Neurobiology of Learning and Memory 167 (2020) 107128

Contents lists available at ScienceDirect

Neurobiology of Learning and Memory

journal homepage: www.elsevier.com/locate/ynlme

The effects of different protocols of physical exercise and rest on long-term memory

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ARTICLE INFO

Keywords:
High intensity interval training (HIIT)
Continuous exercise
Exercise intensity
Wakeful rest
Consolidation
Cognitive enhancement

ABSTRACT

Whilst there are many studies comparing the different effects of exercise on long-term memory, these typically adopt varying intensities, durations, and behavioural measures. Furthermore, few studies provide direct comparisons between exercise and different types of rest. Therefore, by providing a standardised methodological design, this study will ascertain the most effective intensity and protocol of exercise for the modulation of long-term memory, whilst directly comparing it to different types rest. This was achieved using the same old/new recognition memory test and an 80–90 min retention interval. Three experiments were performed (total N = 59), each with a three-armed crossover design measuring the extent to which physical exercise and wakeful rest can influence long-term memory performance. In Experiment 1, the effects of continuous moderate intensity exercise (65–75% HR_{max}), passive rest (no cognitive engagement) and active rest (cognitively engaged) were explored. In Experiment 2, continuous moderate intensity exercise was compared to a type of high-intensity interval training (HIIT) and passive rest. Experiment 3 observed the effects of low- (55–65% HR_{max}), moderate- and high-intensity (75–85% HR_{max}) continuous exercise. Across the three experiments moderate intensity exercise had the greatest positive impact on memory performance. Although not significant, HIIT was more effective than passive-rest, and passive rest was more effective than active rest. Our findings suggest that it is not necessary to physically overexert oneself in order to achieve observable improvements to long-term memory. By also investigating wakeful rest, we reaffirmed the importance of the cognitive engagement during consolidation for the formation of long-term memories.

1. Introduction

Due to advancements in medical technologies and medicine, it is thought that global life expectancy will increase substantially within the coming decades. With age being a significant risk factor for neurodegenerative diseases, such as Alzheimer's Disease (AD), it is of vital importance that research into preserving cognition in older age is not ignored. This research should provide methods that are affordable and easily accessible for both the state and the individual. There is much evidence to support the notion that aerobic physical exercise (PE) has beneficial effects on cognition as a whole (Kramer & Colcombe, 2018; Voelcker-Rehage & Niemann, 2013) for a model, see (Stimpson, Davison, & Javadi, 2018). Current research observes the positive effects of PE on various aspects of memory at different age groups, from young to older adults (Erickson et al., 2011). The growing body of research hopes to encourage the population to partake in frequent exercise as a protective measure against neurodegenerative diseases (Paillard, Rolland, & de Souto Barreto, 2015). Another method shown to benefit cognition, somewhat markedly different to PE, is wakeful rest. Short periods of wakeful rest have been shown to increase performance in a wide range of memory domains (Alber, Sala, & Dewar, 2014; Craig & Dewar, 2018; Craig, Dewar, Harris, Della Sala, & Wolbers, 2016; Dewar, Alber, Butler, Cowan, & Della Sala, 2012). It would therefore be of interest to investigate whether PE promotes greater memory performances than wakeful rest and if so, what the most beneficial protocol of PE is. Here, we investigate this question using two types of PE (namely continuous and interval-training), differing intensities of PE and wakeful rest.

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https://doi.org/10.1016/j.nlm.2019.107128
Received 28 April 2019; Received in revised form 10 November 2019; Accepted 23 November 2019

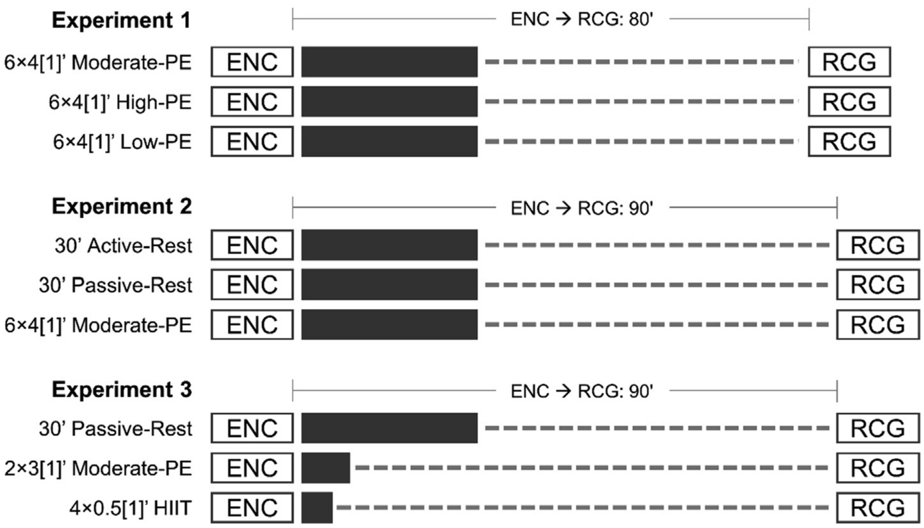

Fig. 1. Summary of different intervention conditions for the three experiments. ENC: Encoding. RCG: Recognition. PE: continues physical exercise. HIIT: High-Intensity Interval Training. Black bars: Visual representation of the intervention duration. Dashed lines: Retention Interval. x[y]': x duration of each block of physical exercise (min), y rest in between the blocks (min). Intervention order was randomised for all experiments.

When observing the current research on PE, the primary focus has been on the effect that continuous, moderate-intensity PE has on cognition, with strong evidence in support (Erickson et al., 2011; Håkansson et al., 2017; Rojas Vega et al., 2006; Statton, Encarnacion, Celnik, & Bastian, 2015). When measuring the impact of different intensities of PE on cognition, mixed results have been found. A study testing associative memory found moderate intensity exercise to yield greater results compared to high-intensity, both 2 h after the exercise intervention and 3 months later (Marin Bosch et al., 2018). Conversely, Hötting and colleagues (Hötting, Schickert, Kaiser, Röder, & Schmidt-Kassow, 2016) found a continuous higher intensity exercise condition to yield better performance than moderate and rest conditions on a word recall task. Relatively unexplored in its relation to cognition is high-intensity interval training (HIIT). HIIT can be defined as anaerobic, short, repeated bursts of high-intensity exercise, typically between 15 s and 4 min, separated by periods of rest of a similar time (Astorino & Schubert, 2018; Keating, Johnson, Mielke, & Coombes, 2017; Ramos, Dalleck, Tjonna, Beetham, & Coombes, 2015). Research has shown HIIT can provide cardiovascular improvements similar to continuous exercise training, but with far less time required (Burgomaster, 2005; Helgerud et al., 2007; Roy, 2013), giving hope for those with busy schedules and little time for typical exercise regimens. One study by Winter and colleagues (Winter et al., 2007) found a bout of HIIT to speed up vocabulary learning by 20%. HIIT protocols have also been shown to improve both motor learning memory and high-interference memory (Heisz et al., 2017; Roig, Skriver, Lundbye-Jensen, Kiens, & Nielsen, 2012).

It is also important not to overlook the importance of rest in studies of memory, with evidence suggesting wakeful rest to be beneficial for memory performance (Craig & Dewar, 2018; Craig et al., 2016). Alber et al. (2014) showed that wakeful rest with minimal sensory stimulation led to 73% more amnesic participants recalling > 30% of a prose, compared to those who completed a cognitive task during wakeful rest (Alber et al., 2014). Many other studies have found similar conditions of wakeful rest to improve recall even when tested 7 days later. It is suggested that a period of cognitive disengagement is vital for the consolidation of newly learned stimuli and interruption of this process can cause new memory traces to be overlooked in favour of another task (Alber et al., 2014; Dewar et al., 2012; Kuschpel et al., 2015).

To measure whether PE and wakeful rest were beneficial to memory performance, we conducted three experiments, each employing similar cognitive methods throughout, to provide a standardised evidence base for the most effective protocol. This study focused on two types of wakeful rest: passive rest and active rest. Passive rest is a period of rest that does not include any overt sensory or motor activity. Active rest is a period of rest that includes one or more cognitively stimulating tasks alongside physical rest, such as listening to music, playing video games, or scrolling through various social media outlets. Active rest is aimed to replicate the mild form of interference we are subject to on a daily basis (Wamsley, 2019).

In the first experiment, the effects of three different continuous exercise intensities (low, moderate, high) on long-term memory were compared using an old/new recognition task. In the second experiment, the most effective exercise intensity from the first experiment was chosen and measured against both active (cognitive engagement task) and passive (no task employed) rest. The third experiment compares the effects of the most effective continuous exercise intensity from the first experiment, against the most effective type of wakeful rest from the second experiment, and a type of high-intensity interval training (HIIT).

2. Methods

2.1. Participants

A total of 59 participants took part in three experiments. Participants were allocated to only one of the three experiments. Experiment 1 compared different intensities of continuous exercise (n = 19, 11 females, age mean[SD] = 21.85[2.43]). Experiment 2 compared different types of rest conditions with moderate continuous exercise (n = 17, 10 females, age mean[SD] = 9.77[1.27]). Experiment 3 compared moderate continuous exercise with a type of HIIT and passive rest (n = 23, 20 females, age mean [SD] = 19.62[1.51]). All participants were naive to the aim of the study, spoke fluent English, and had normal or corrected-to-normal vision. Participants were screened to exclude those with a history of neurological or psychiatric disorders, and no participant was taking centrally-acting medication. All participants gave their written informed consent, and the study was given ethical approval by the Psychology Research Ethical Committee, University of Kent.

2.2. Study design

All experiments followed a within subject design consisting of three conditions. Fig. 1 summarises the conditions and duration of the three experiments. Each experimental session comprised an encoding phase, an intervention phase, a retention interval and a recognition phase. Each participant took part in all three conditions of one experiment in random order, with the sessions taking place seven days apart. Participants watched episodes of the American sitcom “Friends” during the retention interval. This sitcom was chosen based on a survey conducted prior to the study (Javadi, Cheng, and Walsh (2012). The survey indicated that a large majority of participants know and like this sitcom. In the recognition phase, participants were asked to perform an old/new recognition task. Fig. 1 summarises the protocols for each condition of each experiment.

Prior to each experimental session (encoding and recognition), participants were asked to complete Stanford Sleepiness Scale to have a measure of their alertness (Hoddes et al., 1972; Maclean, Fekken, Saskin, & Knowles, 1992). The scale ranged between 1 (fully alert) and 6 (almost asleep).

3. Materials

A collection of 480 image-word pairs of common objects were created. A set of 160 pairs was randomly selected for each experimental session. Our pilot study (n = 30) showed that this number of word pairs, with the given duration of presentation and inter-trial-intervals, results in a good performance after 60–90 min post encoding. The images used in one session were unique to that session and not presented again to the same participant during the subsequent sessions in order to avoid interference. The experiment was run on a desktop computer with a 17-inch monitor. Stimulus presentation and the recording of response time were achieved using MATLAB (v2015b; MathWorks Company, Natick, MA) and the Psychtoolbox v3 (Brainard, 1997).

3.1. Behavioural tasks

The encoding phase consisted of the presentation of 80 image-word pairs. Participants were asked to memorise the objects for a later old/new recognition task. This task has been widely used in the studies of long-term memory (Diana, Reder, Arndt, & Park, 2006; Finnigan, Humphreys, Dennis, & Geffen, 2002; Gehring, Toglia, & Kimble, 1976; Javadi & Cheng, 2013; Javadi et al., 2012; Javadi & Walsh, 2012; Shepard, 1967) and was therefore deemed reliable and appropriate for use. They were instructed to memorise the concept of the image rather than the actual image, as different images of the same concept were presented in the encoding and recognition phases. In each trial, image-word pairs were presented for 1 s followed by a 2 s fixation cross.

In the recognition phase, 160 image-word pairs were presented in random order. The pairs consisted of the 80 image-word pairs presented in the encoding phase (Old stimuli) and 80 new image-word pairs (New stimuli). The image-word pair was presented on the screen until a response from the participant was given. Participants were asked to indicate which stimulus is Old and which stimulus is New. Participants were asked to respond as accurately and as fast as possible.

3.2. Interventions

Throughout the experiments, the interventions were administered immediately after encoding: continuous exercise with three different intensities (low, moderate, high), a type of high-intensity interval training (HIIT), and two types of wakeful rest (active-rest, passive-rest), Fig. 1.

Continuous exercise consisted of six blocks. Each block encompassed 4-min cycling on an ergonomic exercise bike (Stages SC3 Indoor Cycle, Stages Cycling, US) and 1-min of rest, for a total duration of 30 min. Participants were given a speed range (60–70 rpm, 65–75 rpm, 70–80 rpm) at the beginning of each block and were asked to keep their speed within that speed range. Cycling speed range was randomised to ensure that long-term memory performance was not influenced by a specific cycling speed but rather by the heart rate zone that indicates the predefined exercise intensity. The resistance of the bike was adjusted manually based on the participant's maximum heart rate (HR_{max}) and their condition: low-intensity 55–65% HR_{max}, moderate-intensity between 65 and 75% HR_{max}, and high-intensity between 75 and 85% HR_{max}. HR_{max} was calculated based on the age-predicted maximal heart rate equation developed by Tanaka and colleagues: $HR_{max} = 208 - (0.7 \times \text{age})$ (Tanaka, Monahan, & Seals, 2001). Heart rate was monitored using a Mio Fuse Heart Rate Monitor (Mio Global, US). Participants were given 2 min to warm up and cool down with their desired speed and intensity.

The *HIIT* condition employed in this study consisted of four blocks of 30 s cycling and 1-min rest, for a total duration of 6 min. Participants were instructed to cycle as fast as possible throughout the cycling period. The four blocks of 30 s cycling were decided based on a pilot study in which participants in two separate sessions (n = 21) were asked to cycle for six blocks of 30 s as fast as possible or cycle for two blocks of 3-min with moderate-intensity. Two blocks of 3-min of moderate-intensity exercise was calculated based on our previous data from Experiment 1. Four blocks of 30 s HIIT resulted in a similar total energy expenditure as the two blocks of 3-min moderate-intensity exercise (mean[SD] HIIT = 25.476[8.829], moderate-intensity = 27.666[9.355], t(20) = 1.182, $p = 0.251$).

The *active-rest* condition contained a cognitive task simulating the speed thresholds on the continuous exercise condition. Participants were required to monitor and maintain a fluctuating number displayed on the monitor within a certain range. Similar to the continuous exercise condition, this condition consisted of six blocks of a 4-min task and 1-min rest, for a total duration of 30 min. At the beginning of each block, a range (60–70, 65–75, 70–80) was given to the participant in random order. Their task was to monitor and keep the fluctuating number displayed on the monitor within that range: press down or up arrow-key when the number went above or below the range, respectively.

In the *passive-rest* condition, participants were asked to sit quietly and comfortably on a chair for 30 min with their eyes open to ensure that they did not fall asleep. This type of rest condition was chosen as it has been shown to significantly reduce interference (Craig & Dewar, 2018; Dewar, Alber, Cowan, & Sala, 2014). Participants were regularly monitored so as to ensure they did not fall asleep. At the end of the session (after the recognition phase) they were asked what they did during the rest period to identify whether they rehearsed the stimuli or not. Participants who rehearsed (n = 3 for Experiment 1 and n = 1 for Experiment 2) were excluded from the analysis.

3.3. Statistical analysis

Data analysis were performed using SPSS (v19; LEAD Technologies, Inc, Charlotte, NC). Accuracy for the recognition of the old and new words were analysed separately. Using signal detection theory, d' values are also reported. One-way repeated measures of analysis of variance (rANOVA) was used to investigate the main effect of condition with percentage accuracy in recognition and reaction time for the old and new words. Significant threshold of $p < 0.05$ was chosen. Following significant main effect of condition, post-hoc paired-sample t-tests were run to investigate the difference between groups. False discovery rate (FDR) was used for correction for multiple comparisons for post-hoc tests.

4. Results

Table 1 summarises the descriptives for the three experiments. Six separate rANOVA were run, Table 2. These analyses showed significant main effect of condition for the recognition accuracy of the Old words (p's < 0.026, η_p^2's > 0.154), but not New words (p's > 0.095). No effect was observed for the reaction time (p's > 0.191). Post-hoc comparisons between conditions in different experiments showed significant superior performance for the Moderate condition compared to High ($p = 0.002$, $d = 0.847$), Active-Rest ($p = 0.006$, $d = 0.774$) and Passive-Rest ($p = 0.011$, $d = 0.579$), and marginally significant difference with Low ($p = 0.037$, $d = 0.518$; FDR corrected). Table 3 and

Table 1

Summary of the descriptives of the three experiments (mean[SD]) split over old and new words, and the three conditions in each experiment.

Experiment	Measure	Condition	Old Words	New Words	d′
Exp. 1	Accuracy	Moderate	88.496[1.596]	92.782[1.512]	2.834[1.085]
		High	82.105[2.498]	92.030[1.383]	2.481[1.161]
		Low	82.481[3.032]	92.932[1.611]	2.515[1.011]
	RT	Moderate	1.390[0.077]	1.738[0.124]	
		High	1.427[0.090]	1.784[0.147]	
		Low	1.561[0.107]	1.938[0.179]	
Exp. 2	Accuracy	Moderate	81.985[2.874]	88.824[3.063]	2.552[1.232]
		Active-Rest	75.294[3.287]	84.926[3.102]	2.081[1.099]
		Passive-Rest	77.794[3.614]	90.074[2.553]	2.235[1.183]
	RT	Moderate	1.344[0.089]	1.628[0.109]	
		Active-Rest	1.530[0.138]	2.069[0.422]	
		Passive-Rest	1.407[0.164]	1.694[0.191]	
Exp. 3	Accuracy	Moderate	77.337[2.630]	83.859[3.011]	1.978[1.103]
		HIIT	74.348[2.485]	84.620[2.363]	1.773[0.829]
		Passive-Rest	71.467[2.076]	82.717[2.614]	1.779[0.830]
	RT	Moderate	1.219[0.063]	1.400[0.075]	
		HIIT	1.354[0.100]	1.428[0.085]	
		Passive-Rest	1.317[0.100]	1.393[0.103]	

Notes: RT stands for reaction time. Low, Moderate and High indicate low-, moderate- and high- continuous exercise, respectively. HIIT refers to high-intensity interval training.

Fig. 2 summarise post-hoc comparisons between different intervention conditions. Re-running the analysis using d’ did not alter the results.

Ratings of Stanford Sleepiness Scale were also analysed. All the ratings were between 1 and 3 in all experimental sessions in all studies. Three 3 × 2 rANOVA were run on the ratings for the three studies with condition and session (encoding/recognition) as within subject factors. These analyses showed no significant main or interaction effect (p’s > 0.30).

5. Discussion

The aim of this investigation was to investigate whether varying intensities of exercise or different types of rest could directly affect performance on a recognition memory test. Results from all three experiments suggest that continuous moderate-intensity exercise has the greatest positive influence on an old/new recognition task compared to other protocols (continuous, low- and high-intensity/HIIT/passive- and active-rest). Additionally, although not significant, data showed a trend of better memory performance following passive-rest compared to active-rest (Experiment 2), and HIIT compared to passive-rest (Experiment 3).

5.1. Cognitive improvement

It has been shown that hippocampal replay, the process of strengthening previously experienced stimuli, is most effective during an awakened, relatively immobile state (Carr, Jadhav, & Frank, 2011). This process occurs immediately following presentation of stimuli with previous research showing 0–10 min to be the most crucial time period for optimum consolidation (Alber et al., 2014; Craig & Dewar, 2018; Craig et al., 2016; Dewar et al., 2012; Dewar et al., 2014). By using non-recallable, fabricated words, Dewar et al. (2014) showed that during wakeful rest, increases in memory performances could not be attributed to intentional learning or recall, therefore consolidation must be the focal process. This suggests that the cognitive engagement task presented in the active-rest condition likely inhibited consolidation of the recently learnt stimuli (Dewar et al., 2012, 2014; Kuschpel et al., 2015).

The results obtained from this study provide an interesting addition to the current literature on the impact that HIIT has on cognition. On average, our data showed that the HIIT condition yielded higher performance scores on the old/new recognition task, however, statistically, the difference in performance was non-significant. This finding falls in line with the current literature when considering the length of the retention interval used in this study. Previous studies suggest that with higher intensity exercise protocols, temporal proximity may play a key role.

Hötting et al. (2016) found that those who participated in a high-intensity exercise condition (80% HR_{max}) recalled more words than those in other conditions (low intensity; rest), but only after 24 h. Initially, when tested 20 min after the exercise intervention, those in the rest condition achieved better results than those in the two experimental conditions of low and high intensity exercise. A meta-analysis by Chang, Labban, Gapin, and Etnier (2012) showed that effects of exercise had a negative impact on results in a memory test, compared to rest groups, if tested within 20 min of ceasing physical exercise. It appears that with high-intensity exercise, the longer the delay between exercise and testing, the better the results achieved on the recall task. In many cases, scores obtained immediately after high-intensity exercise have been lower than those in the control/rest conditions. This suggests that the time in which the recall task is executed following exercise is key, as consolidation of stimuli is highly sensitive to external influences, whether physiological (exercise), or psychological (engagement

Table 2

Summary of the rANOVA for each experiment separated for old and new words, and performance accuracy (Acc) and reaction time (RT).

Experiment	Measure	Old Words	New Words
Exp. 1	Acc	$F(2,36) = 4.503, p = 0.018, \eta_p^2 = 0.200$*	$F(2,36) = 0.299, p = 0.743, \eta_p^2 = 0.016$
	RT	$F(2,36) = 1.732, p = 0.191, \eta_p^2 = 0.088$	$F(2,36) = 1.266, p = 0.294, \eta_p^2 = 0.066$
Exp. 2	Acc	$F(2,32) = 4.621, p = 0.017, \eta_p^2 = 0.224$*	$F(2,32) = 2.540, p = 0.095, \eta_p^2 = 0.137$
	RT	$F(2,32) = 1.206, p = 0.313, \eta_p^2 = 0.070$	$F(2,32) = 1.111, p = 0.341, \eta_p^2 = 0.065$
Exp. 3	Acc	$F(2,44) = 3.991, p = 0.026, \eta_p^2 = 0.154$*	$F(2,44) = 0.560, p = 0.575, \eta_p^2 = 0.025$
	RT	$F(2,44) = 0.889, p = 0.418, \eta_p^2 = 0.039$	$F(2,44) = 0.114, p = 0.892, \eta_p^2 = 0.005$

* $p < 0.05$.

Table 3
Summary of the post-hoc paired-sample t-tests for the performance on the old words for each experiment.

Experiment	Comparison	t	p	Cohen's d	95% CI
Exp. 1	Moderate vs High	t(18) = 3.691	$p = 0.002^{*}$	$d = 0.847$	2.590–9.439
	Moderate vs Low	t(18) = 2.256	$p = 0.037^{\dagger}$	$d = 0.518$	0.439–12.342
	High vs Low	t(18) = 0.148	$p = 0.884$	$d = 0.034$	−4.961–5.713
Exp. 2	Moderate vs Active-Rest	t(16) = 3.190	$p = 0.006^{*}$	$d = 0.774$	2.244–11.137
	Moderate vs Passive-Rest	t(16) = 2.073	$p = 0.055$	$d = 0.503$	-0.095–8.478
	Active Rest vs Passive-Rest	t(16) = 0.992	$p = 0.336$	$d = 0.241$	−2.843–7.843
Exp. 3	Moderate vs HIIT	t(22) = 1.573	$p = 0.130$	$d = 0.328$	-0.951 –6.930
	Moderate vs Passive-Rest	t(22) = 2.775	$p = 0.011^{*}$	$d = 0.579$	1.482–10.256
	HIIT vs Passive-Rest	t(22) = 1.306	$p = 0.205$	$d = 0.272$	−1.692–7.453

* $p < 0.011$ significant corrected for multiple comparison using false discovery rate (FDR).

† Marginally significant based on FDR; CI: Confidence Interval; Low, Moderate and High indicate low-, moderate- and high- continuous exercise, respectively; HIIT refers to high-intensity interval training.

tasks). To the best of our knowledge, no study has investigated the effects of post-encoding HIIT on long-term memory. However, a study by Kao and colleagues (2018) investigated the immediate and delayed effects of pre-encoding HIIT and moderate-intensity continuous exercise on memory. Their findings suggest that acute bouts of HIIT can enhance memory performance for both immediate and delayed recall tasks compared to rest (Kao, Drollette, Ritondale, Khan, & Hillman, 2018).

The effects of acute physical exercise on memory and cognition has attracted considerable attention over the last decade (Stimpson et al., 2018). Accordingly, this line of research prompted many debates, largely as a consequence of inconsistencies in the methods used across studies. This includes inconsistencies in exercise duration, exercise intensity, type of exercise, onset (pre- or post-encoding) and temporal proximity of exercise relative to encoding. The exercise-memory relationship is complex and robustly influenced by such variability, including memory type. For example, using the protocols of this study to test procedural memory (rather than declarative memory) is likely to yield different results. A study by Thomas et al. (2016) showed that 15 min of high-intensity exercise after learning a visuomotor accuracy tracking task led to enhancements in motor skill retention compared to low-intensity cycling and control groups. The use of motor skills engages the non-declarative, long-term procedural memory domain without any conscious awareness. They suggested that after motor skill training, physical exercise intensity may be key to stimulating certain mechanisms that can trigger the memory consolidation process. They also proposed a possible dose-response relationship in favour of higher physical exercise intensities for enhancing procedural memory.

Several mechanisms may exist by which exercise can induce memory enhancement (for reviews see (Loprinzi, Edwards, & Frith, 2017; Loprinzi, Ponce, & Frith, 2018; Stimpson, Davison, & Javadi, 2018)). Recently, Loprinzi (2019a) evaluated the level of influence that physical exercise may have on long-term potentiation (LTP), which is considered to be an important correlate of episodic memory. They showed that despite the variability in physical exercise protocols, there was consistent evidence showing that chronic physical exercise may enhance LTP in animal models. There was also evidence suggesting that acute physical exercise may enhance LTP in humans, although further work is needed to determine whether the duration of physical exercise – be it acute or chronic – has a differential effect on LTP (Loprinzi, 2019a). Based on the findings across both populations, Loprinzi summarised that physical exercise strongly influences LTP. Additionally, in another review, Loprinzi (2019b) discusses the potential role that glial cells may have in the physical exercise-episodic memory function relationship. The review suggests that physical exercise may increase astrocytic size and increase the expression of a specific integral membrane protein (among others), which in turn, may increase the number of synapses, synaptic structures, and pre- and postsynaptic receptor localisation and, ultimately, influence LTP and memory function (Loprinzi, 2019b).

There is also a well-documented neurophysiological explanation (Stimpson et al., 2018). It has been shown that physical exercise initiates the release of brain-derived neurotrophic factor (BDNF; Hötting et al., 2016; Huang, Larsen, Ried-Larsen, Møller, & Andersen, 2014; Schmolesky, Webb, & Hansen, 2013), which has been shown to be vital for neurogenesis, the maturation and protection of neurons (Bathina & Das, 2015) and neural plasticity (Marin Bosch et al., 2018; Tyler, Alonso, Bramham, & Pozzo-miller, 2002). A higher concentration of BDNF is positively associated with increased hippocampal volume, which is in turn, associated with improved spatial memory (Erickson et al., 2011; for a comprehensive recent review of how BDNF mediates the effects of exercise on memory, see (Loprinzi, 2019)). Further evidence for this is provided in a review by Stimpson et al. (2018) in which they propose a model containing several other short-term effects of PE

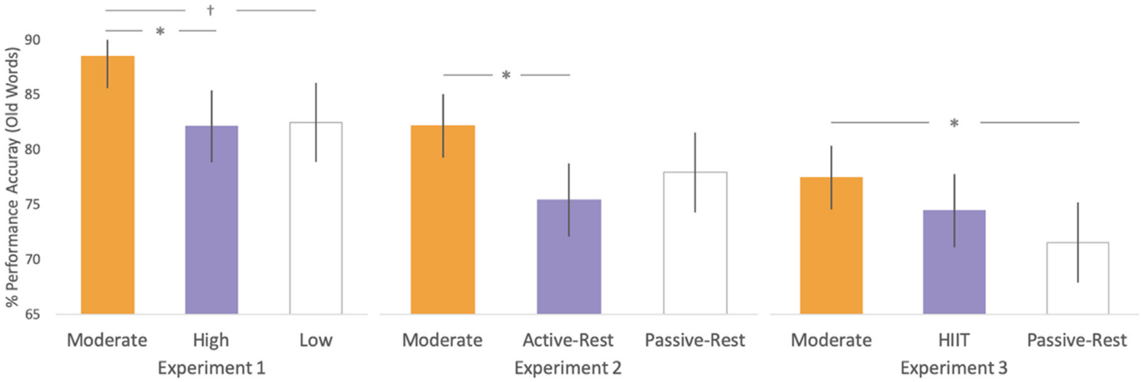

Fig. 2. Performance accuracy for the three experiments split over different conditions. *$p < 0.011$ significant corrected for multiple comparison using false discovery rate (FDR); $^{\dagger}p = 0.037$ marginal significant based on FDR. Error bars represent one standard error of the mean.

on cognition. Increased serum BDNF, serum vascular endothelial growth factor (VEGF), neuronal insulin-like growth factor 1 (IGF-1) uptake and hippocampal VEGF expression all make a cumulative contribution to brain plasticity, which ultimately produces cognitive benefits. Serum BDNF has also been shown to increase significantly following a short bout of high-intensity exercise, although levels drop considerably faster after ceasing (6 min) than a longer bout of continuous exercise (Rojas Vega et al., 2006).

5.2. Cognitive impairment

Potential reasons for short-term decline in cognitive abilities following acute high-intensity exercise may be attributed to the endocrine system. Increased levels of cortisol are released into the brain by the adrenal glands in response to stressful situations in this instance, high-intensity exercise (physical stress; Rojas Vega et al., 2006; Wahl, Zinner, Achtzehn, Bloch, & Mester, 2010). High levels of cortisol are associated with a short-term decline in cognitive abilities (Newcomer et al., 1999; Ouanes et al., 2017). It has been shown that levels of cortisol are higher following intense exercise, but not moderate exercise (Budde et al., 2010; Wahl et al., 2010). Evidence suggests that any exercise exerting > 70% $VO2_{max}$ will facilitate secretion of cortisol in humans (Kirschbaum & Hellhammer, 1994). After cessation of intense exercise, cortisol levels can take between 2 and 4 h to return to the baseline level (Kirschbaum & Hellhammer, 1994). This may suggest that following high-intensity exercise, as cortisol levels are higher, memory is impaired until cortisol levels return to baseline. This notion falls in line with the current study's findings as the recognition task was conducted after only 1 h of completion of exercise. However, recent studies have shown that although acute exercise increases cortisol, increased cortisol does not modulate cognitive function related to working memory (Ponce, Del Arco, & Loprinzi, 2019; Wang et al., 2019). Interestingly, for those partaking in chronic exercise regimes, an increase in basal cortisol levels, typically associated with an increase in stress and thus cognitive impairment, can be viewed differently to that of acute, high intensity exercise or psychosocial stress (Chen et al., 2017). This could be in part due to the influence exercise has in decreasing recovery time for stress induced cortisol (Loprinzi & Frith, 2019).

It is also suggested that an inverted-U relationship between exercise intensity and declarative memory performance exists (Brisswalter, Collardeau, Arcelin, & René, 2002; Easterbrook, 1959; Kent, 2006). Based on the cue utilisation theory (Easterbrook, 1959), optimal performance level corresponds to an intermediate arousal level. As arousal increases, the focus of a participant is tapered and consequently leads to the processing of relevant cues, and filtering out of irrelevant cues. However, if this arousal becomes too high, relevant cues will also be filtered out. This results in the reduction of the availability of important cues for an over-aroused participant, whereas, for an under-aroused participant, there will be a significant influx of irrelevant cues (Brisswalter et al., 2002; Easterbrook, 1959; Kent, 2006). Confirming this, the results of Experiment 2 showed an impaired performance for the high-intensity exercise compared to the moderate exercise, while the moderate exercise showed improvement. Therefore, the evidence suggests that exercise performed at a moderate intensity lies between two thresholds. Firstly, enough exertion is performed to initiate the release of BDNF to aid neurogenesis, thus improving learning and memory, and secondly, it does not reach the threshold at which physical stress becomes an inhibitor to retention and consolidation.

5.3. Considerations

A pilot study ($n = 21$) was run to equate the total energy expenditure achieved from moderate-intensity exercise and HIIT conditions. This is an important procedure as differences between short bouts of high intensity exercise and longer, continuous moderate exercise have considerably different neurophysiological effects. By matching the energy output, any observable differences in scores between the two conditions (moderate and HIIT), were less likely to be attributed to a difference in energy expenditure. It is important to note that the HIIT protocol employed in this study differs from typical HIIT protocols, for example the HIIT protocol used by Tabata et al. (1996) where the aim is to induce complete fatigue. Our choice of HIIT protocol had two folds. Firstly, we wanted to avoid over exhausting participants based on the ability of a typical participant. Secondly, we wanted to equate the overall energy output between HIIT and moderate continuous exercise training to ensure a neutral comparison between the two protocols.

Between the experiments, memory performance scores showed some degree of variability. Reasons for this variance may be due to differences in the retention interval, individual difference in response to exercise in general, as well as differences in baseline cognitive abilities and motivation to complete the tasks (Katz et al., 2017). This perhaps highlights the need to investigate other modulating factors such as fitness level, general cognitive abilities and motivation.

Whilst we have shown cycling, a form of continuous aerobic exercise, to be an effective intervention to improve long-term memory, it is important not to discount other forms of exercise such as resistance training and yoga. Whilst Northey, Cherbuin, Pumpa, Smee, and Rattray (2018) found resistance training to provide cognitive benefits to older adults, a systematic review by Loprinzi, Frith and Edwards (2018) highlights that resistance programmes still require further development in order to achieve cognitive benefits comparable to that of aerobic exercise (Loprinzi, Frith, & Edwards, 2018). Future development of these interventions may provide benefits to those who may not necessarily be able to partake in aerobic exercise, perhaps due to disabilities or older age. Furthermore, additional participant screening such as anxiety or habitual physical activity may provide further understanding of how emotional states or fitness levels can affect the influence of physical exercise on long-term memory.

Lastly, our study compared the effects of active- and passive rest on long-term memory. These types of wakeful rest significantly differ from one another with regards to cognitive engagement during the rest period. Recently, a study by Blough and Loprinzi (2019) evaluated the extent to which various control activities affect cognitive outcomes (Blough & Loprinzi, 2019). Following suit and given that there was a significant difference in performance between moderate exercise and our protocol for active rest, it would be of interest to investigate the effect of different protocols of active rest on long-term memory. For example, it may be interesting to employ several active rest conditions, with varying degrees of cognitive engagement, which utilise different cognitive tasks such as a puzzle or video game. Furthermore, modifying the degree of contextual similarity of the active rest condition from the encoding task may provide further insight into the mechanisms of active-rest-induced interference.

6. Conclusion

Our research has shown that moderate-intensity exercise has the most beneficial effect on memory performance. This indicates that it is not necessary to overexert oneself in order to achieve observable cognitive improvements. It has also shown that short periods of uninterrupted wakeful rest after learning can increase the likelihood of remembering at a later date. Producing clear guidelines for memory enhancement that encompasses the variability in the literature can have major implications in the treatment of patients with memory deficiencies, provide a boost for students in an exam setting, and aid with daily tasks such as remembering the items on a grocery list.

Data Availability

Dataset generated and analysed during the current study can be accessed via https://doi.org/10.17605/OSF.IO/RJC7G.

Declaration Competing Interest

Authors declare no conflict of interest.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nlm.2019.107128.

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