enhancing retrospective memory when compared to open-skilled exercise, and 2) there was no prospective memory difference between the two types of exercise. Given that this latter observation aligns with our past 5 experiments on prospective memory (i.e., no effect of acute exercise on prospective memory),[1,2,6,15,16] the narrative that follows will just focus on our retrospective memory results.

We initially hypothesized that open-skilled exercise (racquetball) would be more effective in enhancing memory than closed-skilled exercise (treadmill). We anticipated that this would occur from greater cognitive demands as well as from potentially higher levels of neurotrophins that are likely to occur with open-skilled exercise. [12,14] However, our retrospective memory results showed the opposite effect. Retrospective memory, particularly long-term retrospective memory, was greater after exercising on the treadmill as opposed to playing racquetball. Importantly, although this effect was statistically significant, the magnitude of this difference was minimal (Cohen’s d ranged from .25-.28). Further, the mean difference between the experimental conditions for trial 5, 20-min delay, and 24-hr delay, ranged from .49 to .88 words.

The present experiment did not collect any mechanistic data, whether it be cognitive, affective or neurophysiological, that may help to explain our unexpected findings. It seemed, however, that most of the participants were new to racquetball. If this is true, then perhaps the racquetball session induced greater cognitive load/demand when compared to treadmill exercise, which involves an unchanging environment requiring minimal cognitive engagement. Speculatively, perhaps exercise that induces greater cognitive demands may be more suitable for executive cognitions, which may require the utilization of multiple cognitive processes, such as inhibition, planning and reasoning. In contrast, perhaps exercise that induces greater cognitive demands has a less favorable effect for cognitions, such as retrospective memory, which may require fewer cognitive processes. As such, it would be worthwhile for future work to evaluate whether open- and closed-skilled acute exercise has a differential effect on distinct cognitive outcomes. Further, perhaps the affective response was different between the two conditions, which may have resulted in our unexpected findings. Although we do not know for certain, it seemed racquetball was new for most of the participants. Perhaps engaging in a new movement pattern, with poorer physical competency, altered their mood state, and in turn, influenced the degree to which they encoded the words for the retrospective memory task. Of course, this is pure speculation, but the possibility for affect to mediate the effects of acute exercise on memory is worth further critical reflection.

A limitation of this experiment is not including a non-exercise control group. Similar to other related work on this topic,[14] we intentionally chose not to include a control group because the aim of this experiment was not to evaluate whether acute exercise influences memory, as this has already been evaluated in numerous studies. The central focus of this experiment was comparing open- to closed-skilled exercise. However, we do acknowledge the benefit of including a non-exercise control group. Strengths of this study include the experimental design, study novelty, and relatively large sample for this type of experiment (see Figure 9 in Pontifex et al.[32]).

In conclusion, the present experiment demonstrates that retrospective memory was greater after closed-skilled acute exercise (racquetball) when compared to open-skilled acute exercise (treadmill exercise). Exercise modality did not have a differential effect on prospective memory.

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