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Does a Single Bout of Exercise Improve Memory and Learning?

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Abstract

Physical activity in general, and a single bout of exercise in particular, has been found to have a positive effect on memory and learning. However, findings have shown different results for declarative memory (explicit knowledge) and procedural memory (implicit knowledge). The aim of this interventional study was to investigate the effects of a single bout of moderate-to-vigorous exercise during memory consolidation on both memory types compared to physical inactivity. A between-within group study design consisted of two test sessions with 24 hours in between. Forty-four participants were randomized into an exercise group (18 males, 4 females, *M* = 24 years) or a control group (18 males, 4 females, *M* = 25.2 years). Both groups underwent memory testing the first day, with the exercise group afterwards performing a single bout of moderate-to-vigorous physical activity (cycling) for approximately 30 minutes. Memory tests were repeated the second day. Results showed that the improvement for the exercise group was significantly better compared to the control group on measures of procedural memory. No differences were found regarding declarative memory.

Keywords: *Physical activity, Learning, Declarative memory, Procedural memory*

Highlights

- A single bout of exercise enhances procedural memory when performed after learning
- A single bout of exercise does not affect declarative memory
- Physical activity can be used in skill development in education

Physical activity has been shown to facilitate learning and memory (Hötting & Röder, 2013) and that these positive effects can be achieved after a single bout of exercise (Roig et al., 2016). An explanatory model for why physical activity facilitates learning and memory is the release of brain-derived neurotrophic factor (BDNF) that occurs with physical activity (Piepmeier & Etnier, 2015). This protein promotes synaptogenesis, i.e. the formation of synapses between nerve cells which contributes to the improvement of motor and cognitive abilities (El-Sayes et al., 2019). Moreover, Montag et al. (2014) emphasises the important role that BDNF plays in the consolidation process that occurs in the transference between short- and long-term memory. However, research results in this area are inconclusive regarding the effect of a single bout of exercise on different aspects of memory (Frisch et al., 2023).

Depending on what type of information that is being consolidated, memory can be divided into two main subcategories, either declarative or non-declarative (Squire, 2004). Declarative memory includes a conscious process of remembering information connected to a specific event (episodic memory) or specific knowledge (semantic memory) (Tulving, 1972). Nondeclarative memories are memories that are learned on an unconscious and implicit level and that cannot be explicitly explained (Gilhooly, 2022). One form of the nondeclarative memory is procedural memory. The procedural memory involves unconscious changes in performance of a task that has been influenced by earlier experiences. Thus, you can indirectly measure improvement in the procedural memory by observing changes in the time needed to finish a task (Eichenbaum, 2011).

Research has concluded that a single bout of exercise had moderate to large effect sizes on aspects of declarative memory, such as episodic memory (see Loprinzi et al., 2019, for a systematic review with meta-analysis). These effects were found when the exercise was performed early in the consolidation process (within four hours after

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encoding) or late in the consolidation process (more than four hours after encoding). Exercise performed before encoding also had a positive effect on the episodic memory, but only for young adults (age 18-24) while older adults (age >60) had a negative effect. In addition, it was found that exercise during the encoding had a negative effect on the episodic memory. This shows that more research has to be done on this topic in order to draw definitive conclusions.

In the cases where significant results are found regarding the positive effect of a single bout of exercise in relation to declarative memory, there have been mixed findings regarding modulators. One of these modulators is timing, i.e. when the exercise is performed in relation to the learning. Amongst many findings it has been shown that declarative memory is enhanced when the exercise is performed before the encoding of new information, i.e. before learning (Ahmed et al., 2024). The explanation behind this phenomenon is that exercise before encoding can create molecular pathways via neurological stimulation that facilitate long-term memory (Loprinzi et al., 2019; Sng et al., 2018). Exercise simultaneously as encoding has shown mixed results. For example, Ahmed et al. (2024) reported no significant benefits while Schmidt-Kassow et al. (2013) found it to have positive effects on verbal learning. Meanwhile, Loprinzi et al. (2019) reported that the exercise had an obstructive effect on learning if it was conducted at the same time as the encoding. There are also studies that show the positive effect that physical exercise has on declarative memory when it is performed during the consolidation process, i.e. after learning (Ahmed et al., 2024; Loprinzi et al., 2019; Schmid et al., 2023; Weinberg et al., 2014). Training intensity is another modulator that can affect the positive effect on declarative memory. According to Loprinzi (2018), high intensity training before encoding has shown to have a good effect on episodic memory since physical exercise produces hormones that expand neuroplasticity in the hippocampus. Low intensity training however did not show any significant effect on episodic memory.

There is also evidence that physical activity affects non-declarative or procedural memory. A meta-analysis by Wanner et al. (2020) found that a single bout of exercise in close proximity to the learning had significant results with a small effect size at follow-up, both one and seven days later. Only high intensity training improved memory and learning, and it was seen that this only had an effect when the physical activity took place just after the learning (during consolidation), but not before (before encoding). In addition, Thomas et al. (2016a) showed that high-intensity exercise benefits procedural memory more than low-intensity and physical inactivity, both at follow-up one and seven days later. Also, it was shown that low intensity exercise was superior to inactivity.

Apart from intensity, timing is also an important factor for modulating the effect of a single bout of exercise on procedural memory. Roig et al. (2012) investigated how a single bout of high intensity exercise can affect procedural memory when performing motor tasks. The results at baseline and when the participants were tested one hour later showed no significant differences between the groups that exercised before or after learning and an inactive control group. However, both exercise groups had better results compared to the inactive group at follow-up one and seven days later. In addition, those who performed physical activity post-learning were significantly better than those who performed the activity before, indicating that the timing of when the exercise is performed modulates the effect of how much the memory is enhanced.

There are a limited number of studies that have investigated the effect of a single bout of exercise on both the declarative and procedural memory. Roig et al. (2013) conducted a literature review with meta-analysis examining the effect from long-term exercise versus a single bout of exercise, including both declarative and procedural memory. Results showed that a single bout of exercise had a moderate to large effect size on long-term memory and showed largest effects on procedural and verbal-auditorial declarative long-term memory. Moreover, newer studies have been published recently. Frisch et al. (2023) concluded that the exercise had a significant effect on the sleep-dependent memory consolidation for the declarative tasks but not the procedural ones. Wang et al. (2020) showed that a single bout of exercise was superior to physical inactivity when it comes to learning and memory, regardless of when the exercise was performed. Furthermore, it was shown that the declarative memory primarily was enhanced when the exercise happened pre-learning, thus before the encoding while the procedural memory was most positively affected when the exercise was post-learning, during consolidation.

In conclusion, the research presented above indicates that individuals in some instances can use a single bout of exercise to optimise their performance in tasks related to both the declarative and procedural memory in a way that cannot be achieved with physical inactivity. Also, some modulators, namely intensity and timing, seem to modulate this effect. In this regard, the body of research of these particular modulators are more conclusive for the procedural memory in comparison to the mixed findings for the declarative memory.

The aim of this study was to examine the effects of a single bout of exercise performed during memory consolidation (i.e. post learning) on declarative and procedural memory. More precisely the two research questions are the following:

1. Is declarative memory improved by a single bout of exercise conducted during memory consolidation compared to physical inactivity?
2. Is procedural memory improved by a single bout of exercise conducted during memory consolidation compared to physical inactivity?

Method

Participants

Participants were recruited through posters, social media posts, word of mouth and class visits at Umeå university. A total of 53 individuals reported interest in participation. Nine did however decline participation before enrolment. Thus, 44 participants were included, 36 males and eight females with a mean age of 24.61 years (*SD* = 3.59). They were randomly assigned into two groups, one exercise group (*n* = 22) and one control group (*n* = 22). Demographics are presented in table 1. The randomization was stratified based on their level of subjective physical activity and gender to have an equal distribution across both groups. The level of subjective physical activity was determined by using the short-form of the International Physical Activity Questionnaire – Short Form (IPAQ-SF, see instruments) which the participants had answered when registering for the study. The inclusion criteria were 18-35 years of age and healthy based on self-report. Exclusion criteria were physical disabilities affecting ability to perform a single bout of exercise, any ongoing illness and being familiarized with the tests used in the study.

Table 1: ***Demographic and baseline information***

	Exercise group (n = 22)	Control group (n = 22)
Male Gender	18 (82%)	18 (82%)
Age	24.00 (2.88)	25.20 (4.16)
IPAQ-SF score		
Low	2 (9%)	3 (14%)
Moderate	6 (27%)	6 (27%)
High	14 (64%)	13 (59%)

Note: Data presented are Mean (Standard Deviation) or count (percentages).

Instruments and material

Subjective physical activity

The International Physical Activity Questionnaire Short Form (IPAQ-SF) was used to assess subjective physical activity levels, classified as ”high”, ”moderate” or ”low” (Craig et al., 2003). The reliability and validity of the IPAQ-SF have shown similar results as other self-assessment forms and is deemed to be an acceptable form of measurement (Craig et al., 2003).

Declarative memory

Two different tests were used to measure declarative memory. First, the Rey Auditory Verbal Learning Test (RAVLT) was used to measure verbal-auditory declarative memory (Rey, 1964). The test contains a main list that includes 15 Swedish words that are repeated during five trials. It also includes a separate list with different words that is conducted for one trial. In addition to the learning trials, a delayed recall and recognition trial is included (20 minutes post-learning). One point is awarded for every remembered word and the maximum is thus 15 points per trial. RAVLT has shown a high degree of reliability and validity and is thus approved for the use in neuropsychological assessment (Magalhaes et al., 2012).

Second, the Brief Visuospatial Memory Test - Revised (BVMT) was used to measure visuospatial declarative memory (Benedict, 1997). The test includes a sheet with six figures that are shown three times. A range of zero to two points are awarded per figure depending on how correct the drawing and location is and the maximum number of points is thus twelve points per trial. In addition to the learning trials, a delayed recall and recognition trial is included (20 minutes post-learning). For the delayed recall trial the maximum number of points was twelve and for the recognition trial it was six. The BVMT has an adequate level of reliability and validity (Benedict et al., 1996).

Procedural memory

The Coding test (Wechsler, 2008) was used to measure the procedural memory. This test includes and measures different aspects of procedural memory such as psychomotor speed, flexibility/ability to shift mental set and ability to learn an unfamiliar task (Groth-Marnat, 1993). The assignment is about pairing symbols with numbers by drawing the symbols in boxes as fast and accurately as possible. In original, the task last 120 seconds. In this study, items completed at 120 seconds were recorded, but participants were asked to complete all items, a total of 135 items. Total points rewarded was the total number of symbols completed minus incorrect symbols during the first 120 seconds, and total time was the time it took to complete the whole answer booklet. Coding displays a high degree of reliability and validity and is thus approved for the use in neuropsychological assessment (Wechsler, 2008).

Rate of perceived exertion

The Borg rate of perceived exertion (RPE) scale was used to measure perceived exertion during the bout of exercise. The scale ranges from “very, very light” and “very, very hard” on a scale from 6-20 (Borg, 1982). The question being asked was “Between 6-20, how would you rate your perceived exertion?” The Borg RPE scale has been shown to have the acceptable level of reliability and validity needed for it to be used as a psychometric tool (Heath, 1998). It has also been shown to be valid for assessing intensity on a cycle ergometer (Dunbar et al., 1992).

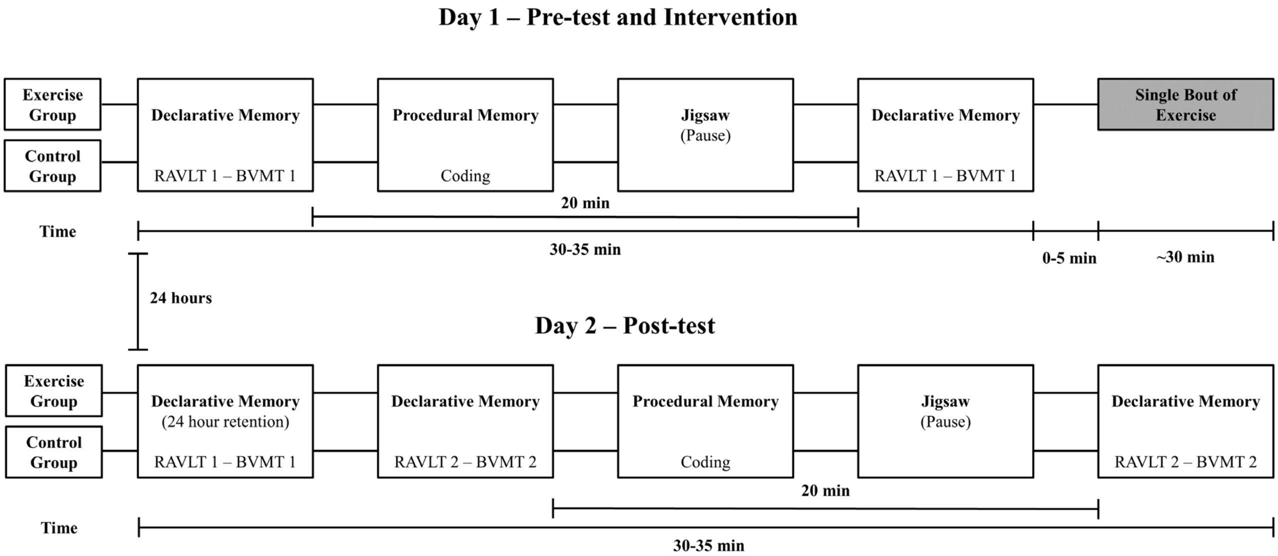
Heart rate

Heart rate was measured with a heart rate monitor as a complement to the Borg scale to get a better idea of how strenuous the single bout of exercise was. Although Borg (1982) emphasises there is no direct correlation between the RPE and the pulse, he argues the latter could be used as a complement to assess the level of strain.

Procedure and study design

Participants were informed about the study and could also find information about the study through an online form. If they gave written consent to participate in the study, they registered by leaving contact information and answering a few background questions regarding subjective physical activity (IPAQ-SF), gender and age. Participants were asked to refrain from strenuous physical activity outside the frame of the study during the two days they participated.

Figure 1



Day 1 – Pre-test

Participants were given standardised instructions for all neuropsychological tests. The tests were performed in the following order: Rey Auditory Verbal Learning Test Learning (RAVLT 1); Brief Visuospatial Memory Test Learning (BVMT 1); Coding; A pause including jigsaw puzzle; Rey Auditory Verbal Learning Test (RAVLT 1) Delayed Recall and Recognition; Brief Visuospatial Memory Test (BVMT 1) Delayed Recall and Recognition.

Day 1 – Intervention

After this, the exercise group performed a single bout of exercise using a cycle ergometer (Monark Ergomedic 839E). Participants were asked to wear a heart rate monitor around their chest and were introduced to the Borg RPE Scale. This exercise followed a standardised manual with four parts to ensure the same duration of the moderate-to-vigorous intensity for all participants. The order, parts, time frame and target RPE was in part replicated from Holman & Staines (2021) and Venezia et al. (2023) who labelled their used exercise protocol as "moderate-intensity" and "moderate-to-vigorous intensity", respectively. One addition to the existing exercise protocol was a part before the main session where they had time to find a level of watt production where they experienced a RPE of 15. The reason for this being included is to make sure that all participants spent the same amount of time at a RPE of 15, since the warm-up can be differently strenuous depending on level of fitness.

1. Warm-up: Participants were asked to warm-up for four minutes by producing 100 watt and holding a cadence of 80-90 Revolutions Per Minute (RPM). RPE and heart rate was noted every two minutes. This was followed by a one-minute break.
2. Achieve "15/hard" RPE: Participants were asked to continue holding a cadence of 80-90 RPM, but were now able to adjust their watt production so that they achieved a RPE of 15, which is defined as "hard". RPE and heart rate was noted as soon as the participant achieved a RPE of 15 or every two minutes. This was followed by a one-minute break.
3. Main session: Participants were asked to continuously hold a cadence of 80-90 RPM and a RPE of 15 during four blocks. Every block was four minutes and a pause of one minute was in between each block. Participants were free to choose how much watt they wanted to produce. RPE and heart rate was noted every two minutes.
4. Winding down: Participants were asked to wind down for two minutes in preferred RPM, RPE and watt production. No RPE or heart rate was noted.

Day 2 – Post-test

The delayed recall and recognition trial from RAVLT 1 and BVMT 1 was repeated on day 2 to test 24-hour retention. After this, the same procedure as day one was performed using parallel versions of RAVLT (2) and BVMT (2). However, the same Coding sheet was used in order to measure possible improvements in comparison with trial 1.

Ethical considerations

Although no formal ethical approval was obtained, the study adhered to the ethical principles outlined in the World Medical Association's Declaration of Helsinki (2013). These principles emphasize prioritizing the well-being, health, and rights of the human subjects involved, ensuring that these are never compromised in pursuit of new knowledge. Particular attention was given to protecting the integrity, dignity, self-determination, privacy, and confidentiality of the participants. The study was designed to ensure that its objectives outweighed any potential burdens, with steps taken to minimize risks associated with both the cognitive and physical aspects of testing. This approach was also reflected in the inclusion criteria, which excluded potentially vulnerable individuals from participation. When registering and consenting in written form for the participation in the study, all participants were given information about what their participation would entail and that they had the right to at any time, without giving an explanation, cancel their participation. They were also informed that all information gathered about them will be handled confidentially in accordance with the principles of the Scientific Council of Sweden (Vetenskapsrådet, 2002), the General Data Protection Regulation (GDPR) and guidelines of Umeå University. No sensitive or personal information was recorded throughout the entire study.

Statistical analysis

Statistical analysis was performed in IBM Statistical Package for the Social Sciences (SPSS) version 28.0.1.1. First, descriptive analysis identified potential extreme outliers. Assessment of the data normality was made through calculation of skewness and kurtosis, where a *z*-value between -1.96 and 1.96 was deemed acceptable (Field, 2018). To complement, the Shapiro-Wilk test of normality and visual inspections of histograms were used. The alpha-value was set to .05 for all analyses. Effect sizes were Cohen's *d* for t-tests, partial eta squared (η_p^2) for analysis of variance and Wilcoxon's *r* for non-parametric tests.

To answer the first research question, a mixed within-between subjects Analysis of Variance (ANOVA) was conducted to compare groups regarding RAVLT Learning. RAVLT Retention, measured by delayed recall score, were not deemed normally distributed, so computed variables (delayed recall score in retention block 24h – delayed recall score retention in block 1; delayed recall score in retention block 2 – delayed recall score in retention block 1) were used. These variables were both deemed normally distributed, so therefore independent samples t-test was conducted. For recognition, direct logistic regression analysis was used for the three different time points due to ceiling effects of the measures. For visuospatial declarative memory, measured by BVMT, learning block data was not deemed normally distributed. Therefore, a computed variable (total score learning block 2 – total score learning block 1) was used. This variable was normally distributed and therefore an independent samples t-test was used. Retention data for BVMT were not deemed normally distributed. Computed variables (delayed recall score in retention block 24h – delayed recall score in retention block 1; delayed recall score in retention block 2 – delayed recall score in retention block 1) were used. These variables were not deemed normally distributed, thus nonparametric Mann-Whitney U Tests were used. For recognition, direct logistic regression analysis was used for the three different time points due to ceiling effects of the measures.
To answer the second research question, two different measures from the test Coding were analysed. Total points were deemed normally distributed as well as having a homogenous variance. A mixed within-between subjects Analysis of Variance (ANOVA) was conducted to examine the main effect of group belonging and time regarding total points acquired. Total time was not deemed normally distributed. A computed variable (total time trial 2 – total time trial 1) was used for this analysis. This variable was deemed normally distributed, so an independent samples t-test was conducted to compare the two groups.

Results

Declarative Memory

On the RAVLT (Table 2), there were no differences between groups at baseline, and no significant interaction effect between group and time regarding learning of verbal-auditory declarative memory, Wilks' Lambda = .99, *F* (1, 42) = .48, *p* = .49, η_p^2 = .01. In addition, there was no significant main effect of either time, Wilks' Lambda = 1, *F* (1, 42) = .12, *p* = .73, η_p^2 = .003 nor group, *F* (1, 42) = .33, *p* = .57, η_p^2 = .008. There were no significant differences between groups in 24 hour retention, *t*(42) = -.36 or changes in retention between retention block 1 and retention block 2, *t*(42) = -.34 on the RAVLT.

Regarding visuospatial memory in the BVMT, there were no significant differences between groups at baseline nor in changes in learning scores between day 1 and day 2, *t*(42) = -.94, 24 hour retention, *U* =162000, *z* = 0 or changes in retention from retention block 1 to retention block 2, *U* = 225000, *z* = -.43.

Direct logistic regression was used to assess the impact of which group you belonged to on the odds of you recognising all the words/figures at the three different retention blocks on both the RAVLT and the BVMT. None of the models were statistically significant (see Table 2).

Procedural Memory

There were no differences between groups in any Coding result at baseline. However, there was a significant interaction effect between group and time regarding changes in number of completed items, Wilks' Lambda = .89, *F* (1, 42) = 5.42, *p* = .025, η_p^2 = .11 (Figure 2), where the exercise group improved more than the control group from day 1 to day 2. There was a significant main effect for time, Wilks' Lambda = .58, *F* (1, 42) = 31.0, *p* = <.001 η_p^2 = .43, where both groups showed an increase in total points across the two time points. The main effect comparing groups was not significant, *F* (1, 42) = .88, *p* = .35, η_p^2 = .021.

While there were no significant differences at baseline, an independent samples t-test showed that there was a statistically significant difference in changes in total time from day 1 to day 2 between groups, *t*(42) = -2.03, *p* = .048 (Table 3). In addition, the differences between groups showed a moderate effect size, *d* = 0.61 (Cohen, 1988).

To further investigate which participants gained more from one single bout of exercise, all participants were divided into low or high performers, based on result on Coding at baseline (cutoff 57). The low performers in the exercise group (n = 14) increased from a mean score of 43.86 (sd 6.74) to 53.43 (sd 9.26) at follow up, while the low performers in the control group (n = 8) increased from a mean score of 50.00 (sd 4.81) to 55.50 (7.64). There was no significant group vs time interaction effect between these groups.

The high performers in the exercise group (n = 8) increased from a mean score of 71.38 (sd 8.21) to 88.75 (sd 13.16) at follow up, while the high performers in the control group (n = 14) increased from a mean score of 68.14 (sd 5.76) to 73.00 (10.26). There was a significant group vs time interaction effect, Wilks' Lambda = .50, *F* (1, 20) = 6.40, *p* = .020, η_p^2 = .24

Table 2: ***Results from declarative memory tests***

	Exercise group (*n* = 22)		Control group (*n* = 22)			
	M	*SD*	*M*	*SD*	*p*	*ES*
RAVLT Learning day 1	54.9	7.56	54.5	9.17	.49	0.1[a]
RAVLT Learning day 2	56.1	7.69	54.0	8.95		
RAVLT Retention 24 h - Retention day 1	-.41	1.56	-.23	1.82	.72	-.11[b]
RAVLT Retention day 2 - Retention day 1	-.95	3.42	-.59	4.25	.74	.09[b]
BVMT Learning day 2 - Learning day 1	1.23	4.06	2.45	4.61	.35	.28[b]
	Md	*IQR*	*Md*	*IQR*		
BVMT Retention 24 h - Retention day 1	0.0	0.0	0.0	0.0	1.0	0.0[c]
BVMT Retention day 2 - Retention day 1	0.0	1.0	0.0	1.25	.67	.09[c]
	n	%	*n*	%		
RAVLT Recognition day 1	21	95.5	18	81.8	.14	
RAVLT Recognition 24 h	19	86.4	19	86.4	1.0	
RAVLT Recognition day 2	20	90.9	21	95.5	.55	
BVMT Recognition day 1	17	77.3	21	95.5	.068	
BVMT Recognition 24 h	18	81.8	19	86.4	.14	
BVMT Recognition day 2	17	77.3	21	95.5	.068	

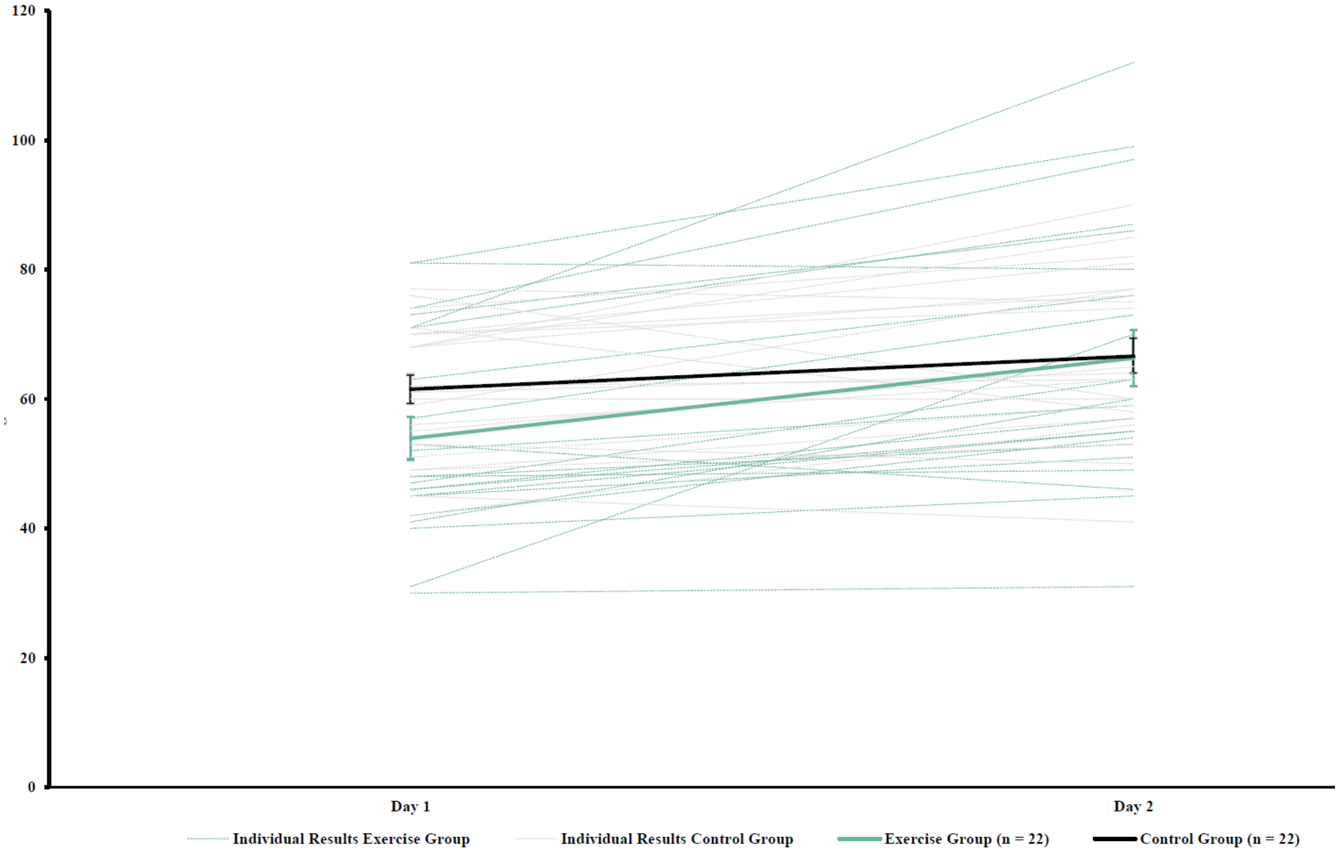
Note: RAVLT = Rey Auditory Verbal Learning Test; BVMT = Brief Visuospatial Memory Test; ES = Effect size according to [a]Partial eta squared, [b]Cohens d or [c]Wilcoxon r. For Recognition scores, n indicates number of participants receiving full score, and % proportion of participants receiving full score.

Table 3: ***Descriptive statistics and results from independent t-test for Coding.***

	Exercise group (*n* = 22)		Control group (*n* = 22)			
	M	*SD*	*M*	*SD*	*p*	*ES*
Total points day 1	53.9	15.3	61.6	10.4	.025	.11[a]
Total points day 2	66.3	20.3	66.6	12.6		
Total time day 1 - Total time day 2	-34.2	26.5	-19.5	21.1	.048	.61[b]

Note: ES = Effect size, according to [a]Partial eta squared or [b]Cohens d

Figure 2



Discussion

The aim of this study was to examine what effect a single bout of exercise performed during memory consolidation (i.e. post learning) would have on declarative and procedural memory. The results show that the group performing a single bout of exercise improves significantly better than the group not exercising when it comes to some aspects of procedural memory, while there were no differences regarding the declarative memory. This indicates that implicit knowledge, such as psychomotor skills, might benefit more than explicit knowledge when a single bout of exercise is conducted during memory consolidation.

The results showed that there might be a beneficial effect of a single bout of exercise with moderate-to-vigorous intensity occurring during the consolidation period on non-declarative or procedural memory. These results are in line with previous research (Holman & Staines, 2021; Roig et al., 2012; Thomas et al., 2016 a, b; Wang et al., 2020; Wanner et al., 2020), and with the explanatory model regarding BDNF. BDNF, which is released in the brain when physical exercise is conducted, enhances the memory through the synaptogenesis it promotes (Huang et al., 2014; Montag et al., 2014; Piepmeier & Etnier, 2015), which facilitates the improvement of motor abilities (El-Sayes et al., 2019). However, some caution must be taken when interpreting the results. Firstly, when it comes to total points, the result showed a significant increase for both groups with the significant interaction effect showing that increase for the exercise group was significantly better than the one of the control group. Important to note is that the exercise group had a lower mean on the first day compared to the control group, with the gap shrinking substantially on the second day. The difference on the first day was not statistically significant, but it opens up for speculation surrounding if the lower starting point made a bigger improvement for the exercise group possible. As Crush & Loprinzi (2017) concluded in their study, participants with a lower declarative memory performance baseline gained the most from physical exercise when it came to memory function. Participants with higher baseline did not receive the same effect, arguing for an eventual ceiling effect being present (Crush & Loprinzi, 2017). Our data on the other hand show that high performance participants benefitted more from a single bout of exercise. This indicates that there might be different processes between procedural and declarative memory gains based on baseline performance. To our knowledge, these different processes have not been investigated, , but nonetheless baseline performance seem to be something that could affect the exercise-memory interaction (Loprinzi et al., 2021).

Non-significant effects on declarative memory contradict some of the previous research that have found that a single bout of exercise during the consolidation process had significant positive effects on declarative memory (Ahmed et al., 2024; Labban & Etnier, 2011; Loprinzi et al., 2019; Schmid et al., 2023; Weinberg et al., 2014). On the other hand, lack of effects has been found in previous research as well (Eich & Metcalfe, 2009; Sng et al., 2018) showing that the relationship between a single bout of exercise and declarative memory is complex. There are several explanatory models that could be possible explanations for the lack of statistically significant results regarding the improvement for the exercise group in comparison to the control group for declarative memory. One factor that could have affected the outcome is the timing of the single bout of exercise, where some argue that declarative memory is benefited from exercise happening before encoding of new information (Labban & Etnier, 2011; Wang et al., 2020). This is attributed to the fact that exercise affects neural pathways (Schmid et al., 2023; Sng et al., 2018), neural arousals which facilitates cognitive improvements (Labban & Etnier, 2011) and the deployment of attentional resources (Ahmed et al., 2024; Schmid et al., 2023). As this study had a single bout of exercise during consolidation, this indicates that the different aspects that enhance performance regarding declarative memory, e.g. the mobilisation of attentional resources came at the wrong timing for maximal effect. The use and allocation of these resources could have been even more crucial in this study since it included two different types of declarative memory tasks. Further, previous research has established that physical exercise releases BDNF in the brain (Piepmeier & Etnier, 2015) which enhances neuroplasticity by synaptogenesis (El-Sayes et al., 2019) and neurogenesis (Pereira et al., 2007) that facilitates the transference process from short- to long-term memory (Montag et al., 2014). This study had a similar exercise protocol to other studies (Holman & Staines, 2021; Venezia et al., 2023) in regard to total time and intensity, so one should assume that the exercise led to the release of similar levels of BDNF which reaches its peak after twenty minutes (Schmidt-Kassow et al., 2012) which raises more questions as to why no significant results were found for the improvement of the exercise group in comparison to the control group. Also, when specifically investigating visuospatial declarative memory, Loprinzi et al. (2021) argued that a single bout of exercise could be beneficial for short-term visuospatial memory rather than long-term, which supports our lack of findings for visuospatial declarative memory. Support for this was also found in Roig et al. (2013) literature review with meta-analysis, indicating that the relationship between the single bout of exercise and visuospatial declarative memory is unclear.

As this study has examined both declarative and procedural memory, the way the memory systems interact with each other can be a part of the explanation behind the findings. The lack of significant results regarding the improvement of the declarative memory might be due to the competition of resources that is instigated between the declarative and procedural memory systems when they are performed in proximity to each other, as argued by Chen et al. (2020). For instance, Chen et al. (2020) found that gains made in procedural memory are negatively affected when they are followed by declarative memory tasks. However, in this study, the order was reversed in the sense that the study design was formed in a way where declarative memory tasks were done before the procedural ones. With that said, Brown & Robertson (2007) have found that declarative memory consolidation also can be disrupted when it is followed by procedural learning. This can specifically be seen when the retesting is done twelve hours after learning without any sleep. However, this disruption disappeared when the retest was done after twelve hours with sleep, promoting the speculation that the procedural memory test did not disrupt any gains done in the declarative memory. This strengthens the results of this study as it primarily relied on the retention block performed 24 hours after learning, i.e. sleep-dependent memory.

Limitations

Despite the mentioned significance of the found results, this study has several limitations that need to be commented on. One of those is that the participants did not remain in the test laboratory during the whole two days of their participation in the study. This means that the environment and behaviour of the participants could not be controlled for the vast majority of the time, which means that basic aspects such as food and sleep could vary widely between participants. Also, despite instructions to not perform strenuous physical exercise outside of the frame of the study it cannot be said for certain that this was avoided. Also, some of the cited studies, e.g. Roig et al. (2012) and Thomas et al. (2016a, b) use peak oxygen consumption and blood lactate samples to determine intensity levels for the single bout of exercise and stratification of the groups. These objective measurements could be seen as superior in terms of accuracy in comparison to the subjective measurements used in this study, namely the Borg RPE scale and IPAQ-SF.

There is also a limitation in the sample used in this study. Using a convenience sample and a relatively small sample may limit the inferences being possible to make. Fewer participants can raise the issue of statistical power, hence the probability to detect significant differences (Maxwell et al., 2008). Publications on the issue argue for larger sample sizes than used in this study (Cohen, 1992), making the argument that there is an increased risk of type 2 errors (Maxwell et al., 2008). Another limitation is the gender distribution within the sample, with a majority of participants being male. Previous research has indicated that there may be a gender difference in response to the single bout of exercise, where women may be more susceptible to exercise induced improvement (Loprinzi et al., 2021). A more evenly distributed sample would therefore possibly have had better premises to find significant findings.

Conclusions and future studies

The conclusions that might be drawn from this study is that a moderate-to-vigorous single bout of exercise during memory consolidation enhances the procedural memory in a significant way when compared to physical inactivity. The same cannot be said for declarative memory. However, because of abovementioned limitations these results must be interpreted with a degree of caution. To determine the relationship between a single bout of exercise and different memory types, future studies should focus on the use of different study designs. The problem with memory disruption can be handled by testing one memory type at a time, having an equal number of tests for each memory type or randomising the order in which the tests are administered. Further, more exercise groups can be included in order to compare how a single bout of exercise before, during and after learning affects the memory types in comparison to physical inactivity. Moreover, there can be a different procedure for the stratification of the groups by including a baseline cognitive test session to determine the cognitive baseline for the participants. This could then be used in the stratification of the groups in order to determine if the single bout of exercise would have a greater impact on those with a lower or higher cognitive baseline and thus providing more valuable insight to the relationship between physical exercise and memory.

In sum, the findings of the current study indicates that the procedural memory is improved when a single bout of moderate-to-vigorous exercise is performed after psychomotor learning. This suggests important practical implications surrounding how physical activity can be used for the optimization of skill development in different domains, for example in education.

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