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The Impact of Exercise on Cognitive Function: A Comprehensive Review

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ABSTRACT

Cognitive health is crucial to learning, productivity, and overall well-being across the lifetime. Exercise is one of the most accessible and promising lifestyle factors that can enhance long-term brain resilience and improve cognitive performance, according to mounting data. This review summarizes recent research on the effects of several exercise modalities, including resistance training, high-intensity interval training, aerobic training, and mind-body techniques, on key cognitive domains, including processing speed, executive function, attention, and memory. Acute effects are discussed with emphasis on the immediate improvements in attention and processing efficiency following single bouts of exercise, alongside moderating factors such as age, fitness level, and exercise intensity. Chronic effects are examined across developmental stages, highlighting how regular physical activity supports neural development in children, optimizes performance in adults, and mitigates age-related cognitive decline in older populations. The neuronal, circulatory, metabolic, inflammatory, and psychological mechanisms that underlie these advantages are examined. Differential effects in certain populations, such as those with moderate cognitive impairment or chronic conditions, are assessed along with comparative data across modalities. Key methodological limitations, such as varied protocols and uneven cognitive testing methods, are addressed. Practical implications for education, clinical practice, and public health settings are offered, along with future research goals focused on standardized outcome measures, dosage response elucidation, and individualized exercise prescriptions. Overall, the data suggest that exercise is a potent, scalable method for improving cognitive performance and fostering brain health throughout life.

Keywords: *Exercise, Cognitive function, Neuroplasticity, Physical Activity, and Brain Health.*

Introduction

Cognitive health has become an increasingly relevant concern as societies face escalating academic, occupational, and aging-related demands on mental function. Research continuously reveals that cognitive skills such as attention, memory, and executive control are crucial for learning, decision-making, and general quality of life [1, 2].

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At the same time, worldwide trends reveal a growing burden of cognitive decline related to sedentary behaviors and noncommunicable diseases, underlining the need for effective preventative interventions [3, 4]. These issues have sparked a great deal of interest in finding lifestyle modifications that can improve cognitive resilience over the course of a person's lifetime. Exercise has become one of the most effective behavioral therapies among them, with empirical backing [5, 6].

Research over the past two decades has demonstrated that exercise influences multiple cognitive domains through mechanisms involving neural, vascular, metabolic, and psychosocial pathways. Aerobic activity has been associated with increased executive function and memory via accelerated neurogenesis and synaptic plasticity [2, 5], whereas resistance training contributes to cognitive enhancement through hormone modulation and improved functional ability [7, 8]. These advantages extend across age groups, with studies indicating increased academic performance in children, heightened cognitive flexibility in adults, and lower risk of neurodegenerative deterioration in elderly persons [1, 9]. Together, this research portrays exercise as an effective, accessible strategy for protecting and enhancing brain function throughout life.

An increasing body of experimental and clinical studies has also exposed the immediate impact of single exercise sessions on cognition.

Due to quick changes in arousal levels, neurotransmitter availability, and cerebral blood flow, brief bursts of aerobic or coordinative activity have been demonstrated to quickly improve working memory, attention, and processing speed [10, 11]. These short-term effects appear sensitive to exercise intensity, fitness level, and age, suggesting personalized responses driven by physiological and developmental factors [12, 13]. As a result of long-term anatomical and functional changes in the brain, chronic exercise therapies also show more resilient neurocognitive results [2, 4]. The intricate relationship between exercise dosage, duration, and cognitive advantages is shown by this contrast between acute and chronic effects.

Despite these consistent findings, the literature exhibits substantial variability in methodology, including differences in exercise modalities, intensities, intervention durations, and cognitive assessment tools. These inconsistencies have made it challenging to compare studies directly and to interpret effect sizes across populations [3, 8]. Additionally, a lot of research lacks mechanistic integration, frequently reporting behavioral findings without matching molecular markers that explain how exercise improves cognition [2, 6]. Comprehensive syntheses that assess evidence across modalities, time periods, and populations while placing findings within accepted theoretical frameworks are therefore still desperately needed. Such integrative analysis is vital for turning research into practical recommendations for public health, education, and clinical practice.

The objective of this review is to present an organized, thorough synthesis of existing research on the impact of exercise on cognitive performance across the lifetime. It explores cognitive domains related to exercise, compares effects across modalities, and differentiates between acute and chronic results. Mechanistic mechanisms incorporating neuroplasticity, vascular function, metabolic control, and psychosocial impacts are also examined to build a cohesive understanding of how exercise alters cognitive performance. Special populations, including children, older adults, and persons with chronic or neurodevelopmental problems, are also examined to highlight differential responsiveness and clinical consequences. Along with identifying objectives for further research, the review also addresses methodological shortcomings in the body of current literature and provides conclusions for real-world application. Overall, this comprehensive approach aims to clarify the scope, strength, and practical relevance of exercise-induced cognitive enhancement, offering guidance for optimized application in academic, occupational, clinical, and community settings.

Cognitive Domains Relevant to Exercise

Cognitive functioning comprises several core domains that underpin learning, decision-making, and adaptive behavior. Among these, attention, executive function, memory, and processing speed are the domains most frequently examined in exercise–cognition research because they directly influence academic performance, daily functioning, and long-term brain health [2, 14]. Attention involves the ability to selectively process relevant stimuli and sustain focus over time, and it is essential for efficient information handling [1, 15]. Planning, problem-solving, and goal-directed behavior are supported by executive processes such as inhibition, working memory, and cognitive flexibility [14, 16]. Across the lifespan, memory, which includes encoding, consolidation, and retrieval, is essential for learning and adaptation [14, 16].

Overall cognitive efficiency is influenced by processing speed, a fundamental domain that controls the quick execution of mental operations, particularly in taxing tasks [3, 17]. These areas provide the backbone of most scientific examinations studying how exercise impacts cognitive ability. Figure 1 illustrates the key domains that collectively form the foundation of human cognitive functioning. Attention, executive function, memory, language, and visuospatial skills are among them. Every domain supports a distinct facet of how people interact with their surroundings, solve issues, and process information. In the context of exercise–cognition research, these domains are essential because they represent the cognitive capacities most responsive to physiological and neurobiological alterations generated by physical activity. By showing these components together, the graphic emphasizes how multiple cognitive processes work in an integrated manner to shape total mental performance.

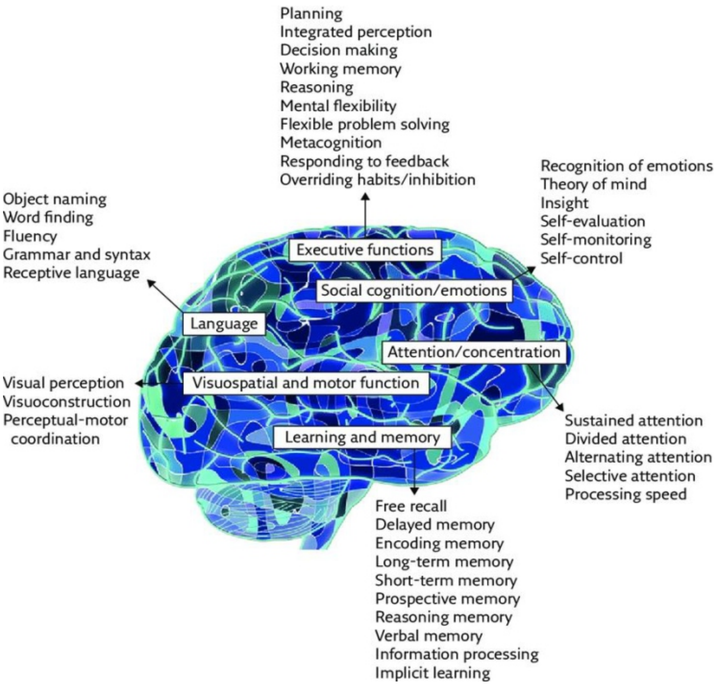

Figure 1. Domains of cognitive function. This figure depicts the major domains of cognitive function, including attention, memory, executive function, language, and visuospatial abilities, which together support overall mental performance.
***Source:** [18]*

These cognitive domains are particularly susceptible to physical activity due to their considerable dependence on brain systems that demonstrate great metabolic and structural plasticity. Exercise generates elevations in cerebral blood flow, neurotrophic factors such as BDNF, and neurotransmitter concentrations that directly support the neuronal circuits underpinning attention and executive activities [10, 11]. Similar to this, memory systems, particularly the hippocampus, are sensitive targets for both acute and long-term training because they react strongly to increases in neurogenesis and synaptic plasticity brought on by exercise [2, 4]. Processing speed benefits from greater white matter integrity and enhanced cardiovascular efficiency, which enable faster neuronal signaling and cognitive throughput [6, 8]. These mechanisms explain why even brief bouts of exercise can transiently enhance attention and processing efficiency, while long-term exercise yields more durable improvements in executive function and memory across age groups [1, 19]. The convergence of neural adaptability, vascular responsiveness, and metabolic regulation positions these domains as highly modifiable through physical activity.

Assessment of these cognitive domains in exercise research is also influenced by the sensitivity of cognitive tests, which varies according to timing, measurement type, and task demands. Timing is critical: acute exercise effects are typically captured within minutes to hours using tasks that detect rapid changes in arousal or processing efficiency, whereas chronic adaptations are assessed after weeks or months using more stable neuropsychological measures [11, 12]. Measurement type also impacts findings, since computerized activities allow exact detection of response time and accuracy changes, while standardized neuropsychological batteries provide broader insights into executive or memory performance [2, 15]. Task demands, including complexity, inhibitory control load, working memory burden, and speed requirements, impact the degree to which exercise-related alterations can be observed [14, 19]. Because they rely on brain networks that are more sensitive to physiological modulation, more difficult tasks, like dual-task evaluations or sophisticated executive-function paradigms, frequently show stronger exercise-related effects [6, 8]. Understanding these methodological factors is critical for assessing diversity in the research and for creating studies that accurately capture the cognitive impact of physical activity.

Table 1. Characteristics of cognitive domains sensitive to physical activity interventions

Cognitive Domain	Core functions	Why It Is Responsive to Physical Activity	Common Assessment Tests
Attention	Selective and sustained focus	Exercise enhances arousal regulation and frontoparietal network efficiency [11, 12].	Continuous Performance Test (CPT); Stroop Attention Subscores
Executive Function	Inhibition, flexibility, planning	Aerobic and acute exercises increase prefrontal activation, improve synaptic efficiency, and modulate catecholamines [14, 20]	Stroop Test; Trail Making Test Part B; Wisconsin Card Sorting Test
Memory	Working and long-term memory processes	Activity stimulates hippocampal neurogenesis and increases BDNF, supporting encoding and consolidation [2, 4]	Digit Span; Rey Auditory Verbal Learning Test (RAVLT)
Processing Speed	Speed of mental operations	Exercise improves white-matter integrity and neural conduction efficiency [21, 22]	Trail Making Test Part A; Symbol Digit Modalities Test

Exercise Modalities and Key Training Characteristics

Exercise influences cognition through diverse physiological and neurobiological pathways, and different activity types produce distinct cognitive outcomes. Recent evidence shows that variables such as modality, intensity, duration, frequency, and progression play critical roles in determining the magnitude and specificity of cognitive benefits [2, 23]. Understanding how exercise type and training characteristics influence neurocognitive responses allows for more targeted and effective interventions designed to enhance brain health across the lifespan [24].

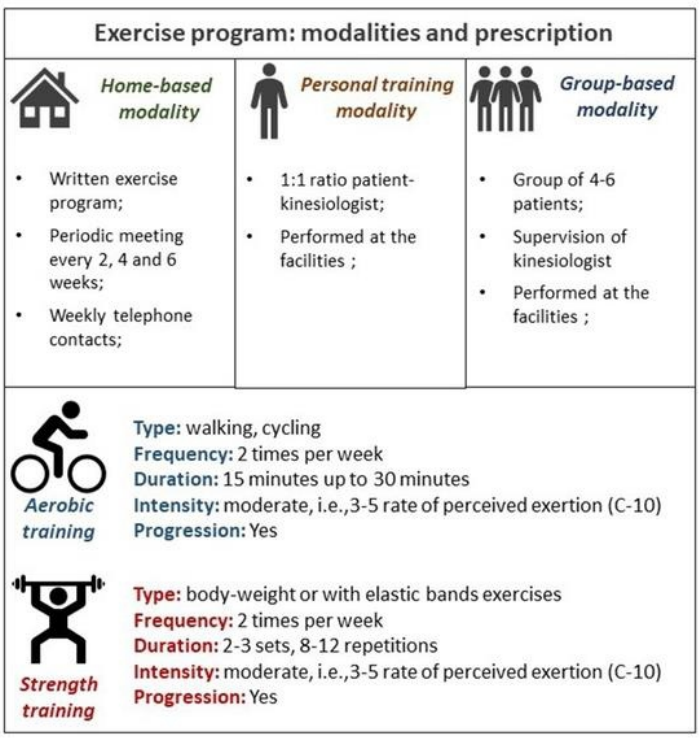

Figure 2. Exercise program modalities and prescription. This figure illustrates different exercise program modalities and their prescription, highlighting variations in type, intensity, frequency, and duration to optimize physical and cognitive outcomes.
***Source:** [25]*

Exercise Types: Aerobic, Resistance, HIIT, Coordination-Based, and Mind–Body

Aerobic exercise is the most consistently linked to cognitive improvements, particularly in executive function and memory, due to its effects on cerebral blood flow, neurogenesis, and hippocampal plasticity [22, 23]. Resistance training contributes to cognitive gains through pathways involving neuromuscular activation, hormonal regulation, especially IGF-1, and enhanced white-matter integrity [8, 24]. High-intensity interval training (HIIT) produces rapid increases in arousal and catecholamines that enhance attention and inhibitory control in the short term [26]. Coordination-based exercises such as dance and complex motor training enhance executive and visuospatial abilities by engaging sensorimotor integration and cognitive motor coupling [27, 28]. Mind–body modalities, including yoga and tai chi, support cognitive performance through stress reduction, autonomic balancing, and improved functional connectivity [29, 30].

Key Training Variables: Intensity, Duration, Frequency, and Progression

Exercise intensity influences cognitive outcomes by modulating arousal, neurotrophic activity, and acute neurochemical responses. Moderate-to-vigorous intensities consistently enhance executive function and memory, whereas very high intensities mainly benefit attention and inhibitory processes [12]. Duration determines the magnitude of acute and chronic neurobiological responses, with longer sessions promoting stronger neurotrophic and cardiovascular effects [31]. Training frequency supports cumulative neural adaptations and maintenance of cognitive gains over time [2, 23]. Progression, gradually increasing exercise intensity, load, or complexity, prevents adaptation plateaus and optimizes long-term cognitive improvements [5].

How Modality and Training Characteristics Influence Cognitive Outcomes

The interaction between exercise type and training variables shapes domain-specific cognitive effects.

Aerobic training combined with moderate-to-vigorous intensity enhances executive function and memory, whereas resistance training with progressive loading improves working memory, attention, and processing speed [8, 22]. HIIT yields rapid but transient cognitive improvements, making it particularly effective for short-term attention and inhibitory tasks [26]. Coordination-based training enhances cognitive motor integration and is especially effective for executive and visuospatial functions [27, 28]. Mind–body exercises require consistent frequency and duration to produce meaningful cognitive changes via regulation of stress, mood, and neural connectivity [29, 30]. Thus, cognitive outcomes are determined not only by what type of exercise is performed but also by how it is structured and progressed over time.

Table 2. Exercise types/modalities, training characteristics, cognitive outcomes and mechanisms

Exercise types/modalities	Key training characteristics	Primary Cognitive Domains Affected	Mechanisms	References
Aerobic	Moderate–vigorous, 20–60 min, 3–5×/week	Executive function, memory	↑ BDNF, cerebral perfusion, hippocampal plasticity	[22, 23]
Resistance	Progressive load, 2–4×/week	Working memory, processing speed	↑ IGF-1, improved white-matter integrity, neuromuscular activation	[8, 24]
HIIT	Short intervals, high intensity, 2–3×/week	Attention, inhibitory control	Catecholamine surge, acute arousal, cardiovascular activation	[26, 32]
Coordination-based	Complex motor tasks, 2–4×/week	Executive function, visuospatial skills	Sensorimotor integration, neuroplasticity, cognitive–motor coupling	[27, 28]
Mind–body	Low–moderate intensity, 3–5×/week	Attention, executive function, stress regulation	Autonomic regulation, functional connectivity, mood improvement	[29]

Acute Cognitive Effects of Exercise

A single session of physical exercise (referred to as "acute exercise") has been increasingly studied for its potential to produce rapid, short-term enhancements in cognitive performance. Rather than long-term training adaptations, acute effects capture immediate neurophysiological responses such as heightened arousal, increased cerebral perfusion, and neurochemical changes that may transiently boost cognition. Recent comprehensive reviews and meta-analyses provide empirical support for such effects across different populations, task types, and exercise modalities [33]. Understanding these immediate effects and their moderators is important for applying exercise strategically, for instance, before exams, work, or cognitively demanding tasks.

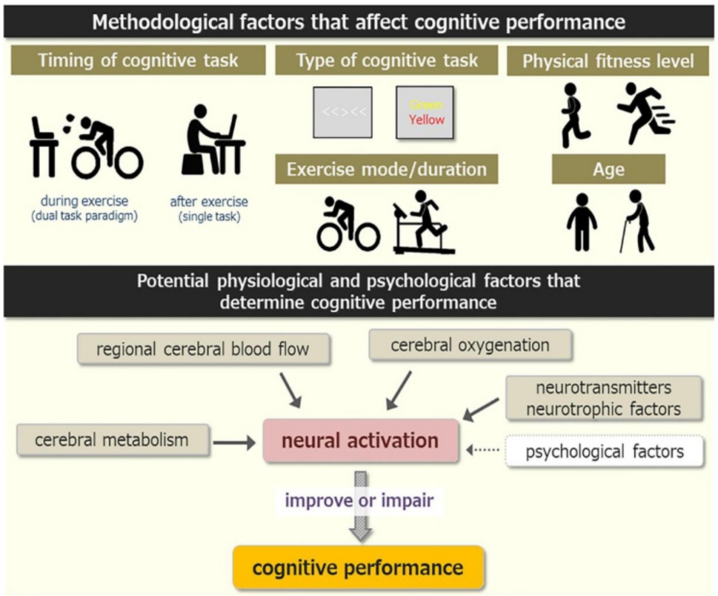

Figure 3. Determinants of Acute Cognitive Performance Following Exercise. The figure shows the determinants of acute cognitive performance following exercise, showing how factors such as exercise type, intensity, duration, and individual characteristics influence immediate cognitive responses.
Source: *[34]*

Immediate Cognitive Changes Following a Single Exercise Bout

Acute exercise, defined as a single session of physical activity, can transiently increase cognitive ability. Short-term neurophysiological changes, such as increased cerebral blood flow, enhanced alertness, and elevated levels of neurotrophic factors like BDNF, are responsible for these instant gains, according to empirical findings [33, 35], as shown in Figure 3. Meta-analytic evidence suggests that a single bout of exercise provides small-to-moderate cognitive benefits. Acute exercise has an overall effect size of SMD = 0.33 on cognition, including attention, executive function, memory, and information processing, according to a meta-analysis of 30 systematic reviews [33].

Further, a Bayesian meta-analysis of 113 studies in healthy young adults found a small but statistically significant improvement in cognitive task performance, particularly in tasks assessing working memory and inhibitory control, with faster reaction times compared to rest conditions [36]. Experimental studies corroborate these findings; for instance, single bouts of high-intensity aerobic or resistance exercise can transiently improve cognitive performance via enhanced cerebral perfusion and neural excitability [37]. These studies collectively indicate that even a single session of physical activity can produce meaningful short-term cognitive benefits, although the magnitude of effect is modest and likely temporary.

Domains Most Influenced Acutely

Not all cognitive domains respond equally to acute exercise. Research consistently identifies attention, processing speed, and executive functions (particularly working memory and inhibition) as the most sensitive to a single bout of exercise [33, 35].

i. Attention and Processing Speed: Tasks requiring alertness, reaction time, and rapid information processing show the largest acute gains. These domains benefit from exercise-induced increases in arousal and catecholamine release, which enhance neural efficiency and response speed [33].

ii. Executive Function: Working memory and inhibitory control tasks are also responsive, though effect sizes are smaller than for attention. Improvements in these domains suggest that acute exercise enhances top-down cognitive control mechanisms temporarily [36].

iii. Memory: Evidence for acute improvements in short-term or episodic memory is mixed; some studies show small benefits, but these are less consistent than for attention and executive function [38].

Thus, acute exercise appears most beneficial for cognitive processes that rely on fast information processing, attentional allocation, and short-term executive control. Tasks with higher cognitive load or complex reasoning show less consistent improvement.

Moderators of Acute Responses

Several factors moderate the cognitive effects of a single exercise bout (**See figure 3 and Table 3**), and they're discussed below:

i. Age: Younger adults generally show more consistent acute improvements compared to older adults, likely due to greater neuroplasticity and vascular responsiveness [33]. Children also benefit in executive function tasks, though effect sizes are modest [35].

ii. Fitness Level: Baseline fitness influences acute responsiveness; individuals with higher cardiorespiratory fitness may exhibit enhanced executive function gains, whereas sedentary individuals may show smaller or more variable improvements [36].

iii. Cognitive Load / Task Complexity: Simple tasks, such as reaction time or attention show the most reliable improvements. In contrast, tasks requiring complex reasoning, multi-step planning, or episodic memory demonstrate smaller or inconsistent benefits [38].

iv. Exercise Intensity: Moderate-to-high intensity aerobic or resistance exercise tends to produce greater cognitive gains than low-intensity activity. High-intensity intervals may transiently boost executive function, but excessively strenuous bouts could potentially induce fatigue and reduce cognitive performance [37].

These moderators explain variability across studies and highlight that both individual characteristics and exercise parameters influence the magnitude of acute cognitive effects.

Table 3. Acute response moderators

Moderate	Impact on Acute Cognitive Response
Exercise Intensity and Type	Moderate-to-vigorous aerobic and strength training appears to yield more stable cognitive benefits; high-intensity bouts exhibit effects over resting control but are not always superior to moderate intensity [37].
Timing of Cognitive Assessment	Maximal effects observed when cognitive testing occurs immediately after exercise. Delays of 30–60 minutes or more tend to reduce or eliminate gains [33].
Baseline Cognitive or Health Status	Individuals with cognitive impairment or lower baseline cognitive performance may experience comparable or slightly stronger acute benefits in executive function, though reactions in memory or processing speed remain inconsistent [38]
Age / Developmental Stage	Evidence in youths (e.g., children/adolescents with neurodevelopmental conditions) shows small improvements in executive function following acute physical activity, though effect sizes are generally modest ($g \approx 0.17$) [39]
Cognitive Task Characteristics / Load	Simple reaction–time or attention tasks tend to show greater improvement than complex tasks (multi-step reasoning, episodic memory), indicating load and complexity moderate effect size [40].

Chronic Cognitive Effects of Regular Exercise

Exercise over an extended period of time results in long-lasting neurocognitive changes that go beyond the short-term gains observed following a single session. Frequent exercise promotes long-term gains in attention, memory, executive functioning, and processing speed by stimulating structural, functional, and biochemical changes. These benefits derive from cumulative effects of higher cerebral blood flow, neurotrophic signaling, metabolic management, and improved cardiovascular fitness, all of which support more efficient brain functioning and long-term cognitive stability [2, 23]. Over time, these adaptations contribute to measurable gains in cognitive performance, increased cognitive reserve, and reduced vulnerability to age-related decline.

One of the most well-established long-term effects of exercise is its capacity to induce structural brain changes, particularly in regions critical for memory and executive function. It has been repeatedly demonstrated that aerobic exercise training increases prefrontal cortex thickness, white-matter architecture, and hippocampus volume alterations linked to improved memory consolidation and cognitive control [41, 42]. Sustained increases in neurotrophic factors, such as brain-derived neurotrophic factor (BDNF), which encourage synaptic plasticity and neurogenesis, assist these structural changes [43]. Frequent exercise also improves neuronal efficiency and supports higher-order cognition by strengthening functional connectivity across large-scale brain networks, including executive control and default-mode networks [44, 45].

Across the lifespan, the chronic cognitive effects of exercise are evident but emerge differently across developmental stages.

In children and adolescents, habitual physical activity supports neurodevelopment by enhancing brain regions responsible for attention, working memory, and academic performance. Higher cardiorespiratory fitness during childhood is associated with superior hippocampal development and improved cognitive flexibility, indicating that exercise contributes directly to neurodevelopmental maturation [46]. In young and middle-aged adults, long-term exercise mitigates cognitive fatigue, enhances working-memory precision, and promotes stress resilience. Evidence shows that consistent physical activity reduces allostatic load and supports sustained executive functioning, even in high-demand environments [44, 45].

Older adults exhibit some of the most pronounced chronic cognitive benefits, as regular exercise helps slow age-related deteriorations in memory, processing speed, and global cognition. Aerobic and resistance-training programs have been shown to reduce the rate of cognitive decline and significantly enhance cognitive performance in individuals aged 60 and above [41, 47]. Importantly, structured long-term exercise contributes to neuroprotection by preserving hippocampal integrity, slowing white-matter degeneration, and maintaining functional network stability, all of which are critical for resisting the progression of mild cognitive impairment (MCI) and dementia [23, 42]. These findings underline the significance of physical exercise as a changeable behavior capable of sustaining cognitive health throughout decades.

Regular exercise also plays a crucial role in cognitive resilience and neuroprotection by influencing multiple biological and systemic pathways. Chronic participation in aerobic and resistance training reduces neuroinflammation, improves insulin sensitivity, enhances endothelial function, and promotes angiogenesis mechanisms that collectively protect neurons and support long-term brain health [2, 45]. Longitudinal research confirms that physically active adults have a substantially lower risk of developing cognitive impairment and dementia compared with sedentary individuals, highlighting the preventive potential of sustained physical activity [23]. These neuroprotective effects reflect the combined influence of metabolic, vascular, and neurotrophic adaptations, which together build cognitive reserve and support lifelong brain resilience.

Table 4. Long-term cognitive outcomes supported by chronic exercise and their evidence strength

Cognitive evidence	Long-Term Effect of Regular Exercise	Strength of evidence	References
Executive Function	Sustained improvement in cognitive control, inhibition, and flexibility	Strong, replicated across multiple RCTs	[23, 41]
Episodic Memory	Improved memory consolidation and reduced age-related decline	Moderate to Strong	[2, 42]
Processing Speed	Faster long-term information processing and reaction time	Moderate	[44]
Risk of Cognitive Impairment / Dementia	Reduced lifetime risk of MCI and dementia with continuous physical activity	Strong (longitudinal evidence)	[23]
Cognitive Resilience / Reserve	Increased resistance to stressors, illness, and aging-related neural decline	Emerging but Growing	[45]

Mechanisms Underlying Cognitive Enhancement

Exercise improves cognition through multiple interacting pathways. Some act rapidly (minutes–hours) after a single bout (e.g., neurotransmitter release, transient BDNF rises, arousal), whereas others require repeated exposure (weeks–months) to produce durable structural and functional brain changes (e.g., neurogenesis, angiogenesis, mitochondrial adaptations). Below we summarize the principal mechanisms neurobiological, vascular/metabolic, inflammatory, and psychosocial and then briefly integrate how these operate across acute versus chronic timescales.

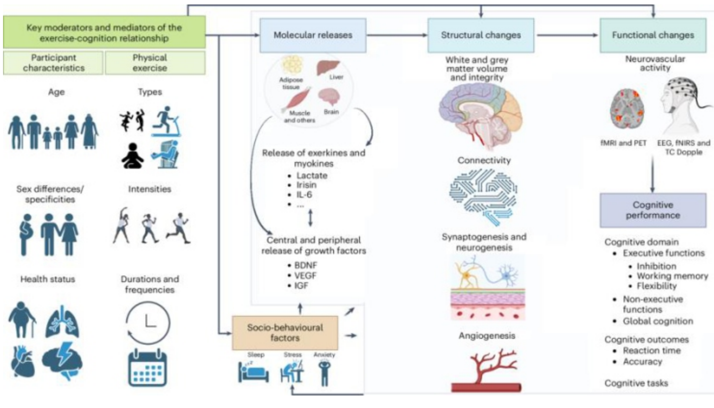

Figure 4. Overview of mechanisms underlying the effects of exercise on cognitive function. Abbreviations: BDNF: brain-derived neurotrophic factor, EEG: electroencephalography, fMRI: functional magnetic resonance imaging, fNIRS: functional near-infrared spectroscopy, IGF: insulin growth factor, IL-6: interleukin 6, PET: positron emission tomography, TC Doppler: transcranial Doppler ultrasound, VEGF: vascular endothelial growth factor.
Source: *[48]*

Neurobiological Pathways: Neurotrophic Factors (e.g., BDNF), Neurogenesis, Synaptic Plasticity

Physical exercise robustly modulates neurotrophic signalling, most notably brain-derived neurotrophic factor (BDNF), which supports synaptic plasticity, dendritic remodeling, and the survival and differentiation of neurons. Meta-analyses and recent trials show that single exercise sessions typically raise peripheral BDNF transiently and that regular training can increase baseline BDNF or augment BDNF responsiveness to activity in some populations [49, 50]. These BDNF changes are mechanistically linked to enhanced long-term potentiation (LTP) and improved memory function in animal models and are consistent with patterning of hippocampal volume gains in humans following months of aerobic training [4, 50]. Exercise also stimulates adult hippocampal neurogenesis in rodents and promotes markers of neurogenic activity in human studies indirectly (via imaging and peripheral biomarkers), supporting improved pattern separation and episodic memory with sustained training [51]. Finally, repeated exercise enhances synaptic efficacy and network reorganization (functional connectivity), providing a cellular substrate for durable gains in executive control and learning [50, 51].

Vascular and Metabolic Mechanisms: Blood Flow, Mitochondrial Function, Glycemic Regulation

Exercise improves brain perfusion, endothelial function, and metabolic support for neurons mechanisms that directly affect cognition. Acute bouts increase cerebral blood flow (CBF) regionally (e.g., frontal and hippocampal perfusion) and chronic training improves autoregulation and baseline perfusion, which supports nutrient delivery and waste clearance [52]. On a cellular level, exercise drives mitochondrial biogenesis, enhances mitophagy, and optimizes mitochondrial efficiency in neurons and glia; these changes reduce oxidative stress and improve synaptic energetics [53]. Moreover, exercise improves systemic metabolic control, insulin sensitivity, and glycemic variability, which lowers metabolic stress on the brain and is associated with better cognitive outcomes in at-risk groups [54]. Together, improved CBF, mitochondrial health, and glycemic regulation provide both immediate (better perfusion/arousal) and long-term (sustained energy supply and reduced metabolic damage) support for cognition.

Inflammatory Modulation: Reduced Systemic and Neural Inflammation

Chronic low-grade inflammation is implicated in cognitive decline and neurodegeneration. Exercise exerts anti-inflammatory effects at multiple levels: it lowers circulating proinflammatory cytokines (e.g., IL-6, TNF-α in chronic contexts, with acute transient rises from muscle), upregulates anti-inflammatory mediators, and modulates microglial phenotype toward a less neurotoxic state [55]. Emerging human studies show that regular exercise reduces markers associated with neuroinflammatory pathways and that these reductions mediate part of the association between activity and cognitive preservation in older adults and clinical groups [55, 56]. Reducing systemic inflammation improves vascular health and preserves neuronal function, which together support long-term cognitive resilience.

Psychosocial and Behavioral Pathways: Mood, Stress, Sleep, Self-Regulation

Beyond biological mechanisms, exercise improves cognition indirectly by improving mood, lowering stress, enhancing sleep quality, and strengthening self-regulatory behaviours.

Regular physical activity reduces symptoms of depression and anxiety, which otherwise impair attention and memory, and enhances sleep continuity and slow-wave sleep, both critical for memory consolidation and daytime cognitive performance [57]. Exercise also enhances self-regulation and executive resources (through routine, mastery experiences, and improved arousal regulation), translating into better sustained attention and task persistence in daily life. These psychosocial pathways interact bidirectionally with biological mechanisms: for example, improved sleep amplifies neuroplasticity and glycemic control, while lower stress reduces inflammatory signalling [58].

Table 5. Summary of key mechanisms linking exercise to cognitive enhancement

Mechanisms Domain	Key Biological/Psychological Processes	Primary Cognitive Outcomes	References
Neurobiological	↑ BDNF, neurogenesis, synaptic plasticity	Memory formation, learning	[49, 50]
Vascular and Metabolic	↑ CBF, angiogenesis, mitochondrial function, insulin sensitivity	Executive function, processing speed	[53]
Inflammatory Modulation	↓ IL-6/TNF-α chronically, microglial phenotype improvement	Cognitive resilience, reduced decline	[55, 56]
Psychosocial/Behavioral	Better sleep, mood, stress regulation	Attention, daily functioning	[57, 59]

Comparative Effects Across Exercise Modalities

Exercise modalities broadly aerobic, resistance, high-intensity interval training (HIIT), and mind–body practices differ in their physiological demands and cognitive engagement, and those differences produce partially distinct cognitive signatures. Comparative work (meta-analyses, systematic reviews, and head-to-head trials) indicates overlapping benefits across modalities but also modality-specific strengths that are important when matching programs to cognitive goals or populations.

Unique Cognitive Impacts of Aerobic vs. Resistance vs. HIIT vs. Mind–Body Modalities

Aerobic training (continuous moderate to vigorous endurance exercise) has the most consistent evidence for improving global cognition and memory-related outcomes, likely via sustained increases in cerebral perfusion, hippocampal plasticity, and cardiorespiratory fitness [41, 60]. Resistance (strength) training shows relatively larger and more reliable effects on executive functions (working memory, inhibitory control, cognitive flexibility) and processing speed, plausibly through anabolic and neuromuscular signaling (IGF-1, motor cortex engagement) and improvements in white-matter integrity [61, 62]. HIIT produces rapid cardiovascular and neurochemical responses, and meta-analytic evidence indicates small-to-moderate effects on executive control and cognitive flexibility, particularly in younger and middle-aged samples and in studies that emphasize repeated, well-tolerated interval sessions [63]. Mind–body modalities (tai chi, yoga, dance, qigong) tend to show particular strength for memory and attention in older adults and clinical groups, effects that may reflect combined physical, balance/coordination, and cognitive-attentional demands plus high adherence and stress-reducing benefits [59].

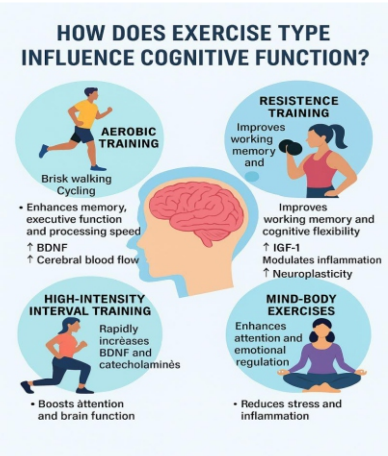

Figure 5. *Influence of exercise types on Cognitive function. This figure illustrates how different types of exercise such as aerobic, resistance, and combined training affect various aspects of cognitive function, including attention, memory, and executive function.*
Source: *[60]*

Evidence from Head-to-Head Comparison Studies

Direct comparisons are fewer than single-modality trials, but available randomized and quasi-experimental studies and multi-arm trials provide useful clues. The SYNERGIC randomized trial (older adults with MCI) found that aerobic + resistance training produced meaningful cognitive gains that were further enhanced by adding computerized cognitive training, suggesting additive or synergistic effects when modalities are combined [64]. Trials focused on resistance training (e.g., AGUEDA protocol and related RCTs) show greater executive-function gains compared with wait-list or low-activity controls and in some studies outperform low-intensity aerobic walking for executive outcomes [61]. Head-to-head meta-analytic syntheses and systematic reviews report that aerobic and resistance programs both improve cognition in older adults but that their domain-specific effects differ (aerobic → memory/global; resistance → executive) and that mind–body programs can be as effective as conventional training for some outcomes [59, 62]. Taken together, head-to-head data indicate modality-dependent strengths rather than a single "best" exercise: selection should therefore be guided by the cognitive domain of interest and participant characteristics.

Dose–Modality Interactions

Dose (intensity, duration, frequency) modulates modality effects. Intensity appears especially important for HIIT and resistance training: higher intensities produce larger acute neurochemical responses (catecholamines, BDNF) and, when appropriately dosed, greater improvements in executive functions [63]. For aerobic training, total volume and frequency (minutes/week and sessions/week) predict hippocampal and memory gains, with many trials showing cognitive improvements after 3–5 sessions/week over 12–24 weeks [41]. Resistance programs that use progressive overload and 2–3 sessions/week (30–60 min) produce the clearest executive benefits [61]. Mind–body interventions show dose dependence too, but adherence and session quality (cognitive challenge, dual-task components) often moderate effects more than raw intensity [59]. Overall, best outcomes are observed when modality and dose are aligned with the targeted cognitive domain (e.g., higher-intensity intervals for acute executive boosts; regular moderate aerobic training for sustained memory gains).

Cognitive Outcomes of Multimodal and Combined Training Programs

Multimodal programs that combine aerobic + resistance elements or pair physical training with cognitive training tend to produce larger and broader cognitive benefits than single-modality programs.

Meta-analyses and RCTs (including the SYNERGIC study and several recent meta-analytic syntheses) show that combined aerobic-resistance training improves global cognition, executive function, and memory more consistently than single-mode interventions, especially in older adults and clinical groups [62, 64]. Multi-component programs that include coordination or cognitive challenges (e.g., dance, exergaming, dual-task training) often yield additional gains in balance, visuospatial skills, and executive control, suggesting complementary mechanistic engagement. In practice, multimodal prescriptions (e.g., 2–3 sessions of aerobic + 2 resistance sessions per week, or integrated exergames) offer a pragmatic route to maximize domain-specific and generalized cognitive benefits across populations.

Table 6. Multimodal and combined training: cognitive outcomes

Training approach	Components	Cognitive outcomes	Reference
Aerobic + Resistance	Combined endurance + strength	Memory, executive function, global cognition	[62, 64]
Aerobic + Cognitive	Endurance + cognitive tasks	Executive function, attention	[63]
Mind–Body + Coordination	Yoga/Tai Chi + dual-task activities	Attention, memory, cognitive flexibility	[59]

Evidence in Special and Clinical Populations

While exercise benefits cognition in healthy adults, the magnitude and mechanisms of these benefits may differ across developmental stages, clinical conditions, and neurodevelopmental or psychiatric profiles. Tailoring interventions to population-specific needs is crucial, as cognitive deficits, neuroplastic potential, and exercise tolerance vary widely across these groups. This section reviews the current evidence across four key populations.

Pediatric Populations and Developmental Considerations

Exercise in children and adolescents supports cognitive development, particularly executive function, attention, and academic performance. Evidence from school-based and structured physical activity treatments demonstrates that moderate-to-vigorous cardiovascular exercise, coordination-rich activities, and structured sports are related to improvements in working memory, inhibitory control, and classroom engagement [40]. Positive brain structural and functional outcomes, such as increased prefrontal cortex volume and improved connections in networks underpinning attention and cognitive control, are also associated with early physical exercise [46, 50]. Importantly, exercise interventions during crucial developmental windows may increase long-term cognitive resilience and prevent early deficits associated with sedentary behavior.

Individuals with Chronic Illnesses

Chronic conditions such as cardiometabolic disease (e.g., type 2 diabetes, hypertension), neurological disorders (e.g., stroke, multiple sclerosis), and metabolic syndromes can negatively impact cognitive function. Exercise interventions in these populations demonstrate improvements in processing speed, memory, and executive function. Aerobic and combined aerobic-resistance programs improve glycemic control, vascular health, and cerebral perfusion, which are key mediators of cognitive improvement in metabolic disorders [22].

In neurological populations, including post-stroke adults, structured exercise enhances neuroplasticity and functional connectivity, translating into gains in attention, working memory, and daily cognitive functioning [50]. These findings highlight that exercise can serve both preventive and rehabilitative cognitive roles in chronic disease contexts.

Older Adults and Mild Cognitive Impairment

Cognitive decline is a fundamental problem in aging populations, with moderate cognitive impairment (MCI) indicating a critical window for intervention. In older persons with and without MCI, regular aerobic, resistance, and multimodal exercise regimens enhance executive function, memory, and overall cognition [41, 59]. Multimodal therapies, combining aerobic, resistance, and balance/coordination training, appear particularly beneficial in improving hippocampus volume and white matter integrity, thus supporting long-term cognitive resilience [50, 64]. Evidence also suggests that even low-to-moderate intensity exercise enhances attention and daily cognitive functioning, highlighting accessibility and adherence as critical aspects.

Neurodevelopmental and Psychiatric Groups

Emerging evidence indicates that exercise benefits cognition in individuals with neurodevelopmental disorders (e.g., ADHD, autism spectrum disorder) and psychiatric conditions (e.g., depression, schizophrenia). In ADHD, structured aerobic and coordinative training enhances executive function, inhibitory control, and attention [33]. In autism, interventions integrating motor coordination, aerobic activity, and cognitive engagement improve working memory and adaptive functioning [65]. Among psychiatric populations, exercise reduces cognitive deficits associated with depression and schizophrenia, particularly in domains of executive function and processing speed, likely mediated by combined neurobiological and psychosocial mechanisms [66]. These studies highlight the potential for tailored exercise interventions as adjunctive cognitive therapies in clinical populations.

Table 7. Chronic cognitive effects of exercise in special and clinical populations

Population	Exercise Type / Intervention	Key cognitive outcome	Reference
Pediatric / Developmental	Moderate-to-vigorous aerobic activity, coordination-rich activities, structured sports	↑Executive function, ↑Attention, ↑Working memory, ↑Academic performance	[40, 46, 50]
Chronic Illnesses (e.g., T2D, hypertension, stroke, MS)	Aerobic, resistance, and combined aerobic-resistance programs	↑Processing speed, ↑Memory, ↑Executive function	[22, 50]
Older Adults / Mild Cognitive Impairment (MCI)	Aerobic, resistance, multimodal (aerobic + resistance + balance/coordination)	↑ Memory, ↑ Executive function, ↑ Global cognition	[41, 50, 59]
Neurodevelopmental & Psychiatric (e.g., ADHD, autism, depression, schizophrenia)	Structured aerobic and coordinative training, motor-cognitive programs	↑ Executive function, ↑ Inhibitory control, ↑ Attention, ↑ Working memory, ↑ Adaptive functioning, ↓ Cognitive deficits in psychiatric conditions	[33, 65, 66]

Current Limitations in the Literature

Despite growing interest in the cognitive benefits of exercise, the existing literature is constrained by a number of important limitations that reduce confidence in definitive conclusions. First, there is a lack of methodological consistency and standardized exercise protocols across studies. Different investigations use highly variable exercise types (aerobic, resistance, multimodal), intensities, frequencies, and durations often without detailed reporting of parameters, which complicates comparison across studies and precludes confident prescription of optimal regimens [67]. Second, there is a lot of variation in cognitive testing and evaluation schedules. Studies employ multiple neuropsychological tests to assess cognition, frequently concentrating on distinct cognitive domains, and perform examinations at varying time points. It is challenging to compile results or determine which cognitive domains benefit from exercise the most because of this variety. Third, there is a dearth of longitudinal studies, and many exercise regimens are brief. Short-term trials may identify minor increases, but cannot tell whether cognitive enhancements are sustained over time, or whether they transfer into long-term neuroprotective effects [68].

Fourth, there is a persistent underrepresentation of diverse populations in the literature. Numerous studies focus on relatively healthy or socioeconomically advantaged groups, often excluding or under-recruiting individuals from varied ethnic, socioeconomic, clinical, or geographic backgrounds. This limits the generalizability of findings across demographic and clinical contexts [69]. Finally, there is a fragmentation between mechanistic and behavioral studies. While some research explores neurobiological mechanisms (e.g., cerebral perfusion, neurotrophic factors, brain structure, neural connectivity) linking exercise to cognitive outcomes, many behavioral studies rely only on cognitive measures without incorporating neuroimaging or biomarkers. This mismatch constrains our capacity to grasp how exactly exercise exerts neurocognitive advantages, and whether those benefits reflect permanent neuroplastic changes or transient functional adjustments [69]. Future studies must employ standardized, transparent exercise regimens, harmonized cognitive assessment batteries, longer-term longitudinal designs, representative and diverse sample sizes, and integrated mechanistic and behavioral techniques to overcome these constraints. The field won't be able to produce trustworthy, broadly applicable data on how exercise impacts cognition in various demographics and stages of life until then.

Future Research Directions

Future research should focus on standardizing exercise protocols and cognitive assessments to improve comparability across studies. Clarifying dose–response relationships is essential to determine the most effective type, intensity, and duration of exercise for cognitive benefits. To evaluate the sustainability of benefits and the underlying brain and vascular mechanisms, long-term and mechanistic experiments are required. Research should also study individualized exercise prescriptions, incorporating age, genetics, baseline fitness, and clinical state. Finally, digital, wearable-assisted, and VR-supported therapies offer prospects for exact monitoring, adherence, and tailored cognitive engagement [23, 41, 67].

Conclusion

In conclusion, regular physical exercise emerges as a robust, modifiable strategy for supporting cognitive health across the lifespan. Evidence indicates that exercise enhances neurodevelopment in youth, sustains executive functioning and resilience in adults, and preserves memory and neural integrity in older age. These benefits extend to clinical and special populations, highlighting the versatility of exercise in both preventive and rehabilitative contexts. Despite promising findings, methodological discrepancies and shortcomings in long-term, mechanistic, and varied population research underline the necessity for properly tailored interventions. Optimizing cognitive results in the future will depend on the integration of emerging digital technology, customized techniques, and standardized protocols. Ultimately, exercise is a practical and accessible way to maintain and boost cognitive function, with important implications for individual well-being and public health.

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Conflict of Interest

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