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THE EXPERIMENTAL EFFECTS OF ACUTE EXERCISE INTENSITY ON EPISODIC MEMORY AND WORKING MEMORY FUNCTION

AKUT EGZERSİZ YOĞUNLUĞUNUN EPİZODİK BELLEK VE ÇALIŞMA BELLEĞİ İŞLEVİ ÜZERİNDEKİ DENEYSEL ETKİLERİ

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Abstract

The purpose of this study was to evaluate the potential intensity-dependent effects of acute exercise on episodic memory and working memory capacity. A counterbalanced, randomized controlled, within-subject design was employed (N=20; M_{age}=20.8 yrs). The three counterbalanced visits included a control visit, moderate-intensity exercise (40% of HRR) and high-intensity exercise (70% of HRR). Episodic memory was assessed from a word-list task, including an immediate and delayed (20-min delay) assessment. Working memory capacity was assessed from the Brown-Peterson task. Immediate episodic memory recall was similar across the three conditions (8.5-8.7 words). However, for the 20-min delay period, the high-intensity exercise condition had a higher word recall score than the two other conditions (5.7 vs. 4.9). For the working memory task, there was a statistically significant main effect for condition (F=4.3, P=0.02, η^2_p=0.18), main effect for delay period (F=30.6, P<0.001, η^2_p=0.61), and condition x delay period interaction effect (F=2.97, P=0.01, η^2_p=0.14); the high-intensity exercise condition was optimal in enhancing working memory capacity. In conclusion, we provide evidence that acute high-intensity aerobic exercise is optimally associated with working memory capacity, with suggestive evidence that it is also more optimally associated with episodic memory function.

Keywords: α_1- and β-adrenoreceptors; cognition; delay cells; memory type; neuronal firing

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Özet

Bu çalışmanın amacı akut egzersizin epizodik bellek ve işleyen bellek üzerindeki yoğunluk bağımlı etkisini incelemektir. Bu amaçla eşleştirilmiş, sırası dengelenmiş, rastgele kontrollü bir araştırma dizaynı oluşturulmuştur (N=20; M_{age}=20.8 yıl). Bu 3 adet sırası dengelenmiş değerlendirmeler, kontrol ziyareti, orta yoğunlukta egzersiz (40% of HRR) ve yüksek yoğunluklu egzersizdir (70% of HRR). Epizodik bellek bir kelime listesi üzerinden anlık ve beklenmiş değerlendirme ile test edilmiştir. İşleyen bellek ise Brown-Peterson testi ile değerlendirilmiştir. Sonuçlarda anlık epizodik bellek geri çağırma süreçleri üç durum arasında benzerlik arz etmektedir (8.5-8.7 kelime). Ancak, 20 dakika sonraki uzamış dönemde yüksek yoğunluklu egzersiz durumunun diğer iki duruma kıyasla daha yüksek seviyede kelime geri çağırma ile sonlandığı tespit edilmiştir (5.7 vs. 4.9 kelime). İşleyen bellek testi ise, ana etki için durumlar arasında anlamlı ilişki bulunmuş (F=4.3, P=0.02, η^2_p=0.18), beklemenin ana etkisi anlamlı (F=30.6, P<0.001, η^2_p=0.61), ve durum X bekleme süreleri ilişkisinin yine anlamlı olduğu bulunmuştur (F=2.97, P=0.01, η^2_p=0.14); buna göre yüksek yoğunluklu egzersiz işleyen bellek kapasitesini arttırmakta en uygun durum olarak saptanmıştır. Sonuç olarak, bu çalışma akut yüksek yoğunluklu egzersizin işleyen bellek ve epizodik bellek kapasitesini optimize etmekte başarılı olduğu gösterilmiştir.

Anahtar Kelimeler: *α_1- ve β-adrenoreseptorleri; biliş; gecikme hücreleri; bellek tipi; nöronal ateşleme*

1. Introduction

There are many different types of memory, namely categorized into short-term memory, long term memory and sensory memory. Explicit (declarative) memory is the knowledge of facts that can be recalled consciously, while implicit (procedural) memory is knowledge of how to act and complete routines, and prospective memory is information to be recalled in the future. Episodic memory, or the recall of past events in a spatio-temporal context, involves three phases. Memory encoding is the initial phase in the formation of a memory trace; consolidation, which can occur at multiple levels (e.g., synaptic consolidation and brain systems consolidation), involves the post-encoding process of transforming material into a long-term form of memory; and retrieval refers to the stimulus-induced or spontaneous activation of the memory.

The field of exercise neurophysiology is a growing field, with emerging evidence suggesting that exercise may enhance memory function (Chang, Labban, Gapin, & Etnier, 2012; Erickson et al., 2011; Heisz et al., 2017; Labban & Etnier, 2011; Pontifex, Gwizdala, Parks, Pfeiffer, & Fenn, 2016; Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009; Roig, Nordbrandt, Geertsen, & Nielsen, 2013; Roig et al., 2016; Suwabe et al., 2017). For example, we have demonstrated that exercise may enhance multiple memory types, including episodic memory (Delancey, Frith, Sng, & Loprinzi, 2018; Haynes Iv, Frith, Sng, & Loprinzi, 2018; Loprinzi, Edwards, & Frith, 2017; Loprinzi, Frith, Edwards, Sng, & Ashpole, 2017), implicit memory (Loprinzi & Edwards, 2017), emotional memory (Loprinzi, Frith, & Edwards, 2018), and semantic memory (Loprinzi & Edwards, 2018). Potential mechanisms through which exercise may influence these memory types has been discussed elsewhere (Frith & Loprinzi, 2018; Loprinzi, 2018a; Loprinzi, Edwards, & Frith, 2017; Loprinzi & Frith, 2018a).

Unlike the above memory types, working memory is defined as maintenance of temporary information in the prefrontal cortex to execute a task, dissipating once the task is complete. While working memory is stored, it is sustained by the continued firing of delay neurons in the prefrontal cortex (Baeg et al., 2003; Khan & Muly, 2011). Working memory is considered to have a limited capacity; only retaining memory over the short term, ensuring this information is available until it is needed.

Neurotransmitter (e.g., glutamate) release and neural oscillations in the brain have been used to evaluate working memory (Khan & Muly, 2011). The amplitude of gamma and theta oscillations (Howard et al., 2003; Mainy et al., 2007; Meltzer et al., 2008; van Vugt, Schulze-Bonhage, Litt, Brandt, & Kahana, 2010) are associated with working memory (Raghavachari et al., 2001). Acute exercise is associated with an increase in neurotransmitter release and neuronal firing (Khan & Muly, 2011). High-intensity exercise increases post-synaptic excitatory activity (Świątkiewicz et al., 2017). Catecholamines, such as dopamine and norepinephrine play a critical role in working memory capacity (Khan & Muly, 2011). For example, D1 receptor stimulation enhances the excitability of prefrontal pyramidal cells and potentiates glutamate gated currents (Khan & Muly, 2011). Importantly, working memory is optimized at intermediate levels of D1 receptor stimulation and is degraded by either too little, or too much activation of this dopamine receptor. Given the exercise-induced effects on dopamine production (Lin & Kuo, 2013), as well as norepinephrine production (McMorris, 2016; McMorris, Turner, Hale, & Sproule, 2016), this provides some plausibility for a potential differential effect of exercise intensity on working memory capacity.

Further demonstration of a potential intensity-specific effect comes from studies showing that both light and moderate-intensity acute exercise, but not high-intensity exercise, are associated with increased P3 amplitude in tasks related to information processing and executive function, whereas only moderate-intensity acute exercise is associated with shortened P3 in tasks involving executive function (Chang, 2016; Kamijo et al., 2004; Kamijo, Nishihira, Higashiura, & Kuroiwa, 2007). High-intensity exercise, on the other hand, may increase levels of norepinephrine (NE) and dopamine (DA) in the prefrontal cortex, activating β-adrenoceptors and D1-receptors, respectively, ultimately activating cAMP, which

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may dampen neuronal activity (via cAMP opening of nearby K+ channels, which may weaken the effectiveness of nearby synaptic inputs (Arnsten, Wang, & Paspalas, 2012)) in the prefrontal cortex, and potentially impair prefrontal cortex function (Arnsten, 2011). Clearly, there appears to be an inverted U-shaped relationship between NE/DA and working memory function, particularly in animal models.

In contrast to reduced working memory in the prefrontal cortex, elevated levels of catecholamines can enhance synaptic plasticity in the hippocampus (Gagnon & Wagner, 2016; Hansen, 2017; Loprinzi & Frith, 2018b), thus, subserving episodic memory function. That is, increased levels of NE can activate various intracellular signaling pathways (e.g., PKA) to induce CREB transcription, and in turn, improve long-term potentiation (Roozendaal & McGaugh, 2011). Relatedly, experimental work in animals demonstrates that increased running speed is accompanied by increases in the frequency of CA1 network oscillations spanning the gamma frequency range (Ahmed & Mehta, 2012).

In addition to the above-stated physiological parameters, psychological models have been developed as a potential mechanistic explanation for individual differences in working memory capacity. Relatedly, cognitive attention plays a critical role in working memory (Khan & Muly, 2011), and in theory, too high or low of an exercise intensity may have a sub-optimal effect on attention-influenced working memory.

Clearly, the above text demonstrates that exercise intensity may, on physiological and psychological grounds, have a differential effect on memory function. The narrative that follows demonstrates that the emerging research in this field demonstrates mixed findings, which underscores the importance of additional investigations evaluating potential intensity-specific effects of exercise on memory capacity.

Tang et al. (2016) employed an older adult sample (50-80 yrs) of stroke patients and did not observe beneficial effects of chronic low or high-intensity exercise training on working memory performance. Similarly, in a young adult sample, chronic interval training was not effective in enhancing working memory (Venckunas et al., 2016). In line with these null findings, in a young adult sample, Bantoft et al. (2016) did not find a differential effect of sitting, standing or low-intensity walking on working memory performance. Brush et al. (2016) used an acute resistance training protocol among young adults and demonstrated a time-course effect of exercise intensity on working memory; at 15-minutes post-exercise, high-intensity resistance exercise improved working memory capacity, but low- and moderate-intensity exercise was more effective in enhancing working memory capacity 3-hours post-exercise. In young adults, Hwang et al. (2016) demonstrated that acute high-intensity treadmill exercise was effective in enhancing post-exercise working memory. Related to this, Lo Bue-Estes et al. (2008) demonstrated that high-intensity acute exercise among young females was effective in enhancing post-exercise working memory performance, but was detrimental in working memory performance when assessed during exercise. Using a cycling protocol in young adults, Weng et al. (2015) demonstrated that acute moderate-intensity exercise was effective in enhancing working memory capacity. Similarly, in a young and older adult sample, Hogan et al. (2013) demonstrated that acute moderate-intensity cycling exercise was effective in enhancing working memory for both age populations. In a young adult sample, recent work by Li et al. (2014) demonstrated that acute cycle exercise was associated with improvements in working-memory at the macro-neural level (increased brain activity), but not on the working memory behavioral level. In contrast to this, in an older adult sample, Tsujii et al. (2013) demonstrated that acute moderate-intensity cycle exercise was effective in enhancing both prefrontal cortex activity and working memory performance.

These discrepant findings of exercise intensity on working memory capacity warrants further investigation. Limited work on this topic has employed a within-subject design to assess multiple exercise intensities on working memory capacity. Thus, to improve clarity on this topic, here we employ a within-subject, counterbalanced randomized controlled trial to investigate if exercise intensity has a differential effect on memory capacity among a young adult sample. The primary outcome of interest was working memory, with a secondary outcome of interest being episodic memory. This was specifically evaluated, as previous theoretical discussions (McMorris, 2016; McMorris, Sproule, Turner, & Hale, 2011; McMorris, Turner, Hale, & Sproule, 2016) suggest that exercise intensity may have a differential effect on memory type, with high-intensity exercise possibly enhancing episodic memory (via activation of β-adrenoceptors in the hippocampus), whereas it may impair working memory (via dampened neuronal activity from excessive stimulation of D1-receptors and β-adrenoceptors). This aligns with our recent review of the literature on this topic (Loprinzi, 2018b). In alignment with previous discussions (Loprinzi, 2018b; McMorris, 2016; McMorris, Sproule, Turner, & Hale, 2011; McMorris, Turner, Hale, & Sproule, 2016), we hypothesize that there will be an inverted U-shaped relationship between exercise intensity and working memory capacity, with a linear association between exercise intensity and episodic memory function.

2. Methods

2.1. Study Design

This study was approved by the authors' institutional review board. Participants provided written consent prior to participating in this study. A total of 20 participants completed three visits (around the same time of day), with these visits occurring at least 48 hours apart. This is based from a power analysis indicating a sample size of 20 would be needed for sufficient power (η^2_p=0.23-0.29) (Etnier et al., 2016; Labban & Etnier, 2011). Further, our employed sample size is similar to other related research that has observed statistically significant effects of acute exercise on memory (Frith, Sng, & Loprinzi, 2017; Sng, Frith, & Loprinzi, 2018).

A counterbalanced, randomized controlled, within-subject design, was employed. The three counterbalanced visits included a control visit, moderate-intensity exercise (40% of HRR; heart rate reserve) and high-intensity exercise (70% of HRR) (Fahey, Insel, & Roth, 2015; Garber et al., 2011).

2.2. Participants

Participants included male and females from the ages of 18 to 35 yrs. Additionally, and similar to other studies (Haynes IV & Loprinzi, 2018; Yanes & Loprinzi, 2018), participants were excluded (to minimize confounding) if they:

- Self-reported as a daily smoker (Jubelt et al., 2008; Klaming, Annese, Veltman, & Comijs, 2016)
- Self-reported being pregnant (Henry & Rendell, 2007)
- Exercised within 5 hours of testing (Labban & Etnier, 2011)
- Consumed caffeine within 3 hours of testing (Sherman, Buckley, Baena, & Ryan, 2016)
- Took medications known to influence cognition (e.g., antiepileptic meds, Adderall, herbal remedies) (Ilieva, Hook, & Farah, 2015)
- Took medications used to regulate emotion (e.g., SSRI's) (Bauer, 2015)
- Had a concussion or head trauma within the past 30 days (Wammes, Good, & Fernandes, 2017)
- Had a diagnoses of ADHD (Hsu, Eastwood, & Toplak, 2017)
- Took marijuana or other illegal drugs within the past 30 days (Hindocha, Freeman, Xia, Shaban, & Curran, 2017)
- Were considered a daily alcohol user (>30 drinks/month for women; >60 drinks/month for men) (Le Berre, Fama, & Sullivan, 2017)

2.3. Recruitment

Participants were recruited by the student researcher using a non-probability convenience sampling approach at the authors' university (i.e., student researchers proposed the study to students enrolled in university courses and sampled via word-of-mouth).

2.4. Experimental Conditions

The control condition involved playing a medium-level, on-line administered, Sudoku puzzle. Participants completed this time-matched puzzle for 20-minutes prior to completing the memory tasks (described below). The website for this puzzle is located here: https://www.websudoku.com/

The two exercise conditions (moderate-intensity and vigorous-intensity) engaged in a 15-min bout of treadmill exercise, followed by a 5-min recovery period. The HRR equation used to evaluate exercise intensity was:

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

To calculate HR_{rest}, at the beginning of the visit, participants sat quietly for 5 minutes, and HR was recorded from a Polar HR monitor. To estimate HR_{max}, we calculated the participants estimated HR_{max} from the formula 220-age. For the moderate-intensity and vigorous-intensity exercise, respectively, 40% and 70% were entered into the above formula (Fahey, Insel, & Roth, 2015; Garber et al., 2011; Mayo-Clinic, 2018).

2.5. Memory Assessments

Two memory assessments were employed, including an episodic memory assessment followed by a working memory task. Difficulty level of these tasks were similar across all three experimental conditions (control, moderate-intensity exercise, and vigorous-intensity exercise).

2.5.1. Episodic Memory.

For the episodic memory assessment, participants listened to 15 words (from the Toronto Word Pool; combination of low and high imagery words), followed by a 10-sec delay, and then re-listened to these words. Immediately after listening to the list the second time, participants recalled as many words as possible. Following this, participants then engaged in the working memory task (described below). After the working memory task, for the 20-min delayed episodic memory assessment, participants then recalled as many words as possible from the word list. For each condition (control, moderate-intensity, and high-intensity), a different 15-item word list was employed.

2.5.2. Working Memory

The Brown-Peterson task was employed to assess working memory capacity. In the Brown-Peterson Task, the participant is presented with three letters at a rate of one letter per second. Following this is a series of delays where the participant is immediately given a two or three-digit random number from which the subject is asked to count backwards from, out-loud, by three's. After this, they then recall the letters that were presented prior to this arithmetic task.

For example, the subject would be presented with the letters "X C P" followed by the number "75". The subject would have 18 seconds to countdown by threes from 75. Once the 18 seconds has passed, the subject would be asked to recall the letters that had been presented prior to the countdown.

Five trials are given for each delay period, with the delay periods including 0, 9, 18 and 36 seconds. All five trials with 0 seconds of delay are presented first, followed by a random order for each of the five trials for the 9, 18, and 36 second delay. The dependent measure is the total number of letters that was correctly recalled at each of the delay intervals. The maximum score for each interval delay is 15.

This test has demonstrated adequate test-retest reliability by Struss et al. (Stuss, Stethem, & Poirier, 1987; Stuss, Stethem, Hugenholtz, & Richard, 1989) in both healthy subjects and individuals who had suffered a head injury. Providing evidence of sensitivity to change of the Brown-Peterson task, Coles and Tomporowski (2008) demonstrated that there was a significant main effect for time following pre- versus post-exercise ($F_{1,\ 17}$= 11.36; p<0.01; n2=0.40). The Brown-Peterson task has been shown to be valid in a study by Anil et al. (2003) in normal individuals where the task was positively correlated with Digit Span Backward scores at each of the delay intervals (r=0.54 to 0.57).

2.6. Additional Assessments

Various behavioral and psychological assessments were completed (at the beginning of the visit) to ensure that conditions were similar on these parameters (to minimize potential confounding). To assess mood status, which may influence working memory capacity (Storbeck & Maswood, 2016), participants completed the Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988), For this mood survey, participants rated 20 items (e.g., excited, upset, irritable, attentive) on a Likert scale (1, very slightly or not at all; to 5, extremely), with half of the items constituting a "positive" mood state, with the other half being a "negative" mood state. As a measure of habitual physical activity behavior, and reported as time spent per week in moderate-to-vigorous physical activity (MVPA), participants also completed a survey (Physical Activity Vital Signs Questionnaire) (Ball, Joy, Gren, & Shaw, 2016). To provide anthropometric characteristics of the sample, body mass index was calculated from measured height and weight. Lastly, before, during and after the exercise and control conditions, heart rate (chest-strapped Polar monitor, F1 model) and rating of perceived exertion (RPE, range 6-20) were assessed.

2.7. Statistical Analysis

Analysis were computed using SPSS (v. 24). To examine the effect of exercise intensity on working memory, a 3 (conditions) x 4 (delay period of 0, 9, 18, 36 seconds) repeated measures ANOVA was computed. For the episodic memory task, a 3 (condition) x 2 (time; immediate vs. delay) factor repeated measures ANOVA was employed. Statistical significance was established as a nominal alpha of 0.05. Partial eta-squared (η^2_p) effect size estimates were calculated.

3. Results

Table 1 displays the demographic characteristics of the participants. Participants, on average, were 20.8 years, predominately female (65%), and were of varied race-ethnicity backgrounds (55% white, 25% black, and 20% other).

Table 2 displays the physiological and psychological parameters across the three experimental conditions. Psychological-related affective state (positive/negative affect) was similar at the beginning of each of the three experimental conditions. Resting heart rates (around 80 bpm) and resting RPE (6.0) was similar across all three experimental conditions. As expected, both exercise heart rate and exercise RPE were substantively different across the conditions. For the 40% condition, heart rate and RPE, respectively, increased to 129 bpm and 10.9. For the 70% condition, heart rate and RPE, respectively, increased to 167.4 bpm and 13.2.

Tablo 1. Characteristics of the study variables (N = 20).

Variable	Point Estimate	SD
Age, mean years	20.8	1.8
% Female	65.0	
Race-Ethnicity, %		
White	55.0	
Black	25.0	
Other	20.0	
BMI, mean kg/m2	27.6	6.5
% Right-handed	80.0	
MVPA, mean min/week	200.2	124.9

BMI, Body mass index
MVPA, Moderate to vigorous physical activity

Table 2. Physiological and psychological parameters across the three experimental conditions

	Control	40% HRR	70% HRR
Baseline Affect, mean			
Positive	26.5 (10.2)	28.0 (10.4)	26.3 (11.0)
Negative	11.5 (3.6)	11.1 (1.4)	12.1 (3.4)
Heart Rate, mean			
Baseline	80.7 (9.4)	78.3 (12.3)	77.9 (8.5)
Mid-Exercise	81.5 (8.2)	126.0 (13.6)	159.7 (7.8)
End-Exercise	80.3 (8.1)	129.0 (11.4)	167.4 (11.3)
5-Min Post Exercise	79.6 (8.3)	85.7 (13.2)	98.1 (10.8)
RPE, mean			
Baseline	6.0 (0.0)	6.1 (0.3)	6.0 (0.0)
Mid-Exercise	6.0 (0.0)	10.1 (1.8)	11.7 (2.0)
End-Exercise	6.0 (0.0)	10.9 (1.6)	13.2 (1.6)
5-Min Post Exercise	6.0 (0.0)	6.0 (0.0)	6.4 (0.8)

RPE, Rating of Perceived Exertion
Variance estimates are standard deviations

Table 3 displays the results for the episodic memory and working memory assessments across the three experimental conditions. Immediate memory recall was similar across the three conditions (8.5-8.7 words). However, for the 20-min delay period, the 70% condition had a higher word recall score than the two other conditions (5.7 vs. 4.9). Statistically, the main effect for condition (exercise intensity) was not significant (F=0.74, P=0.48, and η^2_p=0.04), but the main effect for time was statistically significant (F=101.2, P<0.001, η^2_p=0.84). The condition x time interaction effect was not statistically significant (F=1.01, P=0.37, η^2_p=0.05). A visual schematic of the episodic memory performance across the three experimental conditions is displayed in Figure 1.

Table 3 also displays the results for the working memory

Table 3. Episodic memory and working memory scores across the three experimental conditions.

	Control	40% HRR	70% HRR
Episodic Memory, mean words recalled			
Immediate Recall	8.5 (1.7)	8.5 (2.1)	8.7 (1.4)
20-Min Delay	4.9 (2.5)	4.9 (2.3)	5.7 (2.1)
Working Memory, mean number correct			
0-sec delay	15.0 (0.0)	15.0 (0.0)	15.0 (0.0)
9-sec delay	12.7 (2.5)	11.8 (2.6)	12.2 (2.6)
18-sec delay	11.1 (2.6)	10.1 (3.1)	11.9 (2.3)
36-sec delay	10.9 (2.8)	10.9 (3.6)	12.5 (2.2)

Variance estimates are standard deviations

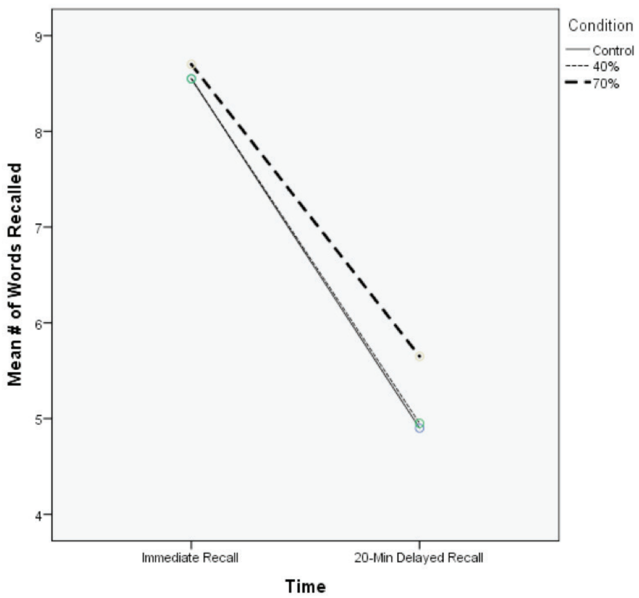

Figure 1. Episodic memory performance across the three experimental conditions.

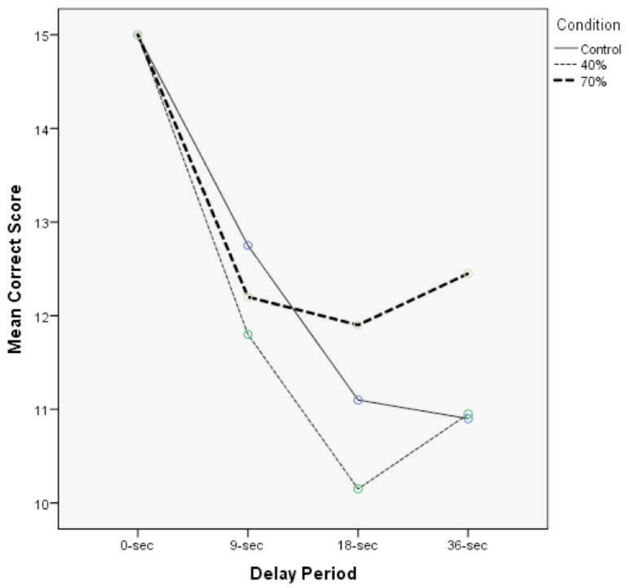

Figure 2. Working memory performance scores across the three experimental conditions.

performance scores across the different experimental conditions. For the working memory task, there was a statistically significant main effect for condition (F=4.3, P=0.02, η^2_p =0.18), main effect for delay period (F=30.6, P<0.001, η^2_p=0.61), and condition x delay period interaction effect (F=2.97, P=0.01, η^2_p =0.14). A visual schematic of the working memory performance scores across the three experimental conditions is displayed in Figure 2.

4. Discussion

The primary purpose of this study was to examine the experimental effects of exercise intensity on memory function. As noted in the introduction section, this is a growing area of research interest in the exercise neurobiology community. There is mechanistic support, from both a biological and psychological perspective, for optimal memory capacity occurring from different exercise intensity levels, and such intensity effects to possibly differentially influence memory type. There are also discrepant results in both animal and human studies regarding the optimal intensity level to enhance memory capacity (as noted in the Introduction). Further, the majority of work on this topic has employed between-subject designs. Couched within all of these factors, the purpose of our study was to employ a within-subject design to shed light on whether there is an optimal exercise intensity to enhance memory capacity, and whether this varies based on memory type. Our main finding was that high-intensity exercise was more effective in enhancing working memory function, particularly for the longest duration working memory trial (36-sec delay). Although not statistically significant, we also observed some evidence of a better episodic memory performance for the high-intensity exercise condition. Thus, our findings do not align with our initial a-priori hypotheses of, in particular, an inverted U-shaped relationship between exercise intensity and working memory function.

As stated recently, "*few studies examining the effects of heavy exercise on working memory have been undertaken* (p. 89),"(McMorris, Turner, Hale, & Sproule, 2016) and similarly, "*…studies comparing performance during heavy exercise with that during moderate intensity exercise are limited in number* (p.89)" (McMorris, Turner, Hale, & Sproule, 2016). This underscores the novelty of our study. As discussed elsewhere (McMorris, 2016), high-intensity exercise will increase norepinephrine release, activating α1- and β-adrenoreceptors, and in turn, reduce neuronal firing in the prefrontal cortex, thereby attenuating the signal-to-noise ratio. However, as discussed previously (McMorris, 2016), not all studies demonstrate impaired working memory from high-intensity exercise. Other studies also provide suggestive evidence that acute high-intensity exercise may enhance working memory (Hwang, Castelli, & Gonzalez-Lima, 2016; Lo Bue-Estes et al., 2008), which aligns with the findings of the present experiment. Also aligning with our episodic memory findings, recent work suggests that high-intensity exercise is also facilitative in subserving episodic memory function (Frith, Sng, & Loprinzi, 2017).

Of notable interest, for our working memory results, the high-intensity bout of exercise, compared to moderate-intensity or the control condition, had an enhanced effect for the longer delay periods (18-sec and 36-sec). This suggests that, although speculative, higher-intensity exercise may have a more enhanced effect on working memory for a more challenging executive function component. Future work is needed to confirm our findings, as well as this speculated possibility. It is also possible that, perhaps, our enhanced working memory results from the high-intensity exercise may be attributed to the current sample. Our sample was fairly active (200 min/week of MVPA; SD, 125). Thus, it seems reasonable that a high-intensity acute bout of exercise may have a more enhanced effect among those who habitually engage in high-intensity exercise. Notably, however, we computed additional analyses to see if habitual exercise engagement played a moderating role in our observations. No significant interactions effects, however, were observed. Future work should consider observing whether cardiorespiratory fitness moderates the effects of exercise intensity on memory function. Although not specifically evaluating this, recent meta-analytic work (Roig, Nordbrandt, Geertsen, & Nielsen, 2013) suggests that fitness level does not influence the effects of acute exercise on short-term memory, with some suggestive evidence that average fitness levels show the largest effects on long-term memory. Additional work is needed to evaluate whether fitness moderates the effect of acute exercise intensity on memory type.

In conclusion, we provide evidence that acute high-intensity aerobic exercise is optimally associated with working memory, with suggestive evidence that it is also more optimally associated with episodic memory function. Future confirmatory work is needed to evaluate whether an intensity-specific effect occurs for different memory types and whether various factors (e.g., fitness level) moderate this effect.

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