Effects of Aerobic Exercise on Memory and Its Neurobiological Mechanisms

Authors: Ke Jinhong, Wang Bo, Wang Bo

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Abstract

Objective: To investigate the effects of aerobic exercise on memory. Methods: Literature with aerobic exercise and memory as subject terms was retrieved through CNKI, Web of Science, and PubMed, and subsequently reviewed. Results: Aerobic exercise can accelerate response speed in working memory tasks; high-intensity aerobic exercise performed before memory encoding and during memory consolidation phases facilitates enhancement of episodic memory; high-intensity aerobic exercise can promote implicit memory. Aerobic exercise can promote the production of neurotrophic factors, induce long-term potentiation, activate memory-related brain regions such as the hippocampus, and promote neurogenesis. Limitations: Future research may investigate the effects of aerobic exercise onset and duration, the influence of aerobic exercise intensity and cognitive engagement, the impact of aerobic exercise on different age and gender groups, and the mediating role of brain-derived neurotrophic factor, thereby elucidating the effects of aerobic exercise on memory and its underlying neurobiological mechanisms. Conclusion: Overall, aerobic exercise is beneficial for memory enhancement, though this effect is modulated by various factors.

Full Text

Preamble

Effects of Aerobic Exercise on Memory and its Neurobiological Mechanism

Ke Jinhong, Wang Bo
(School of Sociology and Psychology, Central University of Finance and Economics, Beijing 100081, China)

Abstract:
[**Objective**] This study aims to investigate the effects of aerobic exercise on memory and its neurobiological mechanism.

[**Methods**] We searched and reviewed literature containing aerobic exercise and memory as subject terms through CNKI, Web of Science, and PubMed.
[**Results**] Aerobic exercise can accelerate response speed in working memory tasks. High-intensity aerobic exercise conducted before memory encoding and during the consolidation phase enhances episodic memory, and high-intensity aerobic exercise can also promote implicit memory. Aerobic exercise promotes the production of neurotrophic factors, induces long-term potentiation, activates memory-related brain regions such as the hippocampus, and promotes neurogenesis.
[**Limitations**] Future research should investigate the moderating roles of exercise timing, duration, intensity, cognitive engagement, and demographic factors, and further elucidate the neurobiological mechanisms underlying the effects of aerobic exercise on different categories of memory.
[**Conclusions**] Overall, aerobic exercise helps improve memory, though this effect is moderated by various factors.

Keywords: aerobic exercise, memory, learning, neurobiological mechanism
Classification Number: B849: G804.8

Aerobic exercise involves rhythmic, sustained movement utilizing large muscle groups under sufficient oxygen supply. Heart rate reserve (HRR) and oxygen uptake reserve (VO2R) are commonly used as indicators of aerobic exercise intensity, with low intensity defined as 30-39% HRR or VO2R, moderate intensity as 40-59% HRR or VO2R, and high intensity as 60-89% HRR or VO2R [?]. Aerobic exercise can be performed in various forms. Indoors, equipment such as jump ropes, stationary bicycles, and treadmills can be used; outdoors, activities like brisk walking, running, roller skating, cycling, and swimming are common options.

Aerobic exercise helps improve memory and alleviates memory impairment induced by stress [?], high-calorie diets [?], hypertension [?], and drug addiction [?]. However, due to time constraints and insufficient facilities, more than half of Chinese adults engage in almost no physical exercise [?]. Research has found that sedentary behavior in children is positively correlated with declines in working memory [?], suggesting that lack of exercise may adversely affect memory function in the population.

This paper examines the effects of aerobic exercise on different types of memory, specifically addressing its impact on working memory, episodic memory, and implicit memory, while identifying variables that moderate the relationship between aerobic exercise and memory. We also explore the neurobiological mechanisms through which aerobic exercise influences memory, focusing on brain-derived neurotrophic factor (BDNF) and the hippocampus. Finally, we propose future research directions investigating moderating effects of memory type, exercise timing and duration, exercise intensity and cognitive engagement, and demographic variables, as well as the mediating role of BDNF, to further reveal the neurobiological mechanisms underlying aerobic exercise effects on memory.

1 Effects of Aerobic Exercise on Different Types of Memory

Based on retention duration, memory can be divided into short-term and long-term memory [?]. The concept of working memory evolved from short-term memory. According to Baddeley and Hitch' s (1974) working memory model, working memory comprises multiple subsystems controlled by a central executive that manages information in the phonological loop and visuospatial sketchpad [?]. Based on the multiple memory systems model, long-term memory can be categorized into semantic memory, episodic memory, and procedural memory [?]. Procedural memory is a type of implicit memory, which also includes priming and classical conditioning [?]. Working memory, episodic memory, and implicit memory are the three types most extensively studied in aerobic exercise research, with accumulating evidence indicating that aerobic exercise has differential effects on each.

1.1 Effects on Working Memory

Meta-analyses have found that two-thirds of studies demonstrate significant beneficial effects of aerobic exercise on working memory [?]. In one study, older adults who walked for 30 minutes at 65-75% of maximum heart rate (HRmax) in the morning, then walked again after every 30 minutes of sedentary time, showed better working memory than those who remained sedentary throughout the day [?].

The n-back task is commonly used to measure working memory, where participants judge whether the current stimulus matches the one presented n trials earlier. Performance on working memory tasks involves a speed-accuracy trade-off. Early meta-analyses found that aerobic exercise substantially improved response speed in working memory tasks but had small-to-moderate detrimental effects on accuracy [?]. Event-related potential technology can reveal subtle temporal changes. Compared to resting participants, those who engaged in aerobic exercise using stationary bicycles or treadmills performed better on visual working memory tasks with faster processing speeds. Electrophysiological data showed that exercising participants exhibited earlier onset of stimulus-locked lateralized readiness potential (sLRP) and larger amplitudes for both sLRP and response-locked lateralized readiness potential (rLRP) [?].

Low-intensity aerobic exercise appears more beneficial for working memory. One hypothesis suggests that high-intensity exercise during memory encoding may impair working memory by diverting cognitive resources to other tasks [?]. Experimental evidence supports this hypothesis: a single session of high-intensity exercise (80% HRR) impaired working memory encoding, while low-intensity (30% HRR) and moderate-intensity (50% HRR) exercise had no effect [?]. In children, aerobic exercise at intensities below 70% HRmax improved working memory capacity and updating functions, whereas high-intensity exercise (70-80% HRmax or 75-85% maximal oxygen uptake, VO2max) showed no benefit [?, ?]. For college students, high-intensity exercise (70-85% HRmax) performed during memory encoding negatively affected working memory [?], possibly due to increased neural signal noise from single-session high-intensity exercise [?].

Cognitive engagement during aerobic exercise positively influences working memory. When the environment is unpredictable, greater cognitive engagement is required; such activities are termed "open-skill" exercises (e.g., table tennis, badminton). In contrast, "closed-skill" exercises involve lower cognitive demands and relatively higher physical and cardiorespiratory requirements (e.g., running, swimming) [?]. Behavioral experiments have shown greater working memory improvements after volleyball compared to running [?]. Another study found that older adults in the open-skill exercise group demonstrated significantly higher accuracy than both closed-skill and sedentary groups under visuospatial interference conditions [?]. Thus, aerobic exercise with higher cognitive engagement appears more effective for enhancing working memory.

1.2 Effects on Episodic Memory

Episodic memory refers to memory for personally experienced events in specific spatiotemporal contexts [?]. The Rey Auditory Verbal Learning Test (RAVLT) is commonly used to assess episodic memory. During the encoding phase, participants learn two word lists, then after a 20-minute or 24-hour delay, they complete a recognition test where original words are mixed with new items, requiring them to identify which list each word belonged to or whether it was new [?].

Aerobic exercise performed at different memory stages—encoding, consolidation, and retrieval—produces differential effects. Experiments show that 15 minutes of walking before memory encoding is more effective than walking during the consolidation phase [?]. Exercise during consolidation may also reduce false memories, though stronger evidence is needed [?]. Meta-analyses support these findings: exercise before encoding promotes episodic memory, exercise during encoding impairs it, and exercise during early and late consolidation phases enhances it [?].

Research has extended beyond single-session timing to examine whether exercising during both encoding and retrieval phases provides additional benefits. The encoding specificity principle suggests that memory retrieval is enhanced when the state or context at encoding matches that at retrieval [?]. One study found no difference between exercising before encoding and during consolidation versus exercising only before encoding [?], though this study lacked a rest control group. Another study with compatible (rest-rest or exercise-exercise) and incompatible (rest-exercise or exercise-rest) conditions found better memory performance in compatible states, supporting encoding specificity, but no significant difference between rest-rest and exercise-exercise groups [?]. Since exercise during encoding typically creates a mismatch between encoding (exercise) and retrieval (rest) states, this may explain why exercise during encoding is detrimental to memory.

Long-term aerobic exercise appears more beneficial than single sessions for episodic memory enhancement. In one study, 75 healthy young adults were randomly assigned to four groups: four weeks of exercise with exercise on the final day, four weeks of exercise with rest on the final day, exercise only on the final day, or no exercise. The exercise protocol consisted of brisk walking for over 30 minutes, four times per week. Results showed significant improvements in object recognition memory only in the group that completed four weeks of exercise plus exercise on the final day [?], indicating that long-term exercise is more effective than single sessions.

High-intensity aerobic exercise is more beneficial for episodic memory. Exercise exceeding 76% HRmax before encoding and during consolidation enhances episodic memory more effectively than exercise below this threshold [?]. For young adults in their twenties, aerobic exercise at 65-75% HRmax produces optimal episodic memory benefits [?].

Exercise modality influences outcomes: walking and running show no significant effects on episodic memory, while cycling demonstrates beneficial effects [?]. This may be because running requires greater attention to balance and coordination, involves vertical displacement, and generates more internal physiological "noise" that interferes with memory processes [?].

Emotion influences memory consolidation, with sadness induction producing better word recognition than anger induction [?]. Aerobic exercise may interact with emotion to modulate memories for traumatic stimuli, which has practical implications for fear memory regulation and anxiety disorder treatment [?]. One study found that participants who walked for 10 minutes after watching a car accident film reported more intrusive memories than those who rested [?]. Jentsch and Wolf (2020) examined the complex interaction between aerobic exercise and gender on emotional memory [?]. They found that for negative images, exercise enhanced memory in women but not men; for positive images, exercise enhanced memory in men but not women. Thus, the effects of aerobic exercise on episodic memory consolidation depend on the emotional content of the material and the individual's gender.

1.3 Effects on Implicit Memory

Implicit memory refers to the unconscious influence of previous experiences on current activities [?]. Implicit and explicit memory represent relatively distinct systems, and aerobic exercise affects them differently. One study found that aerobic exercise correlated positively with explicit memory but negatively with implicit probabilistic sequence learning, particularly in women [?]. However, Eich and Metcalfe (2009) found that marathon running had negative effects on explicit memory but improved implicit memory [?].

Motor memory belongs to implicit memory. In laboratory studies, it is typically measured using visuomotor precision tracking tasks, where participants use a joystick to move a cursor on a screen to rapidly changing target positions

[?]. One study with school-age children used such a task to examine the effects of running during memory consolidation, finding that the running group performed worse than the rest group on immediate tests but better after 7 days [?]. Another study showed that children who performed single short-duration and long-duration aerobic exercise sessions demonstrated better performance on a rotational visuomotor adaptation task and longer retention of motor memory compared to non-exercising children [?]. Thus, aerobic exercise before encoding and during consolidation promotes implicit memory and facilitates acquisition of new motor skills in children. A recent meta-analysis found that single-session aerobic exercise significantly promotes motor memory consolidation, though with a small effect size [?].

Both single and long-term aerobic exercise enhance motor memory, though few studies have examined long-term effects. In one study, 38 chronic stroke survivors were randomly assigned to stationary cycling or stretching groups for 8 weeks (3 sessions/week, 45 minutes/session at 70% HRmax), followed by immediate testing with a serial reaction time task. The aerobic exercise group performed significantly better than the stretching group, but this difference disappeared during delayed testing at week 8 [?], suggesting a relatively transient effect. Recent research found that healthy young adults who cycled for 2 weeks learned a dynamic balance task more rapidly than non-exercising controls [?].

High-intensity exercise (>80% maximal power output, Wmax, measured in Watts) promotes motor memory consolidation, while exercise at 40-79% Wmax shows no significant effect [?]. However, since both aerobic exercise and motor memory tasks involve muscle groups, high intensity may cause fatigue or interference, meaning exercise intensity may not necessarily moderate the relationship between aerobic exercise and motor memory [?]. A recent study found no significant differences in complex motor memory task performance after 17 minutes of cycling at 60-90% Wmax, 25-45% Wmax, or 25 W [?]. Therefore, investigating high-intensity exercise effects requires controlling for cognitive resource overload and muscle fatigue interference.

Classical conditioning and priming also constitute implicit memory. Classical conditioning occurs when a neutral stimulus, after repeated pairing with an unconditioned stimulus, elicits a conditioned response similar to the unconditioned response when presented alone [?]. Most animal studies have examined conditioning after running in mice. One study showed that 2-8 weeks of running enhanced fear conditioning in mice [?], while another found that a single 60-minute high-intensity running session impaired tone fear conditioning [?]. Thus, the effects of aerobic exercise on conditioning-based implicit memory may depend on exercise duration.

Priming refers to how a prime stimulus influences responses to subsequent test stimuli—for example, the prime "parrot" makes people more likely to complete the stem "par___" with "rot" [?]. Only one study has examined the effects of single-session aerobic exercise on priming: Eich and Metcalfe (2009) found that marathon runners showed superior performance on word stem completion tasks compared to resting controls [?].

1.4 Comparison of Effects on the Three Memory Types

Research indicates that long-term aerobic exercise benefits working and episodic memory, whereas single sessions show no significant effects [?, ?]. For motor memory, existing studies show that both single and long-term sessions are beneficial [?, ?], though no research has directly compared these durations. Additionally, single-session aerobic exercise enhances priming effects [?], but no studies have examined long-term exercise effects on priming.

Exercise intensity differentially affects the three memory types. High-intensity exercise (>70% HRmax) impairs working memory [?], while moderate intensity (40-59% HRmax) shows the greatest benefits [?]. Conversely, high-intensity exercise (>76% HRmax) better enhances episodic memory [?], and high-intensity exercise (>80% HRmax) can also promote implicit memory [?], though it may cause fatigue or interference [?].

Regarding exercise modality, open-skill activities (e.g., volleyball) benefit working memory more than closed-skill activities (e.g., running) [?, ?], while cycling promotes episodic memory and running has minimal effect [?]. Cycling also benefits motor memory [?].

The timing of exercise relative to memory stages shows common patterns across memory types. Exercise before encoding benefits working [?], episodic [?], and implicit memory [?]. Exercise during encoding impairs working [?] and episodic memory [?]. Exercise during consolidation enhances episodic [?] and implicit memory [?]. Since working memory consolidation is brief (approximately 500-2000 ms) [?], investigating exercise effects during this phase is challenging. Additionally, no studies have examined how exercise during encoding affects implicit memory.

Overall, aerobic exercise promotes all three memory types to some degree, though these effects are moderated by memory type, exercise duration, intensity, and the memory stage during which exercise occurs, as summarized in Table 1
.

Table 1 Effects of Aerobic Exercise on Working Memory, Episodic Memory, and Implicit Memory and Their Moderating Variables

Level	Working Memory	Episodic Memory	Implicit Memory
Exercise Duration Memory Stage	Long-term exercise		

Note: "↑" indicates significant memory enhancement, "↓" indicates significant memory impairment, "–" indicates non-significant effects.

2 Neurobiological Mechanisms of Aerobic Exercise Effects on Memory

Stillman et al. (2020) proposed that aerobic exercise may affect the brain and cognition at multiple levels: molecular and cellular, brain structure and function, and psychological states and higher-order behaviors [?]. We first describe key molecules (brain-derived neurotrophic factor, BDNF) and brain structures (hippocampus) affected by aerobic exercise, then discuss mechanisms underlying effects on different memory types.

2.1 Effects on BDNF

Aerobic exercise regulates memory-related hormones, promotes BDNF production, alters membrane receptor expression and translocation, activates multiple pathways, and consequently changes synaptic plasticity to enhance memory [?]. Mouse studies show that lactate metabolites released during muscle exercise cross the blood-brain barrier and induce BDNF expression in the hippocampus [?], while simultaneously promoting synthesis of irisin (a fibronectin type III domain-containing protein fragment), which also facilitates BDNF expression [?]. Additionally, FNDC5/irisin stimulates the cAMP/PKA/CREB pathway in mouse and human brain slices, representing a potential mechanism for exercise' s neuroprotective effects in Alzheimer' s disease, though whether FNDC5/irisin mediates other exercise effects on the nervous system (such as neurogenesis) remains unexplored [?].

Animal studies consistently identify BDNF as a mediator between aerobic exercise and memory [?, ?]. However, whether BDNF mediates exercise effects on memory in humans remains debated. In one meta-analysis, 7 of 16 human studies observed increased BDNF levels post-exercise [?]. Of these 16 studies, 10 examined correlations between BDNF and memory, with 4 observing mediating effects of BDNF [?]. These four studies involved young men (~22 years) [?] and older adults (60-77 years, 45% male) [?], all with healthy participants. Exercise protocols included single-session 40-minute running [?], 3-month running [?], and 6-week stationary cycling [?, ?]. All four studies measured episodic memory, with BDNF assessed immediately before and after the final exercise session.

In summary, detecting BDNF' s mediating role may depend on exercise intensity, timing relative to memory stages, memory type, and BDNF measurement timing. High-intensity exercise before encoding may induce BDNF changes that affect episodic memory. Regarding measurement timing, BDNF levels increase after single-session exercise but return to baseline within hours [?]. Therefore, measurements taken long after exercise may miss these elevations. One study examining 5 weeks of aerobic exercise (35 minutes/day, 5 days/week) in older adults measured BDNF an average of 3.8 days post-exercise and found no increase [?], indicating that BDNF changes are relatively transient and best captured immediately after exercise.

Individuals with specific genotypes may show greater BDNF expression and episodic memory improvements with long-term exercise. Hopkins et al. found that allele status (Val-Val or Val66Met polymorphism) relates to BDNF expression [?]. Among participants who completed four weeks of exercise plus exercise on the final day, only Val-Val homozygotes showed significant improvements in object recognition memory, while Val66Met heterozygotes did not, further supporting the link between long-term exercise, BDNF expression, and episodic memory enhancement.

2.2 Effects on the Hippocampus

Aerobic exercise influences brain structure and function through molecular and cellular changes, ultimately affecting memory. For memory encoding and consolidation, increased serum levels of BDNF and other molecules activate memory-related brain regions, thereby enhancing memory. One study found that six weeks of cycling increased BDNF levels and produced significantly different activation patterns in the left anterior hippocampus between exercise and control groups, with activation changes correlating positively with BDNF level changes [?]. Regarding exercise’ s ability to reduce forgetting, Crawford et al. (2020) proposed a hypothetical mechanism: single-session exercise activates the vagus nerve or muscle spindles, transmitting signals via the brainstem to the amygdala, medial prefrontal cortex, and dentate gyrus, increasing neural activity in these regions; long-term exercise promotes cell generation and enhances functional connectivity in these areas, thereby reducing forgetting [?].

Both single and long-term aerobic exercise can alter hippocampal activation. Evidence indicates that even low-intensity (30% VO2max) 10-minute cycling can rapidly enhance functional connectivity between the hippocampal DG/CA3 region and cortical areas [?]. Friedl-Werner et al. (2020) used fMRI to compare episodic memory and hippocampal activation changes between 6-month bed rest and jumping exercise groups, finding no significant differences in episodic memory but increased BOLD signals in the left hippocampus and parahippocampal gyrus in the bed rest group, suggesting functional deficits due to inactivity [?].

Aerobic exercise not only activates the hippocampus but also promotes neurogenesis. Van Praag et al. (2005) demonstrated that exercise promotes hippocampal neurogenesis in adult mice [?]. Adult hippocampal neurogenesis is driven by a neural stem cell pool in the subgranular zone of the dentate gyrus; neural stem cells activate from a quiescent state to produce neural progenitor cells that divide, generate neurons, and integrate into existing hippocampal networks, a process continuously regulated by hippocampal plasticity demands. Neurogenesis levels decline slowly with age [?], but aerobic exercise can slow or even reverse this decline. An fMRI study showed increased cerebral blood volume in the dentate gyrus of both mice and humans after aerobic exercise intervention, correlating with neurogenesis [?]. Additionally, 12 weeks of brisk walking training increased anterior dentate gyrus volume in young participants [?].

2.3 Mechanisms Affecting Different Memory Types

For working memory, single-session low-intensity (30% VO2max) cycling improved spatial working memory while increasing prefrontal oxyhemoglobin levels [?]. In another study, 34 older adults who completed 12 weeks of moderate-intensity (58.2% HRmax) cycling showed enhanced right frontoparietal functional connectivity and improved working memory performance, with positive correlations between connectivity and task performance [?]. An fMRI study with middle-aged and older adults revealed that open-skill exercise groups showed better spatial working memory and stronger activation in the prefrontal cortex, anterior cingulate cortex/supplementary motor area, and hippocampus compared to closed-skill groups [?].

Episodic memory is maintained by the medial temporal lobe and related networks, with long-term potentiation enhancing communication between cells in these regions. BDNF promotes long-term potentiation, thereby improving episodic memory [?]. Endocannabinoid system changes may also represent a mechanism through which exercise influences episodic memory [?].

Aerobic exercise enhances motor memory through dopaminergic mechanisms [?], alters electrical signals in motor cortex [?], and protects motor memory consolidation from interference [?, ?]. Exercise protects the primary motor cortex from rTMS-induced interference, thereby preserving motor memory [?], and enhances motor memory by inducing activation in frontal brain regions and altering white matter microstructure in frontotemporal fiber tracts [?].

3 Summary and Future Directions

Future research should investigate factors related to memory, aerobic exercise, and participants to better understand exercise effects and neurobiological mechanisms. Memory-related factors include memory type; exercise-related factors include timing (when exercise begins relative to memory stages and duration), intensity, and cognitive engagement; participant-related factors include sex and age.

3.1 Effects on Multiple Memory Types

Aerobic exercise effects on various memory types require further investigation. Episodic memory can be subdivided into item memory (memory for event content) and source memory (memory for contextual details and surrounding circumstances) [?, ?]. Future research should examine whether aerobic exercise differentially affects these components. Current findings show that single-session exercise before and after encoding promotes source memory [?, ?], while exercise during encoding impairs it [?]. Event-related potential measurements indicate that parietal old/new effects related to memory processing—brain waves occurring 400-900 ms after stimulus presentation with amplitudes exceeding 8 V during recognition tasks—are observable during exercise but not at rest, possibly due to inefficient source encoding during exercise [?]. The effects of aerobic exercise on source memory and their mechanisms warrant further exploration.

Aerobic exercise may enhance memory for emotionally valenced material. Recent research found that exercise enhanced memory for sad images in women and positive images in men [?]. Future studies should explore effects on other emotion types and, within ethical boundaries, investigate exercise interventions for individuals with anxiety or traumatic memories, which could have practical implications for psychological disorder interventions.

For some memory types, animal models provide substantial evidence, but human research is urgently needed. For instance, 30 animal experiments have examined exercise effects on visuospatial memory, compared to only 2 human studies [?]. Regarding implicit memory priming paradigms, only 3 human studies exist, with none examining long-term aerobic exercise effects [?]. Whether animal findings generalize to humans remains to be tested.

3.2 Effects of Exercise Timing and Duration

Both when to initiate exercise (timing) and how long to exercise (duration) are temporal factors that moderate exercise effects. Exercise timing relative to memory stages shows moderating effects. Current evidence indicates that exercise before encoding and during consolidation benefits implicit memory [?, ?], but no studies have examined exercise during encoding. Research shows exercise during encoding may impair explicit memory, including working [?] and episodic memory [?], possibly due to attentional distraction [?], as both implicit and explicit memory encoding depend on attention [?]. We can hypothesize that exercise during encoding may also impair implicit memory. Investigating exercise during encoding would provide theoretical value for understanding relationships among exercise, attention, and memory and whether exercise affects implicit and explicit memory similarly.

Future research should compare long-term versus single-session exercise effects on implicit memory. While long-term exercise benefits working and episodic memory more than single sessions, whether this generalizes to implicit memory remains unknown. Different exercise durations may benefit different memory types, as one mouse study found single-session running impaired recognition memory while long-term running enhanced spatial learning [?]. This may reflect differential gene expression: the CaM-K signaling system is active in both single and long-term running, while the MAP-K/ERK system is more activated by long-term running [?]. Current research focuses heavily on single-session effects, but individuals with regular exercise habits typically engage in long-term activity, making comparisons between long-term and single-session effects important for ecological validity.

3.3 Effects of Exercise Intensity and Cognitive Engagement

Whether high-intensity exercise enhances memory remains debated, primarily because intensity effects must be considered alongside other moderating factors such as timing and duration. Loprinzi’ s (2018) meta-analysis found that high-intensity exercise before encoding benefited episodic memory, while high-intensity exercise after encoding had no effect [?]. However, this meta-analysis included only one study of post-encoding high-intensity exercise, limiting result stability. If high-intensity exercise occurs after encoding, increasing the interval between exercise and subsequent retrieval may be beneficial. Single-session high-intensity exercise (80% HRR) impairs working memory [?], whereas long-term high-intensity exercise (70% VO2R) benefits it [?]. Future research should incorporate both objective physiological intensity measures and subjective psychological measures like rating of perceived exertion [?].

Beyond intensity, cognitive engagement during exercise warrants attention. Some aerobic exercises require high cognitive engagement, while others do not, with higher engagement potentially benefiting memory more. Although running is common, it has minimal effect on episodic memory when performed before encoding [?]. Volleyball produces greater working memory improvements than running [?]. Future research should explore effects of other exercise modalities, particularly comparing open-skill exercises (e.g., roller skating, ball sports) with closed-skill exercises (e.g., rope jumping, swimming, stair climbing) on working memory.

3.4 Effects on Different Populations

Aerobic exercise may affect memory differently across age groups. Behaviorally, both young and older adults tend to recall or forget events holistically, though older adults show lower levels of holistic retrieval that declines significantly with age [?]. Exercise habits correlate positively with episodic memory in young adults but not in older adults [?]. fMRI research shows age-related differences in hippocampal activation during memory processing, with hippocampal specificity increasing with age [?]. Therefore, age may moderate the relationship between aerobic exercise and memory.

Research has not reached consensus on whether sex moderates exercise-memory relationships. Loprinzi and Frith (2018) summarized psychological and physiological reasons for sex differences in memory, including higher emotional intensity in women, more detailed encoding styles, and differences in estrogen levels and activation of the hippocampus, frontal, and temporal lobes [?]. Behaviorally, exercise enhanced memory for sad images in women and positive images in men [?], yet a meta-analysis on episodic memory found no sex moderation [?]. Future research should focus on sex differences in exercise effects on memory.

3.5 Neurobiological Mechanisms

Mature BDNF (mBDNF) is formed through enzymatic modification of proBDNF (precursor BDNF). One study found that single-session high-intensity cycling (85% VO2R) increased mBDNF but not proBDNF, with Val-Met heterozygotes showing lower mBDNF concentrations than Val-Val homozygotes post-exercise [?]. Although aerobic exercise does not benefit episodic memory in Val-Met heterozygotes, high volumes of exercise can offset Met gene-related working memory deficits [?]. Therefore, Val-Met heterozygotes still need aerobic exercise to improve working memory, and future research should investigate optimal exercise protocols and mechanisms for this population.

Most research focuses on episodic memory, with few studies examining BDNF mediation between exercise and implicit memory, yielding mixed results. One study found higher BDNF levels 1 hour and 7 days after cycling correlated positively with better visuomotor tracking performance [?], while others found no relationship between post-exercise BDNF and motor memory tasks [?, ?]. Future studies should use exercise-sensitive memory tasks like visuomotor precision tracking tasks.

High-intensity exercise may benefit episodic [?] and implicit memory [?], with BDNF potentially mediating dose-dependent intensity effects. Two studies found high-intensity exercise enhanced BDNF levels more than low-intensity exercise and control conditions [?, ?], and a meta-analysis found higher exercise intensity produced greater BDNF concentrations [?]. Therefore, high-intensity exercise may be necessary to elevate BDNF and improve memory.

Exercise intensity may affect brain structure and function, thereby influencing memory. Mouse studies show hippocampal neurogenesis increases linearly with exercise intensity [?]. Future research should examine whether exercise timing, intensity, and cognitive engagement affect neurotransmitter systems and brain activation to understand underlying mechanisms. Aerobic exercise may influence memory through multiple neurotransmitter systems—glutamatergic, cholinergic, dopaminergic, and GABAergic—reducing proactive interference [?]. Neuroimaging can assess exercise effects on memory-related brain activation and volume changes. Herold et al. (2020) recommend stricter study designs with precise exercise protocols and fMRI processing descriptions, applying more complex filtering methods in analyses [?]. Research shows the left hemisphere may undergo more severe age-related atrophy [?], and aerobic exercise effects on brain structure and function show left lateralization—for example, brisk walking increases left anterior dentate gyrus volume [?], and cycling alters left anterior hippocampal activation patterns [?]. Future studies should use lateralization tests to investigate whether aerobic exercise maintains health in brain regions vulnerable to aging.

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(Corresponding author: Wang Bo, E-mail: wangbo@cufe.edu.cn)

Author Contributions: Ke Jinhong: Implementation of research process, manuscript drafting, response to reviewer comments. Wang Bo: Research conceptualization and design, revision suggestions, final version editing.

Note: Figure translations are in progress. See original paper for figures.