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Though the body of literature converges on the notion that acute exercise has a small, positive effect on cognitive performance in general (Chang, Labban, Gapin, & Etnier, 2012; Lambourne & Tomporowski, 2010), effects on certain cognitive domains remain poorly understood. Among these cognitive domains, memory is one of the least studied within the acute exercise literature. Despite the lack of attention in the exercise literature, memory is an intriguing and important domain of study. Most effects of acute exercise on cognitive function abate relatively quickly following exercise cessation. However, if exercise can improve the ability to process and/or store newly acquired information, then it is conceivable that the product of these effects (i.e. – improved recall) could be observed well after exercise cessation.

The purpose of this study was twofold. The primary purpose was to test whether a single bout of aerobic exercise affects performance on a long-term memory task. The secondary purpose was to determine whether that effect operates primarily through the encoding and/or consolidation processes of long-term memory formation. The secondary purpose was tested by manipulating the timing of exercise relative to exposure to the to-be-remembered material (word list). A within-subjects, repeated measures design was used. Participants completed 3 conditions in randomized order, including 2 treatment conditions and one control condition. Treatment conditions involved participants exercising either immediately prior to or immediately following word list exposure.

Exercise prior to exposure could impact encoding or consolidation (E+C); whereas, exercise following exposure could only impact consolidation (C). The control condition involved no exercise (NE) at all. Exercise consisted of 20 minutes, at moderate intensity, on a cycle ergometer, as well as a 5-minute warm-up and a 5-minutecool-down (30 minutes total). Memory for the word list was assessed 60 minutes and 24 hours after participants had finished listening to it. Analyses revealed that the E+C condition produced significantly better recall of the word list following both the 60-minute ($ŋ_p^2 = 0.24$) and 24-hour ($ŋ_p^2 = 0.22$) delays. Pairwise comparisons revealed statistically significant differences in recall for the E+C condition versus the NE condition; however, no differences were observed involving the C condition. These results suggested that acute exercise can benefit long-term memory, and that this benefit is accomplished primarily through an effect on the encoding process.

THE EFFECT OF ACUTE EXERCISE ON THE FORMATION OF LONG-TERM MEMORY

by

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Committee Chair

“To my wife, Allyson, for her unshakable faith, patience, and support throughout this process.”

APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I

INTRODUCTION

Exercise is generally known to be a healthful activity, with benefits for both mental and physiological outcomes. The research concerning exercise and physical health is well-developed and consistently supports positive musculo-skeletal and cardiovascular outcomes. Studies examining the relationship between exercise and mental health have also demonstrated positive effects of exercise on several facets of mental health, including anxiety (Herring, O'Connor, & Dishman, 2010; Petruzzello, Landers, Hatfield, Kubitz, & Salazar, 1991), depression (Barbour & Blumenthal, 2005; Blumenthal et al., 2007; Craft & Perna, 2004; Lawlor & Hopker, 2001; Trivedi, Greer, Grannemann, Chambliss, & Jordan, 2006), and general well-being (Fox, 1999; Windle, Hughes, Linck, Russell, & Woods, 2010). The focus of the present work concerns a relatively less well-developed, yet growing, body of literature that examines the relationship between exercise and cognitive function. Though results from empirical studies exhibit a great deal of heterogeneity, narrative (Brisswalter, Collardeau, & Rene, 2002; Kashihara, Maruyama, Murota, & Nakahara, 2009; McMorris & Graydon, 2000; Tomporowski, 2003a, 2003b; Tomporowski & Ellis, 1986) and meta-analytic (Angevaren, Aufdemkampe, Verhaar, Aleman, & Vanhees, 2008; Colcombe & Kramer, 2003; Etnier, Nowell, Landers, & Sibley, 2006; Etnier et al., 1997; Heyn, Abreu, & Ottenbacher, 2004; Lambourne & Tomporowski, 2010; Sibley & Etnier, 2003; Smith et al., 2010) reviews of the literature generally agree that exercise can have a positive impact on cognitive function.

The exercise literature can be broken down into two basic paradigms, which are based on the type of exercise protocol employed: acute and chronic exercise. Acute exercise studies test cognitive performance during or shortly following a single bout of exercise. Within the acute exercise paradigm, cognitive performance outcomes have most commonly included reaction time (RT) and information processing (Aks, 1998; Allard, Brawley, Deakin, & Elliott, 1989; Arcelin, Brisswalter, & Delignieres, 1997; Arent & Landers, 2003; Brisswalter, Arcelin, Audiffren, & Delignieres, 1997; Brisswalter, Durand, Delignieres, & Legros, 1995; Chang & Etnier, 2009; Chmura, Nazar, & Kaciuba-Uscilko, 1994; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996; Kashihara & Nakahara, 2005; McMorris & Graydon, 2000; Pesce, Cereatti, Casella, Baldari, & Capranica, 2007; Scott, McNaughton, & Polman, 2006), executive function (Emery, Honn, Frid, Lebowitz, & Diaz, 2001; Hogervorst, Riedel, Kovacs, Brouns, & Jolles, 1999; Kubesch et al., 2003; Lichtman & Poser, 1983; McMorris & Graydon, 1996a, 1996b; Netz, Argov, & Inbar, 2009; Netz, Tomer, Axelrad, Argov, & Inbar, 2007; Stones & Dawe, 1993; Travlos & Marisi, 1995), or short-term memory (Coles & Tomporowski, 2008; Di Pietro, 1986; Emery, et al., 2001; Molloy, Beerschoten, Borrie, Crilly, & Cape, 1988; Netz, et al., 2007; Schramke & Bauer, 1997; Tomporowski & Ganio, 2006). Alternatively, chronic exercise research tests for changes in cognitive performance as a function of regular exercise participation. Though many of the outcome variables used in both acute and chronic exercise studies measure similar cognitive domains, the implications for changes in cognitive function differ. Whereas researchers studying acute exercise assume that changes in cognitive function are transient in nature, researchers interested in chronic exercise believe that changes in cognitive function are stable as long as participants remain relatively active. One domain that might be an exception to this dichotomy is memory (Lambourne & Tomporowski, 2010). Whereas a single bout of exercise is not likely to impact RT tested 24 hours later, it is conceivable that it could influence long-term memory of information learned proximal to the exercise bout. Long-term memory has been operationalized as memory tasks involving some delay, ranging from minutes to years, between initial encoding of target material and its retrieval (Baddeley, 1999). Encoding involves the initial attendance to and processing of target material. It is during the delay between encoding and recall that consolidation – the processing of information into a more stable and durable state, such that it can be recalled after a period of inattention – begins to occur. As such, it is conceivable that acute exercise could impose an effect during the encoding and/or consolidation of target material, either of which could impact performance on a long-term memory task.

There is a small body of research testing for an effect of acute exercise on long-term memory function (Cian, Barraud, Melin, & Raphel, 2001; Cian et al., 2000; Coles & Tomporowski, 2008; Hogervorst, et al., 1999; Krebs, Eickelberg, Krobath, & Baruch, 1989; Labban & Etnier, 2011; Molloy, et al., 1988; Pesce, Crova, Cereatti, Casella, & Bellucci, 2009; Potter & Keeling, 2005; Schramke & Bauer, 1997; Sjoberg, 1980;

Tomporowski, Ellis, & Stephens, 1987; Tomporowski & Ganio, 2006; Winter et al., 2007), but there is not a systematic line of research that has been designed to examine the effects of acute exercise on long-term memory with a goal of discerning how the timing of the exercise affects memory performance. Additionally, exercise protocols in these studies are not consistent, ranging from brief walking bouts at a self-determined pace, to structured exercise on a cycle ergometer, to activity during physical education classes. As a result, it is not surprising that the findings from these studies are mixed.

Studies by Cian and colleagues (Cian, et al., 2001; Cian, et al., 2000), Potter and Keeling (2005), and Coles and Tomporowski (2008) provide an example of these inconsistencies. In their two studies, Cian and colleagues found no evidence of a beneficial effect of exercise on long-term memory. However, protocols in these studies involved long bouts of exercise designed to induce fatigue and dehydration. Alternatively, Potter and Keeling found that short, brisk walks led to improved recall of a word list. Somewhat similarly, Coles and Tomporowski found that an acute bout of exercise, involving a 40-minute bout on a cycle ergometer, improved long-term memory for certain portions of a word list. Thus the differences in exercise protocols make interpretation of these results difficult. In fact, in a narrative review focusing on acute exercise and cognition, Tomporowski (2003b) concluded that the overall evidence for an effect on memory is mixed. Tomporowski further asserted that acute aerobic exercise might have a beneficial effect on working memory, but that results from 4 studies yielded no evidence for an effect on long-term memory. Alternatively, in a recent meta-analysis, Lambourne and Tomporowski (2010) identified a small-to-moderate positive effect of acute exercise on memory (*d* = 0.30), though no distinction was made between the types of memory measured in the studies reviewed.

Taken together, these empirical studies and reviews of this literature have not been able to clarify the acute exercise-memory relationship, but rather underscore the need for further systematic examination. In a previous study, Labban and Etnier (2011) tested whether acute exercise before or following encoding impacted long-term memory performance. Participants completed a 30-minute bout of exercise on a cycle ergometer either prior to or immediately following exposure to two brief stories. Participants were then asked to recount the stories 35 minutes after initial exposure. Thus the group exercising prior to story exposure rested during the delay, whereas the group that exercised following exposure recounted the stories almost immediately following exercise cessation. Recall performance of each exercise group was compared to that of a no-exercise control group. Results showed that the group exercising prior to story exposure recalled the stories significantly better than did the control group. While recall performance of the group exercising after story exposure was better than that of the control group, differences did not reach statistical significance. Though results from this study support the notion that acute exercise can impact long-term memory, limitations prevent a clear interpretation of which processes were affected by exercise. Specifically, the timing of exercise relative to both story exposure and story recall did not enable the authors to parse out the effects of exercise on the individual processes involved in long-term memory storage (i.e. encoding and consolidation). Firstly, for the group that exercised prior to story exposure, it is unclear if exercise improved memory performance through an effect on encoding or consolidation. Secondly, because the group exercising following story exposure completed their exercise bout so close to the time of recall, exercise was as likely to impact consolidation as information retrieval. Thus, subsequent study needs to include design elements that allow for the parsing out of exercise's effects on the separate processes involved in long-term memory.

The goal of the present study was two-fold. The primary purpose was to test whether a single bout of aerobic exercise affects performance on a long-term memory task. The secondary purpose was to determine whether that effect operates primarily through the encoding and/or consolidation processes of long-term memory formation. Based upon results from recent studies testing the effects of acute exercise on recall (Coles & Tomporowski, 2008; Labban & Etnier, 2011; Potter & Keeling, 2005), it was hypothesized that exercise would have a positive effect upon long-term memory performance. Further, based upon results from Labban and Etnier (2011), it was expected that any effects of exercise would operate primarily through benefits to encoding. This study was designed to help further our understanding of the relationship between acute exercise and memory function, with the goal of providing insights into the particular memory processes impacted by exercise. If successful, it could also inform future research on design issues relating to exercise protocol and measurement of memory outcomes.

CHAPTER II

REVIEW OF THE LITERATURE

It is well-known that the benefits of exercise extend to mental as well as physiological factors. These mental factors can be separated into psychological and cognitive function outcomes. The literature examining the effects of exercise on psychological well-being has fairly consistently found that exercise improves multiple outcomes ranging from anxiety (Herring, et al., 2010; Petruzzello, et al., 1991) to depression (Barbour & Blumenthal, 2005; Blumenthal, et al., 2007; Craft & Perna, 2004; Lawlor & Hopker, 2001; Trivedi, et al., 2006) to mental well-being (Fox, 1999; Windle, et al., 2010). Research examining cognitive function has also generally agreed that exercise can have a beneficial effect (Angevaren, et al., 2008; Brisswalter, et al., 2002; Colcombe & Kramer, 2003; Etnier, et al., 1997; Tomporowski, 2003b). However, data from this line of research becomes much less consistent when examination moves from the overall relationship to specific outcomes. It is clear that many more questions remain concerning optimal exercise characteristics, cognitive outcome measurements that are most sensitive to the effects, dose-response relationships, and mechanisms.

The exercise literature can be organized by exercise paradigm: acute and chronic. Acute exercise studies employ a single bout of exercise as an intervention to test for effects on cognitive function. These cognitive effects are assumed to be transient in nature, occurring at some point during exercise and lasting for a short time following exercise cessation. Narrative reviews of the acute exercise and cognitive performance literature have reported inconsistent findings. McMorris and Graydon (2000) examined acute exercise studies that compared multiple exercise intensities in an attempt to discern whether support exists for an inverted-U relationship between exercise intensity and cognitive performance. Generally, the authors found that the results related to exercise intensity level were equivocal, and concluded that only speed of cognitive performance clearly benefited from acute exercise. These conclusions are congruent with a later narrative review (Brisswalter, et al., 2002), which identified reaction time and event-related potentials as the only two cognitive outcomes exhibiting a beneficial effect of acute exercise. Lastly, Tomporowski (2003b) suggested that exercise bouts that lasted between 20 and 60 minutes most consistently resulted in cognitive benefits. Contrary to previous reviews, Tomporowski also concluded that bouts of acute exercise that were of moderate duration (20 – 60 minutes) could affect cognitive factors beyond processing speed such as decision-making, problem-solving, and working-memory. The conflicting findings of these narrative reviews underscore the need for a more objective and comprehensive synthesis of the literature.

As a result, the acute exercise literature has been examined by meta-analysis on three separate occasions. As part of a larger review, Etnier and colleagues (1997) reported that acute exercise resulted in a small, positive effect on cognition (ES = 0.16). Sibley and Etnier (2003) also included acute exercise research in an analysis that focused explicitly on children. Again, acute exercise had a small positive effect (ES = 0.37) on cognitive performance. In a more recent analysis that only included within-subject randomized controlled trials with healthy young adults, Lambourne and Tomporowski (2010) identified a small negative effect (ES = -0.14) on cognitive performance during exercise, but a small positive effect following exercise (ES = 0.20). However, it should be noted that a positive effect (ES = 0.39, *n* = 9) on cognitive performance during exercise was observed when participants had been exercising for longer than 20 minutes. This seems to be consistent with the assertion in Tomporowski's narrative review (2003b) that exercise of at least 20 minutes was necessary to observe benefits to cognition. These results provide tenuous support for a positive effect of acute exercise on cognitive performance, though it is clear much more work is necessary to elucidate the relationship.

Alternatively, chronic exercise studies employ exercise protocols of regular frequency and longer duration – multiple sessions per week, over the course of several weeks or months. Researchers using chronic exercise paradigms assume that changes in cognition due to regular exercise are longer lasting than changes due to acute or short-term exercise. Unlike the acute exercise literature, multiple meta-analytic reviews have been conducted for chronic exercise research. Etnier and colleagues (1997) identified a small, positive effect on cognition (ES = 0.33). Most subsequent meta-analyses (Angevaren, et al., 2008; Etnier, et al., 2006; Sibley & Etnier, 2003; Smith, et al., 2010) tended to support this initial review in generally finding small, positive effects (ES = 0.12 - 0.34) for chronic exercise on cognition. One notable exception is the meta-analysis conducted by Colcombe and Kramer (2003), which identified a moderate, positive effect (ES = .48) for cognition in general, and a large, positive effect (ES = .68) for executive function; although, it should be noted that this review was limited to randomized controlled trials with elderly participants. These results are partially corroborated by a subsequent review of randomized controlled trials (Heyn, et al., 2004) that reported an overall effect of 0.57 in elderly participants with cognitive impairment. Though the research more consistently supports a beneficial effect for chronic than acute exercise on cognition, questions remain about the magnitude and mechanisms of effects.

The direct comparison of findings from the acute and chronic exercise literature, with regard to cognitive outcomes, may not be appropriate. Though similar cognitive measures are used for assessment, an important difference exists in the foci of the two paradigms. Cognitive assessment within an acute exercise paradigm is typically concerned with relatively transient changes in cognitive function. Alternatively, cognitive assessment in a chronic exercise paradigm assumes that changes in cognitive function are more stable. One example of the difference between outcomes of interest in the acute and chronic literatures might be exercise-induced improvements in reaction time versus maintenance of cognitive integrity into old age. The first outcome focuses on a specific cognitive process at a singular point in time relative to exercise, whereas the second is more concerned with general cognitive capability irrespective of the temporal proximity to exercise. However, memory is a cognitive domain for which these distinctions can become blurred. If acute exercise can indeed impact memory processes, then improvements in memory for that information or stimuli encoded proximal to the exercise bout may be less transient than other effects of acute exercise (Lambourne & Tomporowski, 2010). Such an effect could have important implications for myriad learning paradigms, and provides a compelling case for the examination of the relationship between acute exercise and memory.

Different Memory Stores

Rather than a singular construct, several distinct types of memory stores have been identified: sensory memory, short-term memory, working memory, and long-term memory. Sensory memory involves a rapid encoding of all physical aspects of stimuli when first encountered. Encoding of information into sensory memory does not rely upon directed attention toward the stimuli, and encoded information decays very rapidly (a matter of seconds) without subsequent attentional focus.

Short-term memory refers to an ability to store information that is intended to be used immediately, or after a very brief delay. Specifically, information relevant to meeting a specific demand receives continual attention until the demand is met. Upon cessation of active attention, most of the information quickly fades from memory. An example would be the mental and/or verbal repetition (a.k.a. – rehearsal) of a phone number until it is dialed. Once the number has been dialed, rehearsal stops and the phone number can no longer be reliably recalled.

Working memory subsumes short-term memory, but also includes the additional ability to manipulate that information for the purposes of completing more complex tasks, such as decision making or problem solving (Baddeley, Eysenck, & Anderson, 2009). An example would include the backward portion of the Digit Span test, in which participants are asked to repeat back a string of numerals in the reverse order from how they were presented. Similar to short-term memory, once the demand is met and continual attention is no longer devoted to the information, it quickly dissipates from the memory store. Thus, information stored within short-term and working memory is considered transient and unstable.

Long-term memory refers to the capacity to store newly acquired or encoded information for use at a later time. However, information encoded for use at a later time is not instantly transferred into long-term memory. The stabilization of information from a transient state to a more permanent state within memory is known as consolidation (Nader & Einarsson, 2010) and can occur over the course of minutes to years (Medina, Bekinschtein, Cammarota, & Izquierdo, 2008). Consolidation is generally thought to occur in two stages: synaptic or cellular consolidation and systems consolidation. Synaptic consolidation occurs on a cellular level within the first minutes to hours after encoding (Wang & Morris, 2010). This initial stage of consolidation involves identification, storage, and synthesis of proteins pertinent to the encoded stimuli (Frey & Morris, 1997). Systems consolidation involves the transfer of memory traces originally consolidated within the hippocampus into different areas of the neocortex (Dudai, 2004), and can run a course of weeks to years (Nader & Einarsson, 2010). This slower reorganization links multiple areas of the brain to form a more durable representation of the memory trace (Medina, et al., 2008). A third stage in the long-term memory process, retrieval, generally involves the accessing or reactivation of information stored within long-term memory (Gardiner, 2007).

Exercise and Memory

Beginning with the Yerkes-Dodson Law (Yerkes & Dodson, 1908) and Easterbrook's (1959) Cue Utilization Theory, arousal has been considered a possible mechanism driving relationships between physical activity and performance. This line of research was later developed into the Inverted-U hypothesis (Davey, 1973), which became one of the main early frameworks in exercise and cognition research. Though the Inverted-U hypothesis has received little support within the acute exercise and cognition literature (Brisswalter, et al., 2002; McMorris & Graydon, 2000; Tomporowski, 2003b), arousal remains a commonly proposed mechanism by which acute exercise might affect cognitive performance. Despite the common usage of increased arousal as a framework in the acute exercise and cognition literature, very rarely has it been applied when memory was an outcome of interest (Craft, 1983). However, the notion that increased arousal might impact cognition is not exclusive to the exercise literature, and there is a distinct body of literature within the cognitive psychology domain devoted to the effects of arousal on memory. Arousal has been defined, within the cognitive psychology literature, as the level of preparedness for stimulus detection and response (Revelle & Loftus, 1990), and generally refers to one's degree of physiological and psychological activation. This degree of activation can range from deep sleep to extreme vigor. Operationally, arousal has been defined in empirical studies both physiologically and psychologically. Physiological measures of arousal have included heart rate, cortisol levels, skin conductance, electroencephalographic (EEG) fluctuation, and body temperature. Psychological arousal assessment consists mainly of self-report measures. In their review of the arousal literature, Revelle and Loftus suggest that arousal consistently exerts a detrimental effect on short-term memory, but can have a facilitative effect on long-term memory and recall. Additionally, multiple sources of arousal – emotionally-arousing material, onlookers/bystanders, exercise, and time of day – were reported effective in benefiting long-term memory performance.

Several recent studies (Cahill, Gorski, & Le, 2003; Cahill & McGaugh, 1995; Quevedo et al., 2003) have provided empirical evidence that arousal increases from multiple sources can improve long-term memory performance. Cahill and McGaugh (1995) had participants view an identical set of slides, which told a story. Half of the participants received an emotionally-neutral narration, whereas the other half received an emotionally-arousing narration. Self-report ratings indicated that the emotionally-arousing narration elicited significantly greater emotional arousal than the emotionally-neutral narration. Recall for the slides was assessed 2 weeks later, and was significantly better for the group that received an emotionally-arousing narration of the slide story. Similarly, Cahill, Gorski and Le (2003) had participants view slide shows varying in degree of arousal induction. However, they also had some participants complete a cold pressor task (CPT) prior to slide viewing. Arousal was assessed by comparing cortisol levels in control and CPT groups. Similar to the previously described study, recall 1 week later was better for emotionally-arousing slides than for emotionally-neutral slides, and this was true regardless of CPT condition. However, results also showed that the CPT group better recalled emotionally-arousing slides than did the control group. Additionally, cortisol levels were significantly higher in participants following the CPT condition versus the control condition. No between-group differences were observed for recall of the emotionally-neutral slides. The authors interpreted these findings as an indication that arousal at the time of encoding is an important factor in memory consolidation.

Quevedo and colleagues (2003) exposed participants to either an emotionally arousing or emotionally neutral story, and compared performance on (what the authors termed) short-term recall and long-term recall. Self-report measures indicated that the emotional story elicited significantly higher emotional arousal in participants than did the neutral story. Though no difference in story recall was observed after a 1-hour delay (short-term recall); after a 1-week delay, the emotionally-arousing story was better recalled than the emotionally neutral story. However, the results from other studies suggest that neither the stimuli nor the arousal need to be emotionally valenced in order to observe an effect. Abercrombie and colleagues (Abercrombie, Kalin, Thurow, Rosenkranz, & Davidson, 2003) compared the effects of arousal, using differing doses of cortisol or placebo, on memory for emotionally-neutral or emotionally-arousing stimuli (words and pictures). Participants were given either 40 or 20 milligrams (mg) of hydrocortisone (cortisol) or a placebo, and then rested for approximately 40 minutes to allow for drug absorption. Following the absorption period, participants were exposed to words and pictures that were either emotionally-neutral or negatively valenced. Participants then completed a brief control task, after which recognition and free-recall trials were administered. Participants returned for a second visit 2 days later to perform follow-up recognition and free-recall trials. Results showed that the group that received

40 mg of hydrocortisone committed fewer errors than the control group during the free-recall trial completed on the first day. Both hydrocortisone groups performed better than the placebo group on the picture recognition trial on day 2. Further, the group that received 20 mg of hydrocortisone also performed better than the placebo group on the word recognition trial on day 2. A significant dose-by-valence interaction was not identified in any of the comparisons, suggesting that the effect of increased arousal was not dependent upon the emotional valence of the stimuli.

In a similar study, that yielded very different results, Rimmele and colleagues (Rimmele, Domes, Mathiak, & Hautzinger, 2003) tested the differential effect of hydrocortisone on long-term memory of an emotionally-neutral or emotionally-arousing story. Participants were either given 25 mg of hydrocortisone or a placebo, and then waited for 75 minutes to allow for drug absorption. Following the absorption period, participants were exposed either to an emotionally-neutral or emotionally-arousing story. Participants returned 1 week later to complete free-recall and recognition memory trials. Overall, the emotionally-arousing story was recalled (recognition and free-recall) better, with no main effect for, or interaction with treatment. Further, hydrocortisone treatment did not impact free-recall of story plot. However, hydrocortisone treatment did improve free-recall of details for the emotionally-neutral story, but hindered recall of details for the emotionally-charged story.

Lastly, Schwabe and colleagues (Schwabe, Bohringer, Chatterjee, & Schachinger, 2008) tested the impact of increased arousal on recall of emotionally-arousing and emotionally-neutral words. Results indicated that increased arousal, as induced by CPT and measured via an 11-point visual analogue scale, improved recall for emotionally neutral words at 24 hours. Overall, however, and similar to the preceding studies, it should be noted that emotionally-arousing words were better recalled than were neutral words. Additionally, increased cortisol levels, elicited by CPT, led to increased recall of negatively-valenced words at one hour; though, the effect dissipated by the 24-hour assessment. This could indicate that the effects of increased arousal on memory are somewhat moderated by the congruency of the emotional valence of arousal with the to-be-remembered material. In sum, these results would suggest that arousal itself can impact memory generally, but that the effect is augmented if the stimuli are also emotionally arousing.

The importance of the timing of the increase in arousal has also been tested as a potential moderator of the effects of acute exercise on cognitive performance. Smeets and colleagues (Smeets, Otgaar, Candel, & Wolf, 2008) tested the impact of increased cortisol at different stages of the memory process. Participants were asked to learn a list of words, with those in the experimental conditions completing a CPT immediately before encoding, during consolidation (immediately following encoding), or immediately prior to recall. Recall was assessed 24 hours following the encoding stage. Participants in the control condition did not complete a CPT, nor were they exposed to another form of stressor. The authors found that only when arousal was increased during consolidation was an improvement over controls observed. This interpretation might seem to run contrary to the findings of studies that induced arousal prior to encoding (Abercrombie, et al., 2003; Rimmele, et al., 2003; Schwabe, et al., 2008). However, arousal induction prior to encoding does not prohibit the effects of arousal acting upon later stages of long-term memory storage. Abercrombie and colleagues (2003) tracked cortisol levels throughout the first day of their study, and clearly illustrate that cortisol levels remained elevated for up to 100 minutes following the absorption period. This means that cortisol levels, and so arousal, were still elevated when the consolidation process was underway.

The results of all of these studies support Revelle and Loftus' (1990) assertion that arousal induction, using any of several different methods, can be effective in positively impacting long-term memory. They also provide limited evidence (Abercrombie, et al., 2003; Rimmele, et al., 2003; Schwabe, et al., 2008) that the target material does not have to be emotionally charged in order to observe an effect of increased arousal. Lastly, these results begin to address the idea that the timing of arousal induction relative to the memory task is an important factor to be considered

Acute Exercise and Memory

Reviews: Acute Exercise and Memory Research

Results from the arousal literature coupled with the arousal frameworks popular within the exercise literature would seem to position memory as a logical cognitive outcome of interest for the acute exercise paradigm. However, memory, and especially long-term memory, has not been a main focus of the acute exercise literature. This current dearth of memory research may be partially explained by the mixed findings in narrative reviews (Tomporowski, 2003b), but perhaps more so by the small effects reported in meta-analytic reviews (Etnier, et al., 1997; Sibley & Etnier, 2003). Etnier and colleagues reported a small, positive overall effect of acute exercise on memory (ES = 0.10) based on 116 individual effects. In their review that focused solely on children, Sibley and Etnier identified an even smaller, and non-significant effect of exercise on memory (ES = 0.03, n = 7). However, due to the small number of individual effects, the authors were not able to specifically examine the effect of acute exercise on long-term memory. Though Lambourne and Tomporowski (2010), in a more recent review, identified a somewhat larger positive effect of acute exercise on memory (ES = 0.30), interpretation is still limited by the small number of individual effects (*n* = 9) used in the calculation. In this instance, the small number of individual effects resulted from the authors' stringent inclusion criteria: within-subjects, repeated-measures design that only sampled young adults. However, this effect must be interpreted cautiously because the smaller the number of individual effects used in the calculation, the fewer unreported null effects required to reduce the overall effect to non-significance. It is also important to point out that none of the meta-analyses made any distinction between the type of memory assessed, combining short-term, working, and long-term memory into a singular construct, "memory". Considering that each type of memory store includes its own distinct set of processes and time courses, it is conceivable that acute exercise may impact each of them differently.

Like the meta-analytic reviews, narrative reviews have also provided very little guidance on the relationship between acute exercise and memory. This lack of guidance can be partially explained by the relatively small number of studies with this focus sampled in each review. Another possible explanation is the lack of specificity in the type of memory assessed in the reviewed empirical studies – studies measuring short-term memory, working memory, and long-term memory have typically been considered together under the single construct, “memory”. Overall, very little support for a consistent relationship between acute exercise and memory is found within narrative reviews.

The first narrative review to focus on acute exercise (Tomporowski & Ellis, 1986) yielded equivocal findings. In that review, only three studies were identified as assessing some form of memory (Davey, 1973; Sjoberg, 1980; Tomporowski, et al., 1987), with none providing strong evidence for an effect on memory. In two experiments, Davey (1973) reported a benefit to short-term memory following 30 seconds and 2 minutes of bicycle pedaling, no effect following five minutes, and memory performance decrements by ten minutes. In the first experiment, Davey recruited 30 college-aged subjects to perform a cognitive task prior to and following a 2-minute stage of stationary bike pedaling, performance of a simple tapping task, or rest. The cognitive task required participants to identify sequences of odd-even-odd integers within a continuous, orally-presented string of integers – a task that taxes aspects of working memory. Results showed that only the exercise group improved from pre-test to post-test on the cognitive task. In the second experiment, Davey recruited 20 college-aged males and randomly assigned them to one of five groups: cycle for 15 seconds, 30 seconds, 2 minutes, 5 minutes, and 10 minutes. Results showed that only participants pedaling for 30 seconds and 2 minutes improved significantly at post-test. These results suggested that acute exercise, in the proper amount, could benefit aspects of working memory. The authors also posited that the tipping point at which the effect of acute exercise on cognitive performance transitions from benefit to non-benefit or decrement would differ slightly across individuals.

Lastly, Tomporowski and his colleagues (1987) conducted two studies in which they tested for effects of strenuous exercise on free-recall of word lists. In the first study, 48 college students were recruited to perform either a treadmill run to exhaustion or a non-exercise condition. Following either exercise or control conditions, participants completed 12 consecutive trials of word-list recall, using a different word list for each trial. For each trial, participants were presented with a word list and then asked to immediately recall as many words as possible. A main effect for word-list trial was observed, with each group improving over time. No main effect for group was observed, nor was there a significant group by trial interaction. In the second study, 12 members of a collegiate track team (high fit group) were compared to 12 participants of average fitness from the exercise group in the previous experiment. The exercise and recall protocols were identical to those used in the previous experiment. Again, only a significant main effect for trial was observed. There was neither a significant main effect for group, nor a significant group by trial interaction. In sum, acute exercise resulted in neither an overall performance benefit to short-term memory, nor did it increase the rate of improvement on the cognitive task.

More recently, Brisswalter and colleagues (2002) reviewed the acute exercise literature, but also failed to discuss more than a few studies examining memory. The authors reached no clear conclusions because all of the memory literature that they reviewed was heavily intertwined with hydration status. In these two very similar studies (Cian, et al., 2001; Cian, et al., 2000), researchers induced dehydration by various methods, one of which included exercise. On both occasions, exercise leading to dehydration resulted in decrements to myriad cognitive outcomes, including short-term and long-term memory. However, exercise-induced dehydration was not special in producing this outcome. Passive dehydration via hyperthermia (heat lamps) produced similar effects on cognitive performance.

The most recent narrative review, by Tomporowski (2003b), included only one empirical study (Hancock & McNaughton, 1986) not sampled in previous narrative reviews. Hancock and McNaughton had experienced orienteers view and immediately answer questions about a series of slides both during rest and during a treadmill run at anaerobic threshold. Questions about the slides were designed to test multiple aspects of cognitive function, including short-term memory, attention, and other skills related to orienteering. The authors found that orienteers performed less well overall on the cognitive task during exercise than during rest; however, differences in responses to questions assessing short-term memory did not reach statistical significance.

Other empirical research has been conducted outside of those studies sampled in these narrative reviews. When considered according to differences in exercise protocols and the types of memory assessed, these studies provide a slightly clearer picture of the relationship between acute exercise and memory.

Empirical Studies: Acute Exercise and Short-term Memory Research

In general, results have not supported a beneficial effect of acute exercise on short-term memory. Multiple studies employing submaximal exercise protocols have yielded null findings. Tomporowski and Ganio (2006) tested the effect of cycling for 30 minutes at 60% VO_{2max} on participants' ability to recall consonant-vowel-consonant trigrams in a within-subjects, pre-post design. Cycling involved a 5-minute warm-up, followed by 30 minutes of steady state exercise at 60% VO_{2max}, and ended with a 5-minute recovery. Cognitive testing was carried out immediately before and following exercise. Trigrams were visually presented to participants for 2 seconds, followed by a retention delay of 0 to 18 seconds. During this delay, participants performed a distracter task that involved counting backwards by 3's. Immediately following the delay, participants were asked to recount the letters of the trigrams in order. Cognitive performance was compared to performance following a no-exercise control condition. Again, results showed no main effect for exercise on short-term memory task performance.

Similarly, Nets and colleagues (2007) tested, in part, the effects of acute exercise at differing intensities on short-term memory. Healthy older participants (aged 50-64 years) were randomly assigned to one of three groups: exercise at 60% heart rate reserve, exercise at 70% heart rate reserve, or a no-exercise control. Cognitive testing included the Alternate Uses test for cognitive flexibility and the Digit Span forward test for attention and short-term memory. Testing occurred 5 minutes following exercise cessation to allow for recovery. Neither exercise nor exercise intensity impacted performance on the Digit Span forward test, indicating no effect on short-term memory.

Studies employing maximal intensity exercise protocols have also been generally ineffective in producing an effect on short-term memory. Tomporowski and colleagues (1987) assessed free recall of word lists immediately following treadmill runs to exhaustion in healthy college-aged participants. Recall was assessed for 90 seconds immediately following the presentation of each word list (n=12), with the recall session lasting approximately 25 minutes. Neither exercise participation nor fitness level led to any differences in number of words recalled.

Féry and colleagues (1997) compared speed and efficiency of short-term memory at varying exercise intensities during and following graded exercise to exhaustion, and during a steady state protocol of 30% VO_{2max}. To assess short-term memory, consonant strings were briefly presented to participants, each followed by a warning signal, and a subsequent probe consonant. Participants were asked to determine whether the probe consonant had appeared in the previous consonant string. Errors and RT were used as indicators of short-term memory function. During the graded exercise session, cognitive testing was carried out 2 minutes into exercise (30% VO_{2max}), again when participants reached predicted 90% VO_{2max}, and finally immediately following volitional exhaustion (reverted to pedaling at 30% VO_{2max}). During the steady state exercise session, cognition was assessed at 3 time points approximately equivalent to those at which testing was carried out during the graded exercise session (2, 13, and 19 minutes into exercise). Again, no effect was found for exercise or exercise intensity on short-term memory.

One possible explanation for the lack of consistent results is that healthy young to middle-aged adults are not sensitive to the effects of acute exercise, but that populations for which cognition is likely still developing or vulnerable to compromise might be more likely to benefit. Several studies have examined such populations, but still fail to consistently observe an effect for exercise on short-term memory.

Di Pietro (1986) tested the effect of short-term, high-intensity exercise on short-term memory in healthy children. Short-term memory was assessed at rest, immediately following the exercise or control condition, and thirty minutes later. Memory was measured using a sequentially increasing memory task (the Simon game). Children in the experimental condition were asked to complete an outdoor obstacle course as quickly as possible – asking them to “beat the clock”. Not only were there no between groups differences in Simon performance, but neither was there any improvement from baseline to post-tests in the exercise group.

Emery and colleagues (2001) examined the effect of maximal exercise on cognition in older participants with chronic obstructive pulmonary disease. Participants were asked to complete a neuropsychological battery, which included the digit span test, following exercise and no-exercise conditions. The digit span test is a common measure of short-term memory. Exercise consisted of a graded maximal test on a cycle ergometer, and lasted 20 minutes on average. The control condition simply involved watching a video. No differences were observed for the measure of short-term memory.

Krebs and colleagues (1989) tested for an effect of brief, intense exercise on learning and short-term memory in young children with spina bifida manifesta. Exercise consisted of a 6-minute protocol, during which participants vigorously flexed their arms in a sequence of four different positions. Memory was assessed using a figural learning task, for which participants briefly viewed a picture of six figures, followed by a picture of five of the figures, and finally a picture of all six figures again. Participants were asked to identify which of the six figures was missing from the previous card. The task was completed when children could successfully identify all missing figures on two consecutive trials. The authors observed that exercisers required significantly fewer trials (4.0) than controls (4.7) to complete the task. However, it should be noted that this effect was observed in an extremely specialized population, with a very small sample size (*n* = 6). As such, these results can only be interpreted in relation to children with spina bifida manifesta, and generalization to all children with this condition would still require replication with a larger sample.

Taken together, neither individual studies, nor narrative reviews provide support for an effect of acute exercise on short-term memory. Though limited in the number of studies (n=9), these findings are consistent with those in the cognitive psychological literature that would indicate a null or detrimental effect of heightened arousal on short-term memory (Revelle & Loftus, 1990, 1992).

Empirical Studies: Acute Exercise and Long-term Memory Research

Though still inconsistent, the long-term memory literature presents more support for an effect of acute exercise than does the short-term memory literature. Schramke and Bauer (1997) examined state-dependent learning and delayed recall of a word list following either exercise or rest. Participants were divided into four conditions: exercise prior to learning and rest prior to recall, exercise prior to both learning and recall, rest prior to learning and exercise prior to recall, or rest prior to both learning and recall. The exercise protocol consisted of a 5-7 minute walk at a self-determined pace. The measure of long-term memory was recall assessed 20 minutes after learning. No between groups differences were identified, suggesting that exercise at either point did not alter long-term memory performance. The authors then collapsed the four groups into state-congruent (walk-walk and rest-rest) and state-incongruent (walk-rest and rest-walk) cells, and again compared their long-term memory performance. Results showed that congruent conditions prior to learning and recall yielded improved memory performance. That is, the state-congruent group correctly recalled more words than did the state-incongruent group. The results of these empirical studies support the position of early narrative reviews (Tomporowski, 2003b; Tomporowski & Ellis, 1986), which suggested that acute exercise was not beneficial to long-term memory processes.

Support for an effect of acute exercise on long-term memory, however, is increasingly present in more recent empirical research. Potter and Keeling (2005) tested verbal memory in young adults following either rest or a brisk, self-paced 10-minute walk. Verbal memory was then assessed using the first 5 trials of the Rey Auditory Verbal Learning Test (RAVLT) – the same word list was presented to participants immediately prior to each recall trial. Though recall in each of these trials relies somewhat on short-term memory, the purpose of the word list repetition is to induce learning. Therefore, as argued by the authors, subsequent recall trials rely increasingly on learning and long-term memory processes. Important to the notion that acute exercise can improve long-term memory of the target material was the observation that the effect of exercise on recall was smallest at the first recall trial, and increased with subsequent recall trials. Not only did exercise produce increased capacity for word list recall, but these effects were observed when assessment began up to 30 minutes following exercise cessation.

A very recent study by Salas, Minakata, and Kelemen (2011) corroborated these findings. Participants were divided into four groups based upon treatment condition before exposure to and recall of a word list: participants either sat or walked before being exposed to a list of words and either sat or walked prior to word list recall. This resulted in four groups: sit-walk, sit-sit, walk-sit, or walk-walk. The walking condition included a "brisk" 10-minute walk around a building. Immediately following word list presentation, participants again either sat or walked for 10 minutes. Recall was assessed shortly following this second 10-minute period. Results showed that participants who walked prior to exposure recalled more words than those who sat prior to exposure. Though very similar in design to the study by Schramke and Bauer (1997), condition congruency had no effect on recall performance in this study.

Most other recent studies have simply compared exercise conditions to no-exercise conditions and have also observed a beneficial effect on memory. Coles and Tomporowski (2008) compared word list recall in undergraduates prior to and following exercise and no-exercise control conditions. Participants completed a battery of cognitive tests, including a 40-item word list, immediately before and following either aerobic exercise or rest. Word list presentation and immediate recall occurred at the beginning of the battery, and delayed recall was assessed approximately 12 minutes later. Other cognitive tests were completed during this 12-minute span. Exercise consisted of 30 minutes of pedaling on a cycle ergometer at 60% of VO_{2max}. While delayed recall of the list overall was unaffected by condition, delayed recall of words in the primacy and recency portions of the list (first and last 10 words) was best following the exercise condition. Similar to previous research, immediate recall was unaffected by acute exercise participation.

Pesce and colleagues (2009) examined free recall of word lists in children following physical education classes or a control condition. Exercise conditions included a physical education class in which students completed circuit training, and a class in which students played team games. Exercise intensity, as measured by heart rate, was approximately equivalent between the two classes. The control condition consisted of memory testing during the first hour of the school day, so that assessment was not preceded by any type of lesson. Similar to the study by Coles and Tomporowski, Pesce and colleagues did not observe a benefit to delayed recall for the list overall, but only to words in the recency portion (end of) of the list.

Most recently, Labban and Etnier (2011) compared delayed recall for participants who completed either a bout of exercise immediately prior to or immediately following exposure to the target material, or a no exercise control. Participants were read two brief paragraphs immediately following or immediately prior to aerobic exercise or during a no-exercise control condition, with recall assessed 35 minutes after encoding. At assessment, participants were asked to recount the paragraphs as close to verbatim as possible. Exercise consisted of 20 minutes on a cycle ergometer, at intensities eliciting ratings of 13-15 on Borg's RPE scale. Results showed that exercise prior to encoding of the paragraphs resulted in better recall than did no exercise at all. Delayed recall for the group that exercised following exposure did not differ significantly from either the control group or the group that exercised prior to exposure. The results from this study seem to support those reported by Salas and colleagues (2011), in that it would appear that the timing of exercise relative to information encoding, consolidation, and recall is important. Specifically, these results suggest that acute exercise carried out prior to exposure to to-be-remembered material is most beneficial to long-term memory. However, results from the study by Schramke and Bauer (1997) did not show a similar effect.

Though many of the recent studies testing the effect of acute exercise on long-term memory have yielded positive results, several issues remain. First, there is very little consistency in methodological design. Exercise modality has ranged from walking (Potter & Keeling, 2005; Salas, et al., 2011), to cycle ergometry (Coles & Tomporowski, 2008; Labban & Etnier, 2011), to physical education classes (Pesce, et al., 2009). Exercise duration has also varied in these studies, ranging from 10 minutes to 30 minutes. The delay between encoding and long-term memory assessment is also variable between studies. These delays ranged from less than 15 minutes (Coles & Tomporowski, 2008; Pesce, et al., 2009; Potter & Keeling, 2005; Salas, et al., 2011) to more than 30 minutes (Labban & Etnier, 2011). Also, consistency between effects has not been achieved –

some studies have found effects for overall recall of the encoded material (Labban & Etnier, 2011; Potter & Keeling, 2005; Salas, et al., 2011), while others have only found an effect for certain portions of the encoded material (Coles & Tomporowski, 2008; Pesce, et al., 2009). These discrepancies raise questions as to the exact nature of the acute exercise – long-term memory relationship. Specifically, how does acute exercise affect long-term memory formation? At what stage in the long-term memory process would acute exercise exert an effect – encoding or consolidation? Does the amount or intensity of exercise interact with length of delay? What is/are the mechanism(s) by which acute exercise affects memory? The existing collection of discrete empirical studies has provided evidence of a relationship between acute exercise and long-term memory, but the inconsistency and paucity of the existing literature limits our ability to answer these more specific questions.

Brain-Derived Neurotrophic Factor: An Emerging Mechanism

Though it is beyond the scope of the present study, this review would be incomplete without some discussion concerning brain-derived neurotrophic factor (BDNF). There is substantial evidence that BDNF plays a critical role in learning and memory formation, as well as in processes important to both – including neuronal plasticity and protein synthesis (Bekinschtein, Cammarota, Izquierdo, & Medina, 2008; Lipsky & Marini, 2007). Recent research has begun to test the viability of BDNF as a mechanism for the effect of exercise on cognitive function.

Ferris, Williams, and Shen (2007) compared peripheral BDNF levels following exercise bouts of varying intensity: maximal, 10% above ventilatory threshold (VT), and 20% below VT. Results showed that BDNF levels increased in dose-response fashion with exercise intensity, with the largest gains over baseline observed following the maximal exercise test. The authors also tested for an effect of BDNF on cognitive function using the Stroop task. Though performance on the Stroop task did improve following exercise, improvement was not related to increases in BDNF. The results concerning BDNF response to acute exercise are important in that they provided insight into the importance of acute exercise intensity. That BDNF levels were not related to Stroop task performance is less important considering it is a measure of executive function and does not rely on long-term memory processes.

Winter and colleagues (2007) also measured changes in peripheral BDNF levels following acute exercise at varying intensities, and following a no-exercise control condition. Additionally, the authors tested for an effect of exercise, as mediated by BDNF increases, on performance of a list-learning task. Exercise conditions included a high-intensity group, which completed a brief set of wind sprints, and a low-intensity exercise group, which completed 40 minutes of light jogging. Results showed that BDNF levels increased most following the more intense exercise condition, followed by low-intensity exercise. The control group showed the least change in BDNF profile across measurements. The high-intensity exercise condition led to list-learning to criterion immediately following exercise, and better retention at 1-week than did the other two conditions. Further, higher BDNF levels at encoding (post-exercise) was related to faster list learning, and to better word recall one week later. Despite findings that suggest a meditational role of BDNF in exercise-induced improvements in performance of a memory task, this study did have some important limitations. First, exercise conditions differed greatly not just in intensity, but also in duration. Though sprinting constituted a much higher intensity, their drastically shorter duration may have allowed a quicker recovery from fatigue than the 40-minute jog. Additionally, the authors did not account for possible changes in BDNF during the 40-minute jog. It is possible that participants' BDNF profiles changed as they began the run, and then changed again as they achieved steady state. Lastly, BDNF levels between conditions were significantly different at baseline, with each condition maintaining its relative rank at each measurement point. Thus, memory performance could also be explained in terms of absolute BDNF levels as well. Further research with more tightly controlled exercise protocols is required to elucidate this relationship.

Summary

Generally, research indicates that acute exercise exerts a small, positive effect on cognitive performance (Etnier, et al., 1997; Lambourne & Tomporowski, 2010). Though most effects of acute exercise on cognition are thought to be transient, memory may be an area for which lasting benefits can occur. Recent studies indicate that a single bout of aerobic exercise can produce improved performance on delayed recall for various verbal memory tasks (Coles & Tomporowski, 2008; Labban & Etnier, 2011; Pesce, et al., 2009; Salas, et al., 2011). However, it is unclear exactly how, or to what degree this relationship exists. Specifically, upon what stage of long-term memory formation does acute exercise act: encoding or consolidation? One emerging mechanistic possibility is that acute exercise can advantage long-term memory by increasing circulating levels of BDNF (Winter, et al., 2007). Given the strong evidence that BDNF plays a critical role in both learning and consolidation (Bekinschtein, et al., 2008), and that acute exercise can increase circulating BDNF levels (Ferris, et al., 2007; Vega et al., 2006), it seems plausible that acute exercise could impact the encoding and/or consolidation stages of long-term memory formation. Up until now, research examining acute exercise and long-term memory has consisted of discrete studies performed by different research groups. Lacking has been a systematic examination of the relationship, including research designed to tease out the memory processes upon which acute exercise acts. Studies by Salas and colleagues (2011) and by Labban and Etnier (2011) provide initial, albeit limited, insight into this question. Results from these studies were consistent in showing a positive effect when exercise was completed prior to encoding. However, conditions that required exercise following encoding always ended the bout immediately prior to recall. Thus, in these conditions, exercise could as likely have impacted retrieval as consolidation. Without a better understanding of mechanisms, it may be presumptuous to assume that the effect of acute exercise should only be observed immediately following exercise cessation. Therefore, it is still unclear if pre-exposure exercise impacts encoding, consolidation, or both. Further, it is also unknown if post-exposure exercise can impact long-term memory formation if given more time between exercise cessation and recall assessment (retrieval).

Hypothesis

The primary purpose of this study was to determine whether an acute bout of exercise would affect performance on a long-term memory task. Consistent with most of the recent research, it was hypothesized that participants completing aerobic exercise prior to exposure to the to-be-remembered material would perform better on the memory task than they would following no-exercise. Additionally, this study sought to determine which process or processes involved in long-term memory formation are influenced by acute exercise: encoding, consolidation, both, or neither. If pairwise comparisons reveal only a significant difference in recall between the condition in which participants exercise prior to encoding (encoding plus consolidation; E+C) and the no-exercise control (NE) conditions, then this would provide evidence that acute exercise only affected encoding. If pairwise comparisons reveal only a significant difference in recall between the condition in which participants exercise following encoding (consolidation; C) and the no-exercise control (NE) conditions, then this would be evidence that acute exercise only affected consolidation. If differences between all three conditions are observed, then the nature of those differences will inform which processes and to what degree they are affected by acute exercise. As discussed previously, the existing literature does not provide clear guidance concerning this hypothesis. However, similarly designed studies by Labban and Etnier (2011) and Salas and colleagues (2011) suggest that exercise performed prior to encoding is most likely to produce an effect on recall performance. Given that neither of these past studies observed a significant difference in recall when exercise followed encoding (i.e., when exercise was not given the opportunity to benefit encoding, but could benefit consolidation), it was hypothesized that acute exercise would benefit the encoding process, but not consolidation.

CHAPTER III

METHODS

Overview

The objective of the study was two-fold. The first objective was to test whether a single bout of aerobic exercise could affect performance on a long-term memory task. The second objective was to determine which process(es) involved in long-term memory formation are influenced by acute exercise. Long-term memory was assessed using a word-list task, with 60-minute and 24-hour recall, and 24-hour recognition. Word lists are widely accepted, and broadly used within the memory literature. Lists were used in the present study to provide 3 equivalent memory assessments that could be randomized within the 3 experimental conditions. Identification of the processes affected by exercise was accomplished through the manipulation of the presence and timing of exercise relative to exposure to a word list. Exercise occurred directly prior to (encoding plus consolidation condition; E+C) or directly following (consolidation condition; C) list exposure, or not at all for the no-exercise control (NE) condition. The 60-minute delay was chosen to provide adequate time during the C condition for exercise completion and recovery, so that possible effects of exercise on consolidation would not be confounded by possible effects of exercise on retrieval. The 24-hour delay was chosen to test the duration of possible effects. If exercise does improve performance on the memory task, then degree of improvement by condition would inform on the process that was affected. That is, the E+C condition would allow for an effect of exercise upon both the encoding and consolidation stages; whereas, the C condition only allowed for an exercise effect on the consolidation stage. If acute exercise enhances encoding only, then the E+C condition should show the only improved performance over control. If exercise enhances consolidation, then both the C and E+C groups should exhibit the best long-term memory performance respectively. If acute exercise positively impacts both processes, then the E+C condition would be expected to exhibit the best long-term memory, followed by the C condition. Finally, no differences in recall across conditions would suggest that acute exercise does not affect long-term memory formation.

Sample

The sample consisted of 15 students from the university campus. Recruitment was accomplished through the posting of flyers around campus, as well as oral recruitment in individual classes. This sample size was determined by power analyses that were based upon the results observed in the study by Labban and Etnier (2011) and from data presented by Etnier and colleagues (Etnier et al., 2011). These studies were chosen due to their similarity in design and purpose to this study. Large effect sizes were reported by Labban and Etnier (Cohen’s d = 1.04) and by Etnier and colleagues ($\eta_p^2 = 0.29$), so power analyses were also computed using more moderate effects ($\eta^2 = 0.1 – 0.15$). The final sample size of 15 was a conservative estimate of the number of participants needed to achieve adequate power (0.80) with a moderate effect size. In general, exercise is a very safe activity. However, there is some risk, albeit minimal, associated with physical exertion. Therefore, the age range was limited to 18-35 years, and all participants completed and qualified on a medical screening form, approved by the university internal review board, concerning known risk factors associated with exercise, in order to further reduce the slight risks associated with the exercise required to complete this study.

Exercise Protocol

All exercise was completed on a Lode Corival recumbent ergometer (Groningen, Nederland). Exercise was composed of a 30-minute bout on the cycle ergometer. Participants began with a 5-minute warm-up, pedaling at 60 rpm with minimal resistance (25 W). Participants were asked to pedal at 60 rpm for the remainder of the exercise bout. Resistance was gradually increased during the warm-up until a minimum perceived exertion rating (RPE) of 13 on Borg's RPE (1998) scale had been achieved. RPE was assessed every 3 minutes for the remainder of the exercise bout, with the resistance level adjusted to keep ratings between 13 and 15. The use of RPE to determine exercise intensity ensured that each participant was always exercising at a level he or she determined to be "moderate". The exercise protocol was chosen to be similar to that used in the study by Labban and Etnier (2011). The only difference being that, whereas Labban and Etnier kept resistance constant and varied pedaling speed, the present study kept pedal rate constant and varied resistance. For the E+C condition, exercise ended immediately prior to exposure to the word list. For the C condition, exercise began immediately following exposure to the word list. The NE control condition required participants to simply sit quietly, or read if they so chose, preceding and following exposure to the word list. Participants had free access to water throughout each visit.

Perceived Exertion

Ratings of perceived exertion were assessed every 3 minutes during exercise with Borg's RPE scale (Borg, 1998). Borg's RPE scale is a widely accepted and used measure, possessing acceptable reliability ($\alpha > 0.90$). Criterion validity, relative to VO_2max, is also high when exercise is performed on a cycle ergometer ($r = 0.83$, $CI_{95(2,46)} = 0.735\text{-}0.912$; Chen, Fan, & Moe, 2002). The scale consists of numbers, ranging from 6-20, some of which are paired with verbal descriptors. For example, a rating of "7" is labeled as "very, very light"; whereas, a rating of "17" is labeled "very hard". Participants in this study were instructed to exercise between 13-15 on the RPE scale.

Descriptive and Demographic Measures

Potential participants completed a medical screening questionnaire to ensure that it was safe for them to complete the exercise required for the study. General demographic variables were also collected, such as gender, ethnicity, and education level. Current lifestyle physical activity participation was assessed using the National Health Interview Survey, Part E (Benson & Marano, 1998).

Memory Measure

Memory was assessed using word lists created for the Rey Auditory Verbal Learning Test (RAVLT; Lezak, 1995). Each word list consisted of 15 words, and was pre-recorded, with words read at one word per second. During exposure trials, participants heard the word list 5 times consecutively, with no delay in between trials. Word order was kept the same for each exposure trial. Multiple, consecutive exposure was used in place of the typical multi-trial listen-recall protocol of the RAVLT in order to maximize encoding opportunity and minimize opportunity for consolidation through rehearsal. Prior to and following the exposure trials, participants were asked not to mentally rehearse the words. Sixty minutes following word list exposure, participants were asked to recount all of the words they could remember from the list. A follow-up phone call was placed to participants 24 hours following word list exposure, at which time they completed a second free-recall trial, and then a recognition memory task of the word list. This recognition task involved reading a list of 30 words to the participants. Each word from the previous day’s list appeared on this longer list, along with 15 distracter words. For each word on this longer list, participants were asked to identify whether the word had appeared on the list from the previous day. Words that were correctly identified as appearing on the list heard the previous day were counted as “Hits”; whereas, distracters that were erroneously identified as appearing on the previous day’s list were counted as “False Alarms”. Hit Rate (HT) and False Alarm Rate (FA) were calculated by dividing the number of Hits or False Alarms observed by the total number possible (n=15 for both). All responses were manually recorded (typed) by the experimenter during the recall and recognition assessments.

Procedure

The study was conducted using a within-subjects, repeated measures design, requiring 3 test days and 3 recall days for each participant. Participants were instructed not to participate in physical activity, outside of that included in the experimental procedure, from the morning of testing days until after they had completed the corresponding follow-up phone call to assess long-term memory. Upon the first test day, participants provided informed consent, as well as completed a medical screening questionnaire and general demographics form. Participants were also randomized to condition order at that time. The procedures for each test day were identical except for the presence and timing of the exercise condition. Exercise involved pedaling the cycle ergometer for 30 minutes, at 60 revolutions per minute, at a resistance level eliciting perceived exertion ratings (RPE) within a specified range (13-15) on Borg's RPE scale (Borg, 1998). Participants were exposed to a word list, during which they heard a list of 15 words 5 times consecutively. Depending upon condition assignment for that day, participants exercised immediately prior to (E+C) or immediately following (C) exposure to the list, or did not exercise at all (NE); see Figure 1. Following list exposure, 60 minutes elapsed (which did or did not include exercise dependent upon condition) before participants were asked to recount all the words from the list that they could remember, regardless of order. Participants were allowed to pick among a selection of magazines, from which they could read quietly during all rest periods. Participants were contacted by phone 24 hours following list exposure; again, asked to recall all the words they could remember, and then given a word recognition task. Each test day was separated by a minimum of two days to reduce interference from the previous test day's list. Pairing of word lists and conditions was counter-balanced, such that, to the extent possible, word lists were evenly distributed among conditions (see Appendix B). Condition order was also counter-balanced, and randomly assigned to participants in order to avoid systematic order effects. The time of day during which testing took place was kept consistent within participants: that is, each participant completed all test days and follow-up phone calls during the same time of day (morning or afternoon), with start times separated by no more than 2 hours.

	Pre	Exposure	Consolidation		60-min	24-Hr Recall
	(30 min)	(5 min)	(30 min)	(30 min)	Recall	& Recog
E+C	Exercise	List	Rest	Rest	YES	YES
C	Rest	List	Exercise	Rest	YES	YES
NE	Rest	List	Rest	Rest	YES	YES

Note: Pre = Pre-exposure; Exposure = listens to word list; YES = performed the task described.

Figure 1. Diagram of within-subject testing conditions

Data Analysis

Exercise data (HR, RPE, RPM's and work load) were compared across the two exercise conditions using repeated measures analysis of variance (ANVOA) to determine whether any systematic differences in intensity occurred.

Memory performances after the 60-minute delay and after the 24-hour delay were analyzed separately. Recall memory performance was quantified as the number of words correctly recalled following each delay. Recognition memory performance was quantified by calculating the discriminability index (d'), which accounts for both correct word recognition as well as errors. To calculate d', formulas from the test manual were followed. Specifically, HT and FA were converted to z-scores, and the difference was taken: $d' = z(\mathrm{HT}) - z(\mathrm{FA})$. A bias score ($A'$) was calculated in association with d' to determine whether recognition responses were likely due to chance:

$$A' = \frac{1}{2} + \frac{(\mathrm{HT} - \mathrm{FA}) \times (1 + \mathrm{HT} - \mathrm{FA})}{4 \times \mathrm{HT} \times (1 - \mathrm{FA})}$$

A' scores near 1.0 indicate good discriminability; whereas, scores near 0.5 indicate a more random pattern of response. Repeated-measures ANOVAs were performed for each outcome variable to test for differences in long-term memory performance. Planned contrasts, using Tukey's Honestly Significant Difference test, were used to determine the exact nature of differences between conditions. Specifically, these contrasts were conducted in order to test the secondary hypothesis: that exercise prior to encoding would result in greater recall as compared to that observed during the control condition. All memory results are displayed in Tables 2 and 3. Raw recall and recognition data is presented in Appendix A.

CHAPTER IV

RESULTS

Sample

Participants (N = 15) were healthy, regularly active, young adults with a mean age of 22.73 years (*SD* = 3.11). One participant was replaced as an outlier due to a failure to recall any words at the 60-minute assessment in the C condition. The value of 0 words recalled at the 60-minute assessment fell more than 2 standard deviations away from the mean for the C condition. Further, this marked a drastic departure from the participant's 60-minute recall for the other two conditions (n = 13 and 9 words). The final sample consisted of 5 males, and 10 females. Multiple ethnicities were represented in the sample, including 4 African Americans, 9 Caucasians, 1 Hispanic, and 1 Asian. Participants were regularly active (3.6 METs per day), and had completed an average of 3.73 years (*SD* = 0.70) of post-secondary education.

Exercise

Exercise characteristics (Table 1) were similar across the E+C and C conditions. No differences were observed in HR ($F_{1,14} = 1.35$, $p = 0.27$), RPE ($F_{1,14} = 2.13$, $p = 0.17$), RPM's ($F_{1,14} = 0.123$, $p = 0.731$), or workload ($F_{1,14} = 0.02$, $p = 0.88$) across exercise conditions.

Table 1

Mean Exercise Characteristics (SD)

	Condition		Test of significance between conditions
Exercise Characteristic	Encoding + Consolidation	Consolidation	*p*
RPMs	61.5 (1.8)	61.3 (1.5)	0.731
WATTs	90.5 (21.6)	90.9 (28.7)	0.878
Heart Rate	139.5 (17.3)	136.1 (18.8)	0.265
RPE	13.9 (0.3)	14.1 (0.5)	0.166

60-Minute Recall

Significant differences in word recall were observed at 60 minutes ($F_{2,28} = 4.30$, $p = 0.02$, $\eta_p^2 = 0.24$). Planned contrasts revealed that, on average, participants recalled significantly ($p = 0.03$, $\eta_p^2 = 0.39$) more words following the E+C condition ($M = 7.53$, $SD = 2.90$) as compared to the NE condition ($M = 4.93$, $SD = 2.66$). Differences in the mean number of words recalled following the C condition ($M = 6.00$, $SD = 2.90$) as compared to E+C or NE conditions did not reach significance ($p = 0.21$ and 0.66 respectively).

24-Hour Recall

A second participant was removed from this analysis, because that participant could not be reached for the 24-hour recall and recognition follow-up to the E+C condition test day. Therefore, the 24-hour recall and recognition analyses were carried out with a total sample size of 14. Significant differences in word recall were also observed following a 24-hour delay ($F_{2,26} = 3.58$, $p = 0.04$, $\eta_p^2 = 0.22$). Planned contrasts again revealed that, on average, participants recalled significantly ($p = 0.03$, $\eta_p^2 = 0.40$) more words following the E+C condition ($M = 6.57$, $SD = 3.08$) as compared to the NE condition ($M = 4.21$, $SD = 2.58$). Differences in the mean number of words recalled following the C condition ($M = 4.64$, $SD = 2.56$) as compared to E+C or NE conditions did not reach significance ($p = 0.22$ and 0.97 respectively).

24-Hour Recognition

No differences in participants' ability to correctly recognize words were observed across conditions ($F_{2,26} = 0.39$,$p = 0.68$). Additionally, no differences were observed among pairwise comparisons ($p > 0.05$). Results for *A*' indicated that recognition responses were not random, but showed good discriminability. See Table 2 for mean data.

Table 2.

24-Hour Recognition Results

	Hit Rate	False Alarm Rate	*d*’	A’
No Exercise	0.707	0.187	1.760	0.841
Encoding + Consolidation	0.782	0.129	2.308	0.891
Consolidation	0.733	0.204	1.764	0.839

Table 3.

Memory Results: Words Recalled or Recognized at Each Assessment Point

	Mean Words Remembered (SD)		
	60-Min Recall	24-Hr Recall	24-Hr Recognition
Encoding + Consolidation	7.53 (2.90)*	6.57 (3.08)*	11.79 (1.63)
Consolidation	6.00 (2.90)	4.64 (2.56)	11.21 (2.16)
No-Exercise	4.93 (2.66)	4.21 (2.58)	10.64 (2.10)
P	0.02	0.04	--

Note: * pairwise comparison with No-Exercise condition is statistically significant, $p < 0.05$; no *p*-value is provided for 24-Hr Recognition because comparisons for this assessment were made using *d*’ rather than total words correctly recognized.

CHAPTER V

DISCUSSION

The primary purpose of this study was to test whether a single bout of moderate intensity, aerobic exercise could impact performance on a long-term memory task. A secondary purpose was to test whether separate processes involved in long-term memory formation would be differently affected by acute exercise. Specifically, this study was designed to observe whether an effect would be exerted on the encoding process, consolidation process, both, or neither. Participants completed all study conditions (NE, E+C, and C), totaling 3 test days, each coupled with a follow-up phone call 24 hours later. During exercise, participants were asked to exercise at a partially self-determined, moderate intensity: work at a resistance level that elicited ratings of 13-15 on the perceived exertion scale (RPE). Analyses showed that participants exercised at moderate intensities on all exercise days, with no differences in perceived exertion, HR, or work load across conditions. Further, mean RPE ratings at all time points fell within the prescribed range of 13-15.

The primary hypothesis, that an acute bout of exercise can affect performance on a long-term memory task, was partially supported. Consistent with the previous literature (Coles & Tomporowski, 2008; Labban & Etnier, 2011; Potter & Keeling, 2005; Salas, et al., 2011), moderate aerobic exercise performed prior to encoding led to greater ability to freely recall words following delays of 60 minutes and 24 hours. For both delays, comparisons that included all three conditions yielded smaller effects ($\eta_p^2 \sim 0.24$); whereas, pairwise comparisons that included only E+C and NE conditions yielded more moderately sized effects ($\eta_p^2 \sim 0.40$). These results were consistent with earlier research that has tested the effects of completing a bout of moderate exercise either prior to or immediately following exposure to to-be-remembered material (Labban & Etnier, 2011). Similar to the present study, Labban and Etnier only observed a significant effect on recall when exercise was completed prior to exposure to the to-be-remembered material. However, in that study, recall was assessed only following a 35-minute delay. The present study extends those results by demonstrating similar effects at 60 minutes and 24 hours. That effects remained significant after a 24-hour delay was not completely unexpected either, as previously presented data from our lab (Etnier, et al., 2011), using the same word lists, have shown that an exercise bout of maximal intensity performed prior to list learning could yield better word recognition at 24-hour delay, when compared to list learning following moderate exercise intensities. Dissimilar to this earlier research was that the current study did not employ the traditional listen-recount protocol common to most verbal learning tasks. The recounting of to-be-remembered material directly following encoding trials provides a further opportunity for learning the material, which could result in better or more stable recall at 24 hours. Therefore, by not allowing participants to recall words after each exposure to the list in the present study, learning opportunities were limited. No differences in recognition memory were observed. This was somewhat unexpected given results from data previously collected in our lab (Etnier, et al., 2011). However, in that study the traditional RAVLT protocol was used, which includes the listen-recount learning trials. The reduced opportunity for learning in the present study could have led to reduced signal strength at the time of recognition testing, which might reduce the ability to observe an effect following longer delays. Additionally, because only one list per condition was presented to participants in the present study, recognition assessment only included 15 possible hits and 15 possible false alarms. This is reduced from 30 possible hits and 20 possible false alarms in the normal recognition assessment protocol of the RAVLT. Such reductions in the potential for both correct responses and mistakes may have served to simplify the assessment to the degree that sensitivity was poor for this sample.

The secondary purpose of this study was to determine which processes involved in long-term memory formation are affected by acute exercise. Previous literature that manipulated the timing of exercise relative to different stages of a memory task (Labban & Etnier, 2011; Salas, et al., 2011) has reported that, when compared to a no-exercise condition, better recall was observed when exercise preceded encoding rather than followed encoding. The present study's results are consistent with this previous literature in that recall was best when exercise preceded encoding; and also, in that recall when exercise followed encoding was not significantly different from either the no-exercise conditions, or from the condition in which exercise preceded encoding. Generally, the pattern of results from previous literature could already suggest that encoding, but not consolidation, is sensitive to the effects of acute aerobic exercise. However, the difficulty with this interpretation of the previous studies is that, when exercise followed encoding, it lasted the entire delay between encoding and recall. Such designs limit interpretation regarding long-term memory processes in two ways. First, exercise was ongoing during the entire delay between encoding and recall (i.e. – the consolidation period). If, as reviews suggest (Lambourne & Tomporowski, 2010; Tomporowski, 2003b), exercise needs to be of moderate intensity and duration to exert an effect on cognitive performance, then much of the consolidation period would have occurred before exercise reached an effective level. Second, in previous designs, exercise cessation directly preceded retrieval. A failure to provide an adequate delay between exercise cessation and the recall trial leaves open the likelihood that exercise would influence retrieval as well as consolidation. In fact, this aspect of previous research designs not only makes interpretation problematic, it also might make observation of an effect difficult. Revelle and Loftus (1992) reviewed the cognitive psychological literature concerning arousal and memory processes, and suggested that increased state arousal at the time of recall assessment might differently affect retrieval depending upon the particular personality traits of the individual. Specifically, the authors suggested that increased state arousal might benefit retrieval for participants with higher levels of trait arousal, but hinder retrieval in low trait-arousal participants. Therefore, even if exercise following encoding does affect consolidation, any effects might be washed out if exercise cessation is quickly followed by recall. The current study was designed to guard against these possible confounds by ending exercise 30 minutes prior to the first recall trial.

Beyond the general study design, the memory assessment protocol used in some previous studies has also limited our ability to decipher which long-term memory processes are affected by acute exercise. In particular, studies that used memory measures which incorporated a recall trial immediately following encoding (Labban & Etnier, 2011; Potter & Keeling, 2005) confounded interpretation of the observed beneficial effects of exercise completed prior to encoding. That is, exercise may have had an effect on the encoding process; or, exercise may have interacted with retrieval or learning processes that are concomitant with a recall trial. Thus, it is impossible to know whether exercise benefitted the encoding process, or acted upon the consolidation and learning process inherent in immediate recall. Similarly, the results of the study by Salas and colleagues (2011) are difficult to interpret due to the extended time interval between words during list presentation. In that study, each word was presented for 6 seconds. This longer latency between words provides greater time for study and mental rehearsal of individual words during list presentation. So again, it is difficult to know which processes (i.e. – encoding, learning through rehearsal, or consolidation) were impacted by the recently-completed exercise. The present study was designed with this potential confound in mind, and for this reason did not include an immediate recall trial or an extended latency between words during list presentation.

Consistent with previous studies (Labban & Etnier, 2011; Salas, et al., 2011), there was no significant difference in the number of words recalled when exercise followed encoding (C condition) versus the no-exercise condition (NE). However, it could be argued that acute exercise actually did have an impact on consolidation in the E+C condition, and that the lack of an effect at 60 minutes during the C condition stemmed from the lesser amount of time between exercise completion and recall. In other words, in the E+C condition, exercise could potentially have affected consolidation for 60 minutes; however, in the C condition, exercise could only have affected consolidation for approximately 30 minutes. Thus, it is possible that exercise affects consolidation, but requires a longer consolidation period for these effects to be observed using this behavioral measure. While possible, the further observation that after a 24-hour delay, recall results following the C condition were nearly identical to that of the NE condition, while 24-hour recall following the E+C condition remained high, would seem to provide evidence contrary to this argument. Thus, the more plausible conclusion based upon these results is that the effects of acute exercise on memory are a result of the effects on encoding, and that acute exercise does not affect consolidation.

The current study does include several limitations. The primary limitation is that the current design still does not eliminate the possibility that exercise completed prior to encoding also impacts the consolidation process. A more complete understanding of the mechanisms and time courses of the effects of acute exercise on long-term memory is likely required to completely address this limitation through design. However, it should be reiterated that the similarity of recall performances between NE and C conditions at 24 hours lends credence to the argument that encoding, and not consolidation, was benefitted by exercise. Related to this concern is the difficulty in interpreting non-significant differences in recall between the E+C and C conditions and between the C condition and the NE condition. Looking at the means at 60-min (E+C: *M*=7.53; C: *M*=6.00; NE: *M*=4.93), it is tempting to interpret the results as an indication that exercise benefits both encoding and consolidation; and, that these effects tend to be somewhat cumulative, with greater effects observed when both processes are impacted by exercise. . However, an examination of the means at 24 hours provides evidence that the C and NE conditions produce almost identical long-term memory effects.

Though these results help to clarify the relationship between acute exercise and long-term memory, further study is required. First, this study needs to be replicated with a larger sample. Future studies should also extend recall delays past 24 hours to determine the duration of the effects of a single session of exercise on long-term memory. Additionally, memory assessment should extend beyond simple word lists to tasks more directly generalizable to real-world applications. These studies could employ the more traditional learning paradigm (listen-recount) to test whether the effects of acute exercise prior to learning are augmented (magnitude and duration) over those observed with simple exposure (listen only) to the to-be-remembered material.

Finally, given the importance of brain-derived neurotrophic factor (BDNF) to learning and memory (Bekinschtein, et al., 2008; Lipsky & Marini, 2007), future studies should explore this mechanistic pathway to further our understanding of how and why acute exercise affects memory. To date, there is only one study with humans in which BDNF has been studied as a potential mechanism to affect memory performance (Winter, et al., 2007). In contrast to human studies, there is a developing body of animal literature that supports BDNF as a mechanism for the effects of exercise on memory. Firstly, animal research has provided evidence that exercise can increase levels of BDNF in the hippocampus (Cotman & Berchtold, 2002; Vaynman & Gomez-Pinilla, 2006), a region of the brain critical to learning and memory. Secondly, results have suggested that exercise can improve performance on spatial learning and memory tasks via increased BDNF expression (Vaynman & Gomez-Pinilla, 2005). Lastly, and perhaps more compelling, are data that show blockage of exercise-induced increases in BDNF attenuates the improvements to learning and memory (Ang & Gomez-Pinilla, 2007; Cotman & Berchtold, 2007). However, it cannot be assumed that such results would directly translate to human behavior. As such, further study of BDNF as a mediator of the effects of acute exercise on memory is warranted.

REFERENCES

Abercrombie, H. C., Kalin, N. H., Thurow, M. E., Rosenkranz, M. A., & Davidson, R. J. (2003). Cortisol variation in humans affects memory for emotionally laden and neutral information. *Behavioral neuroscience, 117*(3), 505-516

Aks, D. J. (1998). Influence of exercise on visual search: implications for mediating cognitive mechanisms. *Perceptual and motor skills, 87*(3 Pt 1), 771-783

Allard, F., Brawley, L. R., Deakin, J. M., & Elliott, D. (1989). The effect of exercise on visual attention performance. *Human Performance, 2*(2), 131-145

Ang, E. T., & Gomez-Pinilla, F. (2007). Potential therapeutic effects of exercise to the brain. *Current medicinal chemistry, 14*(24), 2564-2571

Angevaren, M., Aufdemkampe, G., Verhaar, H. J., Aleman, A., & Vanhees, L. (2008). Physical activity and enhanced fitness to improve cognitive function in older people without known cognitive impairment. *Cochrane database of systematic reviews*(3), 1-70

Arcelin, R., Brisswalter, J., & Delignieres, D. (1997). Effect of physical exercise duration on decisional performance. *Journal of Human Movement Studies, 32*(3), 123-140

Arent, S. M., & Landers, D. M. (2003). Arousal, anxiety, and performance: a reexamination of the Inverted-U hypothesis. *Research quarterly for exercise and sport, 74*(4), 436-444

Baddeley, A. D. (1999). *Essentials of human memory*. Hove, England: Psychology Press.

Baddeley, A. D., Eysenck, M. W., & Anderson, M. (2009). *Memory*. Hove England ; New York: Psychology Press.

Barbour, K. A., & Blumenthal, J. A. (2005). Exercise training and depression in older adults. *Neurobiol Aging, 26 Suppl 1*, 119-123

Bekinschtein, P., Cammarota, M., Izquierdo, I., & Medina, J. H. (2008). BDNF and memory formation and storage. *The Neuroscientist : a review journal bringing neurobiology, neurology and psychiatry, 14*(2), 147-156

Benson, V., & Marano, M. A. (1998). Current estimates from the National Health Interview Survey, 1995. *Vital and health statistics. Series 10, Data from the National Health Survey*(199), 1-428

Blumenthal, J. A., Babyak, M. A., Doraiswamy, P. M., Watkins, L., Hoffman, B. M., Barbour, K. A., . . . Sherwood, A. (2007). Exercise and pharmacotherapy in the treatment of major depressive disorder. *Psychosomatic medicine, 69*(7), 587-596

Borg, G. (1998). *Borg's Perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Brisswalter, J., Arcelin, R., Audiffren, M., & Delignieres, D. (1997). Influence of physical exercise on simple reaction time: effect of physical fitness. *Perceptual and motor skills, 85*(3 Pt 1), 1019-1027

Brisswalter, J., Collardeau, M., & Rene, A. (2002). Effects of acute physical exercise characteristics on cognitive performance. *Sports medicine, 32*(9), 555-566

Brisswalter, J., Durand, M., Delignieres, D., & Legros, P. (1995). Optimal and non-optimal demand in a dual task of pedalling and simple reaction time: Effects on energy expenditure and cognitive performance. *Journal of Human Movement Studies, 29*, 15-34

Cahill, L., Gorski, L., & Le, K. (2003). Enhanced human memory consolidation with post-learning stress: interaction with the degree of arousal at encoding. *Learning & memory, 10*(4), 270-274

Cahill, L., & McGaugh, J. L. (1995). A novel demonstration of enhanced memory associated with emotional arousal. *Consciousness and cognition, 4*(4), 410-421

Chang, Y. K., & Etnier, J. L. (2009). Exploring the dose-response relationship between resistance exercise intensity and cognitive function. *Journal of sport & exercise psychology, 31*(5), 640-656

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 research, 1453*, 87-101

Chen, M. J., Fan, X., & Moe, S. T. (2002). Criterion-related validity of the Borg ratings of perceived exertion scale in healthy individuals: a meta-analysis. *Journal of sports sciences, 20*(11), 873-899

Chmura, J., Nazar, K., & Kaciuba-Uscilko, H. (1994). Choice reaction time during graded exercise in relation to blood lactate and plasma catecholamine thresholds. *International journal of sports medicine, 15*(4), 172-176

Cian, C., Barraud, P. A., Melin, B., & Raphel, C. (2001). Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. *Int J Psychophysiol, 42*(3), 243-251

Cian, C., Koulmann, N., Barraud, P. A., Raphel, C., Jimenez, C., & Melin, B. (2000). Influence of variations in body hydration on cognitive function: Effect of hyperhydration, heat stress, and exercise-induced dehydration. *Journal of Psychophysiology, 14*, 29-36

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychological science : a journal of the American Psychological Society / APS, 14*(2), 125-130

Coles, K., & Tomporowski, P. D. (2008). Effects of acute exercise on executive processing, short-term and long-term memory. *Journal of sports sciences, 26*(3), 333-344

Cotman, C. W., & Berchtold, N. C. (2002). Exercise: a behavioral intervention to enhance brain health and plasticity. *Trends in neurosciences, 25*(6), 295-301

Cotman, C. W., & Berchtold, N. C. (2007). Physical activity and the maintenance of cognition: learning from animal models. *Alzheimer's & dementia : the journal of the Alzheimer's Association, 3*(2 Suppl), S30-37

Craft, D. H. (1983). Effect of prior exercise on cognitive performance tasks by hyperactive and normal young boys. *Perceptual and motor skills, 56*(3), 979-982

Craft, L. L., & Perna, F. M. (2004). The Benefits of Exercise for the Clinically Depressed. *Prim Care Companion J Clin Psychiatry, 6*(3), 104-111

Davey, C. P. (1973). Physical exertion and mental performance. *Ergonomics, 16*(5), 595-599

Di Pietro, J. A. (1986). Effect of physical stimulation on motor inhibition in children. *Perceptual and motor skills, 63*, 207-214

Dudai, Y. (2004). The neurobiology of consolidations, or, how stable is the engram? *Annual review of psychology, 55*, 51-86

Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological review, 66*(3), 183-201

Emery, C. F., Honn, V. J., Frid, D. J., Lebowitz, K. R., & Diaz, P. T. (2001). Acute effects of exercise on cognition in patients with chronic obstructive pulmonary disease. *American journal of respiratory and critical care medicine, 164*(9), 1624-1627

Etnier, J. L., Labban, J. D., Pendleton, D. M., Dvorak, K. K., Becofsky, K. M., & Wideman, L. G. (2011). Acute exercise and memory: A dose response study. *Journal of sport & exercise psychology, 33*(supplement), S144

Etnier, J. L., Nowell, P. M., Landers, D. M., & Sibley, B. A. (2006). A meta-regression to examine the relationship between aerobic fitness and cognitive performance. *Brain research reviews, 52*(1), 119-130

Etnier, J. L., Salazar, W., Landers, D. M., Petruzzello, S. J., Han, M., & Nowell, P. (1997). The influence of physical fitness and exercise upon cognitive functioning: A meta-analysis. *Journal of Sport and Exercise Psychology, 19*, 249-277

Ferris, L. T., Williams, J. S., & Shen, C. L. (2007). The effect of acute exercise on serum brain-derived neurotrophic factor levels and cognitive function. *Medicine and science in sports and exercise, 39*(4), 728-734

Fery, Y. A., Ferry, A., Vom Hofe, A., & Rieu, M. (1997). Effect of physical exhaustion on cognitive functioning. *Perceptual and motor skills, 84*(1), 291-298

Fox, K. R. (1999). The influence of physical activity on mental well-being. *Public Health Nutr, 2*(3A), 411-418

Frey, U., & Morris, R. G. (1997). Synaptic tagging and long-term potentiation. *Nature, 385*(6616), 533-536

Gardiner, J. M. (2007). Retrieval: On its essence and related concepts. In H. L. Roediger, Y. Dudai & S. M. Fitzpatrick (Eds.), *Science of Memory: Concepts* (pp. 221-224). New York: Oxford University Press.

Hancock, S., & McNaughton, L. (1986). Effects of fatigue on ability to process visual information by experienced orienteers. *Perceptual and motor skills, 62*(2), 491-498

Herring, M. P., O'Connor, P. J., & Dishman, R. K. (2010). The effect of exercise training on anxiety symptoms among patients: a systematic review. *Archives of internal medicine, 170*(4), 321-331

Heyn, P., Abreu, B. C., & Ottenbacher, K. J. (2004). The effects of exercise training on elderly persons with cognitive impairment and dementia: a meta-analysis. *Archives of physical medicine and rehabilitation, 85*(10), 1694-1704

Hogervorst, E., Riedel, W., Jeukendrup, A., & Jolles, J. (1996). Cognitive performance after strenuous physical exercise. *Perceptual and motor skills, 83*(2), 479-488

Hogervorst, E., Riedel, W. J., Kovacs, E., Brouns, F., & Jolles, J. (1999). Caffeine improves cognitive performance after strenuous physical exercise. *International journal of sports medicine, 20*(6), 354-361

Kashihara, K., Maruyama, T., Murota, M., & Nakahara, Y. (2009). Positive effects of acute and moderate physical exercise on cognitive function. *J Physiol Anthropol, 28*(4), 155-164

Kashihara, K., & Nakahara, Y. (2005). Short-term effect of physical exercise at lactate threshold on choice reaction time. *Perceptual and motor skills, 100*(2), 275-291

Krebs, P., Eickelberg, W., Krobath, H., & Baruch, I. (1989). Effects of physical exercise on peripheral vision and learning in children with spina bifida manifesta. *Perceptual and motor skills, 68*(1), 167-174

Kubesch, S., Bretschneider, V., Freudenmann, R., Weidenhammer, N., Lehmann, M., Spitzer, M., & Gron, G. (2003). Aerobic endurance exercise improves executive functions in depressed patients. *The Journal of clinical psychiatry, 64*(9), 1005-1012

Labban, J. D., & Etnier, J. L. (2011). Effects of acute exercise on long-term memory. *Research quarterly for exercise and sport, 82*(4), 712-721

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. *Brain research, 1341*, 12-24

Lawlor, D. A., & Hopker, S. W. (2001). The effectiveness of exercise as an intervention in the management of depression: systematic review and meta-regression analysis of randomised controlled trials. *BMJ, 322*(7289), 763-767

Lezak, M. D. (1995). *Neuropsychological assessment* (3rd ed.). New York: Oxford University Press.

Lichtman, S., & Poser, E. G. (1983). The effects of exercise on mood and cognitive functioning. *Journal of psychosomatic research, 27*(1), 43-52

Lipsky, R. H., & Marini, A. M. (2007). Brain-derived neurotrophic factor in neuronal survival and behavior-related plasticity. *Annals of the New York Academy of Sciences, 1122*, 130-143

McMorris, T., & Graydon, J. (1996a). Effect of exercise on soccer decision-making tasks of differing complexities. *Journal of Human Movement Studies, 30*(4), 177-193

McMorris, T., & Graydon, J. (1996b). The effect of exercise on the decision-making performance of experienced and inexperienced soccer players. *Research quarterly for exercise and sport, 67*(1), 109-114

McMorris, T., & Graydon, J. (2000). The effect of incremental exercise on cognitive performance. *International Journal of Sport Psychology, 31*(1), 66-81

Medina, J. H., Bekinschtein, P., Cammarota, M., & Izquierdo, I. (2008). Do memories consolidate to persist or do they persist to consolidate? *Behavioural brain research, 192*(1), 61-69

Molloy, D. W., Beerschoten, D. A., Borrie, M. J., Crilly, R. G., & Cape, R. D. (1988). Acute effects of exercise on neuropsychological function in elderly subjects. *Journal of the American Geriatrics Society, 36*(1), 29-33

Nader, K., & Einarsson, E. O. (2010). Memory reconsolidation: an update. *Annals of the New York Academy of Sciences, 1191*, 27-41

Netz, Y., Argov, E., & Inbar, O. (2009). Fitness's moderation of the facilitative effect of acute exercise on cognitive flexibility in older women. *Journal of aging and physical activity, 17*(2), 154-166

Netz, Y., Tomer, R., Axelrad, S., Argov, E., & Inbar, O. (2007). The effect of a single aerobic training session on cognitive flexibility in late middle-aged adults. *International journal of sports medicine, 28*(1), 82-87

Pesce, C., Cereatti, L., Casella, R., Baldari, C., & Capranica, L. (2007). Preservation of visual attention in older expert orienteers at rest and under physical effort. *Journal of sport & exercise psychology, 29*(1), 78-99

Pesce, C., Crova, C., Cereatti, L., Casella, R., & Bellucci, M. (2009). Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. *Mental Health and Physical Activity, 2*, 16-22

Petruzzello, S. J., Landers, D. M., Hatfield, B. D., Kubitz, K. A., & Salazar, W. (1991). A meta-analysis on the anxiety-reducing effects of acute and chronic exercise. Outcomes and mechanisms. *Sports medicine, 11*(3), 143-182

Potter, D., & Keeling, D. (2005). Effects of moderate exercise and circadian rhythms on human memory. *Journal of sport & exercise psychology, 27*, 117-125

Quevedo, J., Sant'Anna, M. K., Madruga, M., Lovato, I., de-Paris, F., Kapczinski, F., . . . Cahill, L. (2003). Differential effects of emotional arousal in short- and long-term memory in healthy adults. *Neurobiology of learning and memory, 79*(2), 132-135

Revelle, W., & Loftus, D. A. (1990). Individual-Differences and Arousal - Implications for the Study of Mood and Memory. *Cognition & Emotion, 4*(3), 209-237

Revelle, W., & Loftus, D. A. (1992). The implications of arousal effects for the study of affect and memory. In S. A. Christianson (Ed.), *The Handbook of Emotion and Memory: Research and Theory* (pp. 113-149). Hillsdale, NJ: Erlbaum Associates.

Rimmele, U., Domes, G., Mathiak, K., & Hautzinger, M. (2003). Cortisol has different effects on human memory for emotional and neutral stimuli. *Neuroreport, 14*(18), 2485-2488

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

Schramke, C. J., & Bauer, R. M. (1997). State-dependent learning in older and younger adults. *Psychology and aging, 12*(2), 255-262

Schwabe, L., Bohringer, A., Chatterjee, M., & Schachinger, H. (2008). Effects of pre-learning stress on memory for neutral, positive and negative words: Different roles of cortisol and autonomic arousal. *Neurobiology of learning and memory, 90*(1), 44-53

Scott, J. P., McNaughton, L. R., & Polman, R. C. (2006). Effects of sleep deprivation and exercise on cognitive, motor performance and mood. *Physiology & behavior, 87*(2), 396-408

Sibley, B. A., & Etnier, J. L. (2003). The relationship between physical activity and cognition in children: A meta-analysis. *Pediatric Exercise Science, 15*, 243-256

Sjoberg, H. (1980). Physical fitness and mental performance during and after work. *Ergonomics, 23*(10), 977-985

Smeets, T., Otgaar, H., Candel, I., & Wolf, O. T. (2008). True or false? Memory is differentially affected by stress-induced cortisol elevations and sympathetic activity at consolidation and retrieval. *Psychoneuroendocrinology, 33*(10), 1378-1386

Smith, P. J., Blumenthal, J. A., Hoffman, B. M., Cooper, H., Strauman, T. A., Welsh-Bohmer, K., . . . Sherwood, A. (2010). Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. *Psychosomatic medicine, 72*(3), 239-252

Stones, M. J., & Dawe, D. (1993). Acute exercise facilitates semantically cued memory in nursing home residents. *Journal of the American Geriatrics Society, 41*(5), 531-534

Tomporowski, P. D. (2003a). Cognitive and behavioral responses to acute exercise in youths: A review. *Pediatric Exercise Science, 15*(4), 348-359

Tomporowski, P. D. (2003b). Effects of acute bouts of exercise on cognition. *Acta psychologica, 112*(3), 297-324

Tomporowski, P. D., & Ellis, N. R. (1986). Effects of exercise on cognitive processes: A review. *Psychol Bull, 99*(3), 338-346

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

Tomporowski, P. D., & Ganio, M. S. (2006). Short-term effects of aerobic exercise on executive processing, memory, and emotional reactivity. *International journal of sport and exercise psychology, 4*, 57-72

Travlos, A. K., & Marisi, D. Q. (1995). Information processing and concentration as a function of fitness level and exercise-induced activation to exhaustion. *Perceptual and motor skills, 80*(1), 15-26

Trivedi, M. H., Greer, T. L., Grannemann, B. D., Chambliss, H. O., & Jordan, A. N. (2006). Exercise as an augmentation strategy for treatment of major depression. *Journal of psychiatric practice, 12*(4), 205-213

Vaynman, S., & Gomez-Pinilla, F. (2005). License to run: exercise impacts functional plasticity in the intact and injured central nervous system by using neurotrophins. *Neurorehabilitation and neural repair, 19*(4), 283-295

Vaynman, S., & Gomez-Pinilla, F. (2006). Revenge of the "sit": how lifestyle impacts neuronal and cognitive health through molecular systems that interface energy metabolism with neuronal plasticity. *Journal of neuroscience research, 84*(4), 699-715

Vega, S. R., Struder, H. K., Wahrmann, B. V., Schmidt, A., Bloch, W., & Hollmann, W. (2006). Acute BDNF and cortisol response to low intensity exercise and following ramp incremental exercise to exhaustion in humans. *Brain research, 1121*, 59-65

Wang, S. H., & Morris, R. G. (2010). Hippocampal-neocortical interactions in memory formation, consolidation, and reconsolidation. *Annual review of psychology, 61*, 49-79, C41-44

Windle, G., Hughes, D., Linck, P., Russell, I., & Woods, B. (2010). Is exercise effective in promoting mental well-being in older age? A systematic review. *Aging Ment Health, 14*(6), 652-669

Winter, B., Breitenstein, C., Mooren, F. C., Voelker, K., Fobker, M., Lechtermann, A., . . . Knecht, S. (2007). High impact running improves learning. *Neurobiology of learning and memory, 87*(4), 597-609

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18*(5), 459-482

APPENDIX A

RAW DATA

The following tables display the raw memory data by subject, per condition. Recall tables list the number of words correctly recalled. The recognition tables list discriminability scores (*d*') and bias scores (*A*').

Table 4.

60-Minute Recall Raw Data

60-Minute Recall			
Id	No Exercise	Encoding + Consolidation	Consolidation
1	7	10	10
2	9	7	1
3	1	7	6
4	3	5	10
5	6	3	6
6	4	9	5
7	8	14	8
8	2	5	4
9	4	7	8
10	6	6	3
11	9	9	9
12	7	6	5
13	2	8	4
14	3	5	2
15	3	12	9
Mean	4.93	7.53	6.00
SD	2.66	2.90	2.90

Table 5.

24-Hour Recall Raw Data

	24-Hour Recall		
Id	No Exercise	Encoding + Consolidation	Consolidation
1	4	2	7
2	7	7	1
3	1	7	6
4	2	4	10
5	4	3	4
6	3	9	5
7	8	12	5
8	1	4	2
9	4	7	5
10	5	1	3
11	9	10	6
12	7	5	4
13	2	7	2
14	3	4	1
15	4	11	7
Mean	4.27	6.20	4.53
SD	2.49	3.30	2.50

Table 6.

24-Hour Recognition Discriminability Raw Data

24-Hour Recognition (*d* ')			
Id	No Exercise	Encoding + Consolidation	Consolidation
1	1.92	1.57	4.22
2	2.09	3.93	4.22
3	3.53	1.68	1.74
4	1.28	2.60	1.28
5	0.69	1.23	1.68
6	1.57	2.95	1.10
7	0.87	2.32	2.95
8	2.32	0.51	1.05
9	1.97	1.74	1.23
10	1.57	2.09	0.92
11	3.93	2.60	1.74
12	1.73	1.57	1.40
13	1.05	3.70	0.69
14	1.38	1.92	0.52
15	0.52	4.22	1.74
Mean	1.76	2.31	1.76
SD	0.96	1.04	1.15

Table 7.

24-Hour Recognition Bias Raw Data

	24-Hour Recognition (*A* ')		
Id	No Exercise	Encoding + Consolidation	Consolidation
1	0.89	0.86	0.97
2	0.90	0.95	0.97
3	0.92	0.88	0.88
4	0.82	0.94	0.82
5	0.71	0.82	0.88
6	0.86	0.96	0.79
7	0.75	0.92	0.96
8	0.92	0.67	0.79
9	0.90	0.88	0.82
10	0.86	0.90	0.76
11	0.95	0.94	0.88
12	0.86	0.86	0.82
13	0.78	0.93	0.71
14	0.83	0.89	0.67
15	0.67	0.97	0.88
Mean	0.84	0.89	0.84
SD	0.08	0.08	0.09

APPENDIX B

COUNTERBALANCING AND RANDOMIZATION

The Following table illustrates the counterbalancing and randomization-by-condition-order, and list-by-condition pairing. Conditions were designated by number (1 = No Exercise, 2 = Encoding + Consolidation, & 3 = Consolidation); whereas, word lists were designated by letters (A, B, & C).

Table 8.

Counterbalancing and Randomization

ID	Sex	Condition Order	List Assignment By Condtion		
			No Exercise	Encoding + Consolidation	Consoldation
1	Female	123	A	C	B
2	Male	312	B	C	A
3	Female	321	A	B	C
4	Female	312	C	A	B
5	Male	312	B	C	A
6	Male	321	A	B	C
7	Female	132	C	A	B
8	Male	123	B	A	C
9	Female	213	A	C	B
10	Female	231	C	B	A
11	Male	123	B	A	C
12	Female	132	B	C	A
13	Female	213	A	B	C
14	Female	231	C	A	B
15	Female	231	C	B	A