

**The Positive Impact of Physical Activity on Cognition During Adulthood:
A Review of Underlying Mechanisms, Evidence, and Recommendations**

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Synopsis

A growing body of literature suggests that physical activity beneficially influences brain function during adulthood, particularly frontal lobe-mediated cognitive processes, such as planning, scheduling, inhibition, and working memory. For our hunter-gatherer ancestors, times of famine interspersed with times of feast necessitated bouts of intense physical activity balanced by periods of rest. However, the sedentary lifestyle that pervades modern society has overridden the necessity for a physically active lifestyle. The impact of inactivity on disease processes has received a great deal of attention; the growing understanding that physical activity also has the benefit of enhancing cognitive performance strengthens the imperative for interventions that are successful in increasing physical activity, with the outcomes of promoting health and productivity. Population health and performance programs that promote physical activity provide gains for employees and employers through improvements in worker health and performance and financial returns for the company. In this review, we examine the mechanisms by which physical activity improves cognition. We also review studies that evaluate the effects of physical activity on cognitive executive performance in adulthood, including longitudinal studies that address the impact of physical activity during early adulthood and

midlife on preservation of cognition later in life. This is of particular importance given that adulthood represents prime working years and that physical activity promotion is a key component of population health and performance programs. Finally, we provide recommendations for maximizing the lasting benefits of movement and physical activity on cognition in adulthood.

Introduction

A growing body of literature indicates that physical activity is associated with improvements in brain function and cognition during childhood /1–2/ and throughout adulthood /1,3–6/. Studies in older adults suggest that aerobic activity robustly and preferentially improves performance on tasks that involve executive cognition function, such as planning, scheduling, inhibition, and working memory /4,7/. Executive cognitive processes are mediated by the frontal lobes of the brain and are subject to age-related declines /1/. Physical activity is an important component of healthy aging and preservation of cognitive function /8–10/. For example, better aerobic fitness in older adults reduces loss of brain volume in regions that mediate executive cognitive function /8,11/ and is associated with more efficient performance of executive function tasks and increased activity in brain regions that subserve such tasks /12/. Similarly, older adults with better aerobic fitness demonstrate better spatial memory performance and related increases in hippocampal volume /13/.

In addition to preservation of cognition during older adulthood, it is important to examine the acute and lasting effects of physical activity on cognition during early adulthood and midlife. In this review, we will examine potential

mechanisms by which exercise and physical activity improve brain function, particularly with respect to executive processes and performance. We will also review studies evaluating the effects of acute bouts of exercise and longer-term physical activity interventions on cognitive performance in adulthood as well as longitudinal studies that address the role of physical activity during early adulthood and midlife in preserving cognition later in life. Finally, we will provide evidence and recommendations for maximizing the benefits of physical activity on cognition through full engagement in physical activity programs, including population health and performance programs in the workplace. Population health and performance programs that promote physical activity have reported positive effects on employee health and productivity /14–16/ that translate into financial savings for employers /15,17/. In light of the growing evidence that improved cognitive performance is one of the many benefits related to physical activity, workplace interventions that are successful in increasing physical activity may promote both physical and mental health. The rationale for population health and performance programs is further strengthened by their potential to optimize cognitive performance in addition to employee health.

Evolutionary perspective on physical activity and cognition

From an evolutionary perspective, the need for movement is probably programmed into our genes /18/. Physical activity was required by our hunter-gatherer ancestors to compete for energy resources for survival. It is likely that the human genome evolved to support increased metabolic demands associated with hunting and foraging for food. Moreover, “thrifty” genotypes /19/ that maximized the human body’s ability to efficiently store and utilize fuel sources such as muscle glycogen and triglycerides likely evolved to support survival during periods of famine /20/. In other words, the intake of glucose and fat when food was plentiful allowed our hunter-gatherer ancestors to store fuel sources in adipose tissue during periods when little physical activity was required (ie, feast). Periods of feast were balanced by periods of famine that required physical activity for food procurement; during periods of famine, fuel sources in adipose tissue were metabolized by skeletal muscle.

Thus, the human genome has adapted to support a constant demand for movement as well as bursts of physical activity and metabolic fluxes associated with proper energy homeostasis during periods of feast and famine /18,20/.

Although the human genome has remained relatively unchanged for the past

10,000 years, the sedentary lifestyle that pervades modern society, along with the unlimited food supply, has overridden the necessity for a physically active lifestyle and natural metabolic fluxes. The disruption of naturally evolved energy homeostasis brought on by physical inactivity contributes to the growing incidence of metabolic diseases (eg, diabetes, obesity) in today's sedentary society /18,20–22/. According to data from the National Center for Health Statistics, physical inactivity accounts for approximately 200,000, or 1 in 10 disease-specific deaths each year in the US adult population /23/. In addition to being an individual risk factor for disease-specific deaths, physical inactivity contributes to other dietary, lifestyle, and metabolic risk factors for chronic diseases through effects on body mass index (BMI), blood pressure, glucose, and low-density lipoprotein cholesterol.

Physical activity may be evolutionarily related to cognition in that the need to generate movements for the purpose of successful food foraging may have necessitated mental activity /24/. As Rudolfo Llinás articulates in *I of the Vortex: From Neurons to Self* /25/, successful movements led to our thinking brain: "That which we call thinking is the evolutionary internalization of movement."

Potential mechanisms that mediate the beneficial effects of physical activity on cognition and performance

The effects of physical activity on cognition are seen at the systemic, molecular, and cellular levels (**Figure 1**). At the systems level, electrophysiologic and neuroimaging studies have shown that neural systems that underlie attention, learning, and memory are primed for efficient and flexible functioning by physical activity. At the molecular level, physical activity increases the availability of neurotrophins and growth factors in the brain. Signaling cascades induced by these factors regulate cellular effects that support brain function, including synaptic plasticity, neurogenesis, and angiogenesis.

Systems level: Increased activity in brain regions mediating attention, learning, and memory

Many studies have shown that physical activity influences neural systems involved in attention, learning, and memory. Electrophysiologic studies have provided insight into the effects of exercise and fitness on cognition by using electrodes placed on the scalp to record event-related brain potentials, a measure of electrocortical activity. In particular, P300 is a well-studied component of event-related brain potentials that occurs approximately 300 to 800 milliseconds

after stimulus onset and provides an indication of attentional resources allocated to the stimulus /26/. This attention-driven neural activity signal is thought to be generated by multiple brain regions involved in information processing and memory encoding, including the frontal lobes, anterior cingulate cortex, temporal lobe, and parietal cortex /27/. The frontal lobes mediate tasks that require executive cognitive function, such as planning, scheduling, inhibition, and working memory /7,28/. The anterior cingulate cortex is a limbic structure in the medial wall of the brain and is thought to monitor response conflict and signal the need for adaptation in the attentional network /12/. Temporoparietal activity is thought to be associated with attention and subsequent memory processing, particularly by the hippocampal formation in the medial temporal lobe /27/.

The amplitude of P300 is proportional to the amount of attention needed to encode the stimulus in working memory, whereas the latency of P300 reflects the speed of cognitive evaluation of the stimulus /29/. In an electrophysiologic study of 20 young adults, Hillman et al /29/ recorded P300 amplitude and latency during an executive cognitive task performed at baseline and after a single bout of treadmill exercise. Results indicated that P300 amplitude during task

performance was larger after the exercise session than at baseline, suggesting that exercise increased allocation of attention and memory resources at the neuroelectric level. Other studies have reported that adults with better physical fitness have larger P300 amplitudes and shorter P300 latencies than less fit adults while they perform executive tasks /26,30–32/. These studies support a role for physical activity in improving cognitive function through attentional mechanisms.

In addition to findings from electrophysiologic studies, neuroimaging studies have provided insights into the effects of physical activity on brain activity and cognition. Structural magnetic resonance imaging (MRI) studies in older adults have revealed that physical fitness is related to preservation of brain volume. Adults with better fitness have significantly greater brain volume in frontal, temporal, and parietal cortices compared with less fit adults /11,33/. Moreover, older adults who participated in a 6-month regimen of aerobic training had significant preservation of these brain areas /8/. A recent study provided a more direct link between brain volume and preservation of cognition during aging; older adults with better aerobic fitness not only had increased hippocampal

volume compared with less fit adults but also had better performance on a task of spatial memory, a cognitive process subserved by the hippocampus /13/.

Functional MRI studies support and extend the findings that exercise affects brain structure, by demonstrating changes in brain function/activity after participating in a regimen of physical exercise. Colcombe et al /12/ observed increased brain activity coupled with better cognitive performance in older adults who were more fit or who underwent 6 months of aerobic training compared with less fit or untrained study participants. Participants underwent functional MRI while they performed an executive/attention task known as the Eriksen flanker task, a task-switching test in which a target stimulus (eg, B) is flanked by congruent (eg, BBBB) or incongruent (eg, AABAA) stimuli. A correct response during the incongruent condition requires participants to inhibit or filter misleading information (ie, the incongruent flanking cues); successful inhibition of the misleading information is signified by faster reaction time to the incongruent cues. Highly fit and aerobically trained adults had faster reaction times during the incongruent condition of the task, indicating that these participants processed conflicting cues more efficiently than less fit and untrained participants. In addition, highly fit and aerobically trained adults had

greater activity during the task in the attentional circuitry of the brain, including key regions of the frontal and parietal cortices. Thus, improved fitness was associated with better task performance, as well as enhancements in structure and function of brain areas thought to underlie executive functions.

In another study, 11 adults aged 21 to 45 years participated in a 3-month aerobic exercise regimen /34/. Performance on a word recall memory task, the Rey Auditory Verbal Learning Test, along with changes in regional cerebral blood volume (CBV) in the hippocampus, was assessed before and after the exercise training period. CBV in the hippocampal dentate gyrus significantly increased after aerobic training and was positively associated with the fitness level achieved (as assessed by the maximum volume of oxygen consumption). Moreover, performance on the Rey Auditory Verbal Learning Test improved after exercise training and correlated with dentate gyrus CBV. Thus, exercise induced a selective increase in CBV that correlated with fitness level and cognitive performance (**Figure 2**). The dentate gyrus is a hippocampal structure to which new neurons are added throughout life /35/; the potential role of neurogenesis in mediating exercise-induced changes in the brain is discussed in more detail later.

Molecular level: Neurotrophins and growth factors

In addition to studies reporting that neural systems underlying attention, learning, and memory are primed for efficient and flexible functioning after physical activity interventions, other studies have begun to elucidate molecular mechanisms by which physical activity affects cognition. Among various potential molecular mediators of the effect of exercise on cognition /5,24/, 2 well-studied candidates are brain-derived neurotrophic factor (BDNF) and insulin-like growth factor-1 (IGF-1).

Studies in rats and mice /36/ have shown that voluntary exercise on a running wheel increases hippocampal levels of BDNF, a molecule important for synaptic plasticity, learning, and memory. Animal studies have shown that exercise improves performance on the Morris water maze, a task that involves spatial learning and memory, and that injection of a drug that blocks BDNF activity in the hippocampus also blocked the benefit of exercise on the water maze task /37–38/. In exercising mice, hippocampal BDNF levels increased immediately after exercise and remained elevated for several weeks before returning to baseline levels /39/. Moreover, the cognitive improvement in water maze training and memory performance paralleled the time course of hippocampal BDNF

availability. In humans, acute exercise increased serum BDNF levels in young adults /40/. In older women (but not older men), decreased levels of plasma BDNF were significantly associated with poorer performance on multiple cognitive tasks /41/. Thus, the effects of BDNF on hippocampal function, learning, and plasticity make it a potentially important factor in the mediation of the effects of exercise on cognition /5/.

IGF-1 is produced mainly in the liver and works closely with growth hormone to mediate somatic growth and tissue remodeling /42–43/. IGF-1 also provides trophic support to the brain, both through serum IGF-1 that crosses the blood–brain barrier and through IGF-1 produced locally in the brain /42/. Animal studies have shown that exercise stimulates uptake of IGF-1 from the bloodstream into specific brain areas, including the hippocampus, and that blocking IGF-1 uptake in the brain also blocks exercise-mediated increases in adult neurogenesis /43/. Animals with decreased IGF-1 levels have impaired learning and memory /44/. In humans, IGF-1 levels decrease with age, and in older adults, serum IGF-1 levels are positively correlated with cognitive performance /45/.

BDNF and IGF-1 appear to act in concert to mediate exercise-induced effects on the brain /5/. For example, IGF-1 influences BDNF production in the hippocampus in response to exercise. Other growth factors also contribute to the beneficial effects of exercise on the brain. For example, vascular endothelial growth factor (VEGF) may work together with IGF-1 to mediate exercise-induced vascular changes in the brain /5/. Moreover, experimentally increasing VEGF levels in the hippocampus in rats resulted in a 2-fold increase in neurogenesis that was associated with improved performance on the Morris water maze, and blocking VEGF levels inhibited both neurogenesis and learning /46/. Fibroblast growth factor-2 (FGF-2) is another growth factor with effects on neurogenesis; animal studies have shown that FGF-2 increases neurogenesis in the hippocampus of adult and aged animals /47–48/. Like IGF-1, VEGF and FGF-2 exhibit age-related declines in the rat hippocampus, and the loss of growth factor activity with aging may contribute to age-related decreases in neurogenesis and brain function /49/.

Cellular level: Synaptic plasticity, neurogenesis, and angiogenesis

Neurotrophins and growth factors can promote a cellular environment that supports cognition by increasing synaptic plasticity, neurogenesis, and vascular function /5/.

Exercise increases long-term potentiation (LTP) in the hippocampus, a neural correlate of learning /50/; rats given access to a running wheel had significantly greater LTP induction than did sedentary litter mates, indicating that exercise lowers the threshold for synaptic plasticity. In addition, expression of BDNF and specific glutamate receptor subtypes in the hippocampal dentate gyrus was increased in running rats, indicating that increased BDNF signaling and glutamate-mediated synaptic transmission may have contributed to the exercise-induced enhancement of synaptic plasticity. Additional work has shown that exercise affects synaptic plasticity through BDNF- and IGF-1-activated kinase signaling cascades (eg, mitogen-activated protein kinase, calcium/calmodulin protein kinase II), which in turn promote transmission at the synapse through upregulation of synaptic proteins, such as synapsin I /24/.

Research studies in rodents have demonstrated that voluntary running increases the production of new neurons in the dentate gyrus of the hippocampus /51–52/. Moreover, running increases neurogenesis in aged mice that had been sedentary until old age /53/. Mice with access to a running wheel also had better performance on the Morris water maze than did nonrunning controls. Running increases neurogenesis in mice through effects on cell proliferation /101/, cell survival /51–54/, and functional maturation and incorporation of newly generated cells into hippocampal circuitry /54/.

Exercise may promote the survival of newly generated cells in the dentate gyrus through effects on the phosphatidylinositol 3-kinase/protein kinase B (PI3K-Akt) signaling pathway /55/. A recent rodent study found that phosphorylation/activation of Akt and several of its downstream antiapoptotic targets occurs in the dentate gyrus in response to running wheel exercise and that inhibiting PI3K blocks exercise-induced activation of these prosurvival proteins as well as blunts exercise-induced neurogenesis /55/. In addition, inhibition of PI3K blocked LTP induction, indicating that synaptic plasticity in the dentate gyrus depends on PI3K signaling. These results collectively suggest that neurogenesis is a key mechanism by which physical activity may improve

synaptic plasticity and cognition and that growth factor cascades such as the PI3K-Akt signaling pathway induced by IGF-1 /56/ may contribute to the exercise-induced effects on cognition /44,55/.

Running increases the growth of new microvessels in the cerebral vasculature of young and old rats /57–58/. In addition, angiogenesis is coupled with neurogenesis; the vascular environment in the dentate gyrus may help circulating growth factors influence the proliferation and survival of newly generated cells /59/. Expression of VEGF is increased in running rats /57/, and blocking VEGF abolishes the exercise-induced increase in neurogenesis in running animals /60/. Exercise increases the size of blood vessels in the dentate gyrus in mice, potentially increasing the blood supply to support neurogenesis /53/.

Mice with low levels of circulating IGF-1 (and thus reduced uptake of IGF-1 into the brain) have deficiencies in both angiogenesis /61/ and neurogenesis /43/, suggesting that the vascular environment in the hippocampus affects the delivery of important, neurogenic growth factors to the dentate gyrus. Consistent with these findings, another study showed that exercising mice have increased

CBV and neurogenesis in the dentate gyrus /34/. Blocking neurogenesis by exposing the mice to irradiation also blocked changes in CBV, suggesting that neurogenesis is the mechanism by which exercise directs blood flow to the dentate gyrus. Taken together, these studies indicate that exercise promotes angiogenesis by increasing the effects of VEGF and IGF-1 on vessel growth /5/ and that angiogenesis is linked with neurogenesis.

Overall, mechanistic studies have demonstrated that physical activity has a role in priming mental function at the systems level and directly influencing cognition at the molecular and cellular levels, maximizing the brain's potential to process new information /62/. Studies that have evaluated the connection between physical activity and cognitive performance on a variety of tasks in humans are discussed in detail later.

Beneficial effects of physical activity on cognition and performance

Published studies on the impact of physical activity on cognitive performance generally have 2 types of designs: controlled studies of the effects of exercise interventions and studies of the correlation between exercise and cognitive performance. Exercise interventions range from a single bout of acute exercise to

weeks-long fitness programs. Correlation studies have addressed whether adults who are already physically active are more likely than inactive adults to have better performance on various cognitive tasks, or whether better fitness in early adulthood and midlife is associated with better cognition later in life.

A single bout of exercise can improve specific aspects of cognition

Studies have shown that a single bout of exercise, such as 30 minutes of cycling or running, can improve automatic aspects of cognition such as reaction time and speed of information processing /63–66/. Acute exercise also improves performance on higher-order cognitive processes, including executive cognitive tasks such as planning, scheduling, inhibition, and working memory /7/.

One common test of attention and executive function that has been used to measure the effects of exercise is the Stroop test /67/. This test measures the amount of time it takes to do 3 tasks: reading words, naming ink colors, and naming the ink color of words that are color names (eg, the word “red” printed in green ink). Although people find the first 2 tasks to be simple, the third is much more difficult because it involves inhibiting the automatic response to read the word rather than name the color. Thus, whereas the word and color subtasks

of the Stroop test evaluate speed of information processing, the incongruent color–word subtask assesses the executive functions of selective attention, shifting, and inhibition of habitual responses /68/.

Improved executive function as demonstrated by better performance on the Stroop color–word subtask has been shown in young adults after a single bout of aerobic exercise /64,69/ or resistance exercise /68/. In a study of 41 middle-aged adults (mean age, 49 years), improvement in information processing speed and a trend toward improvement in executive function were found after resistance exercise /70/. Other studies have shown increased working memory performance (eg, verbal memory, visual memory) after acute aerobic exercise in young adults /71–73/ and enhanced cognitive flexibility (ie, thinking beyond conventional uses of objects to alternate uses) after acute aerobic exercise in middle-aged adults (aged 50–64 years) /74/.

Longer-term exercise interventions improve cognition

Prospective studies have shown that exercise interventions that range from 2 to 12 weeks can effectively improve cognitive function. In a report published more than 30 years ago, Young /75/ found that a 10-week exercise program for 32

adults aged 23 to 62 years improved performance on executive function tasks, including the Wechsler Adult Intelligence Scale Digit Symbol and Block Design subtests and the Trail Making Test, along with other tests of learning and information processing speed (**Figure 3**). In addition, participants reported improved health status and decreased levels of anxiety at the end of the program.

In another study of 66 adults aged 18 to 48 years, participants who improved 15% or more in physical fitness after a 10- to 12-week exercise regimen had more efficient information processing compared with adults with stable fitness levels /76/. Similarly, a smaller study of 30 women aged 27 to 66 years showed that participation in a physical fitness program consisting of 3 exercise sessions per week for 8 months improved physical fitness by 17% and was associated with significant gains in information processing and decision-making capabilities /77/.

A short-term exercise program may also be an effective way to improve working memory and cognitive flexibility. A 14-day healthy lifestyle program that combined mental and physical exercise, stress reduction, and healthy diet was associated with significant improvement in a verbal fluency test of working memory in 17 adults aged 35 to 69 years with mild self-reported memory

problems /78/. Another study reported that 6 weeks of running (30 minutes 3 times weekly) by 14 adults aged 17 to 29 years improved visuospatial memory and positive mood /79/. Another recent study of 91 adults aged 18 to 70 years randomized participants to minimal aerobic exercise (0–2 d/wk, the control group), moderate aerobic exercise (3–4 d/wk), or high aerobic exercise (5–7 d/wk) for 10 weeks /80/. Participants took the CNS Vital Signs battery of cognitive tests at study entry and after the 10-week intervention. Compared with the control group, the moderate and high exercise groups had significantly improved cognitive flexibility. In addition, participants who exercised 5 to 7 days per week had better reaction time, attention, and cognitive flexibility than participants who exercised 3 to 4 days per week /80/.

Higher levels of physical activity are associated with better cognition

In addition to promising results from randomized studies of short-term exercise interventions, correlation studies have shown that adults who are generally more physically active are more likely than adults who are generally inactive to have better performance on various cognitive tasks, including those involving executive functions. In a study of 241 community-dwelling individuals aged 15 to 71 years, Hillman et al /81/ evaluated whether participants' self-reported

physical activity levels were associated with performance on the Eriksen flanker task, a task that requires focusing attention and inhibiting responses to the incongruent stimuli. The authors found that younger (mean age, 26 years) and older (mean age, 50 years) participants who got more physical activity had faster reaction times for congruent and incongruent conditions of the flanker task. In addition, older participants with higher physical activity levels displayed better response accuracy on the incongruent condition /81/. Smaller studies in young adults showed an association between physical activity and task-switching performance /31,82/; together, these studies provide evidence that regular physical activity during adulthood improves executive function.

In a study that used a battery of neuropsychological tests in 1927 healthy adults age 45 to 70 years, individuals with more intense weekly physical activity had better processing speed, memory, mental flexibility, and overall cognitive function /83/. In addition, participation in a greater variety of activities (eg, walking, bicycling, housekeeping, doing odd jobs, gardening, sports activities) was associated with significantly better performance on all evaluated cognitive domains.

Finally, in a prospective, occupational cohort study of 10,308 adults aged 46 to 68 years who were employed by 20 London-based civil servant departments, those who reported lower levels of physical activity had lower scores on various cognitive tests of executive function, including measures of inductive reasoning and verbal fluency /84/.

Physical activity in early and middle adulthood can preserve cognition in later life

Several studies have investigated the lasting benefit of physical activity on cognition in later years. The largest study included a population-based analysis of all Swedish men born from 1950 to 1976 who enlisted for military service at the age of 18 years (N=1,221,727) /85/. This large population represented approximately 97% of the male Swedish population born from 1950 to 1976. Cardiovascular fitness was measured with ergometer cycling, and cognitive ability and performance were assessed with a combination of 4 tests: a logical performance test, a verbal test of synonyms and opposites, a test of visuospatial/geometric perception, and a test of technical/mechanical skills with mathematical/physics problems) as measures of general cognitive ability. Cardiovascular fitness as well as performance on the individual cognitive

domains (logic, verbal, visuospatial, and technical) at age 18 years was significantly associated with general cognitive ability. Interestingly, additional analyses of brother pairs (N=268,496) and twin pairs (N=3147, of which 1432 were monozygotic twin pairs) showed that the positive correlation between fitness and cognition was mainly due to environmental rather than genetic factors. The authors also examined the longitudinal effect of cardiovascular fitness on cognitive performance. They found that changes in fitness from 15 to 18 years of age were linked to changes in cognition; participants with improved fitness had better scores on global, logic, verbal, visuospatial, and technical cognitive tests compared with participants with a decline in fitness levels. Finally, cardiovascular fitness at age 18 years predicted educational attainment (university vs high school) and socioeconomic status (professions ranked with high vs low socioeconomic index) later in life /85/.

In addition to this large, longitudinal study of young adults /85/, other studies have found that physical activity during midlife may preserve cognition later in life /84,86–92/. These studies, outlined in **Table 1**, report that participation in physical activity may significantly slow the rate of cognitive decline during later adulthood /84,87,90/ or reduce the risk of developing dementia or Alzheimer's

disease /86,88,91/ and that being overweight or obese during midlife may be associated with poorer cognition or increased odds of developing dementia later in life /89,92/.

Additional insights and recommendations for maximizing the benefits of physical activity on cognition

The American College of Sports Medicine and the American Heart Association recommend that to promote and maintain health, all healthy adults aged 18 to 65 years should partake in a minimum of 150 minutes per week (ie, 30 minutes for 5 days) of moderate-intensity aerobic physical activity as well as at least 2 days per week of muscle-strengthening activities that work the major muscle groups /93/. Unfortunately, most adults in the United States currently do not obtain the recommended level of physical activity /94/. In light of the large body of evidence that supports the positive effects of physical activity on cognition, and the ample evidence of the impact of exercise on physical health and disease, effective interventions to increase level of exercise and effectiveness of exercise regimens are needed. In this section, we will discuss evidence that engaging in focused periods of exercise and rest, along with avoiding prolonged periods of sedentary behavior at work and at home, can improve physical health and

cognitive performance. We also review evidence supporting participation in population health and performance programs that promote physical activity. Given that employed adults spend about half of their waking hours at work /14/ and that the nature of contemporary work is increasingly sedentary owing to automation and process efficiencies /15/, workplace interventions that promote physical activity are urgently needed and uniquely positioned to impact employee health and productivity. Our recommendations for focused periods of exercise and participation in workplace programs support both physical and mental health benefits (**Table 2**).

Engage in focused periods of exercise and rest

The recommended amount of weekly physical activity for healthy adults is a minimum of 150 minutes of moderate-intensity aerobic physical activity or 60 minutes of vigorous-intensity activity in addition to muscle-strengthening activities on 2 or more days /93/. The level of intensity of physical activity may affect cognitive performance. Although the impact of exercise on cognition is not uniform across individuals /72/, several studies have suggested a dose-response relationship between exercise intensity and cognitive function /68,82/. Among 1927 adults aged 45 to 70 years, individuals with more intense weekly physical

activity (assessed by summing weekly physical activities and calculating the metabolic equivalent value of the summed activity) had better processing speed, memory, mental flexibility, and overall cognitive function /82/. However, the time spent weekly on physical activities did not affect cognitive performance, suggesting a selective effect of exercise intensity on cognitive function. A more recent study reported that the relationship between exercise intensity and cognitive performance depended on the type of cognitive task /68/; in this study of 68 adults (mean age, 26 years) who participated in an acute bout of resistance exercise, high-intensity exercise was found to benefit speed of information processing, whereas moderate-intensity exercise was most beneficial for executive performance (ie, inhibition, working memory, attentional flexibility).

Regardless of the level of intensity applied during physical activity, a highly focused, purposeful routine can provide motivation to stay engaged in an exercise regimen over the long term /95/. A study of 50 adults aged 20 to 40 years reported that mindfulness was associated with better cognitive function. The study included meditators and nonmeditators across a wide range of professions and reported that mindfulness was associated with better performance on the Stroop task and d2-concentration and endurance test /96/. Meditators

demonstrated greater mindfulness than did nonmeditators and had better attentional control, accuracy, and cognitive flexibility. Practical suggestions for increasing mindfulness during physical activity include commitment, focus, and elimination of distractions during the exercise period.

Periods of intense physical activity should be balanced by periods of rest and energy renewal /95/. Balance is key, as prolonged periods of sedentary behavior during waking hours have been associated with poorer health /97/. Healy et al /97/ reported an association between metabolic health and avoidance of prolonged periods of sitting in 168 adults aged 30 to 87 (mean age, 53 years). Sedentary time and physical activity breaks (ie, avoiding prolonged periods of physical inactivity) were monitored during waking hours for 7 days, and biomarkers of metabolic risk were assessed. Findings indicated that the number of physical activity breaks was associated with lower waist circumference, BMI, triglycerides, and 2-hour plasma glucose levels. The recorded breaks were relatively short in duration and light in intensity, suggesting that brief, simple disruptions in sedentary time may have a significant impact on metabolic health. The authors provided practical suggestions for implementing easy physical activity breaks at home and in the workplace, such as taking brief ambulatory

breaks during commercial breaks on television and during prolonged periods of sitting at work. Other approaches for avoiding prolonged periods of sedentary behavior at work by expending energy in the office setting include innovative office equipment, such as treadmill workstations, or holding meetings while walking /98–101/.

In a study of 20 self-professed “couch potatoes,” including 10 lean (BMI, 23 ± 2 kg/m²) and 10 mildly obese (BMI, 33 ± 2 kg/m²) participants, Levine et al /102/ used microsensors to record participants’ movements and body positions every 0.5 seconds for 10 days. Obese participants were seated an average of 2 hours longer per day than lean participants. This result is consistent with the finding that prolonged sedentary time has detrimental effects on physical health.

Moreover, in light of evidence that being overweight or obese during midlife is associated with poorer cognition or increased odds of developing dementia later in life /89,92/, these findings suggest that avoiding prolonged periods of sedentary behavior may have positive effects not only on physical health but also on preservation of cognition.

In addition to evidence supporting intense physical activity and avoidance of prolonged sedentary time, other studies have reported positive associations between participation in leisure activities and cognition. Studies in middle-aged adults have shown that participation in leisure activities involving mental engagement (eg, brain teasers, courses or evening classes, playing chess or bridge), social engagement (eg, volunteer work, attending the cinema, theatre, or concerts), or spiritual engagement (eg, church or religious activities) improved performance on various cognitive tests of executive function, including measures of inductive reasoning and memory /78,90,103/. Moreover, participation in mental, social, and physical activities protected against cognitive decline in 830 adults aged 49 to 81 years assessed at baseline and 3 years later /87/.

Engaging in physical and leisure activities affects not only cognitive function but also emotional satisfaction and quality of life. The association between exercise participation and well-being was assessed in approximately 8000 adults aged 18 to 65 years from the Netherlands Twin Registry. Exercisers were more satisfied with their life and happier than nonexercisers at all ages /104/. A systematic review of 14 studies related to physical activity and health-related quality of life

reported that higher levels of physical activity in healthy adults were linked to better health-related quality of life outcomes /105/.

Taken together, these studies suggest that engaging in focused periods of physical activity and rest has significant physical and mental health benefits. In addition, the likelihood of preserving physical health and cognition throughout adulthood may be maximized by avoiding prolonged sedentary time and participating in leisure activities that provide opportunities for physical, emotional, mental, and spiritual engagement.

Participate in workplace wellness programs

An increasing body of evidence suggests that promoting physical activity in the workplace has a significant positive effect on worker health and productivity /14–15/. The workplace is an opportune setting for implementing and monitoring physical activity interventions that support the employee population and, indirectly, their families /16/. The corporate environment is well suited to leverage resources to increase employees' awareness of the benefits of physical activity and to encourage adoption and maintenance of physical activity regimens. For example, companies can use e-mail communications, departmental

meetings, and online programs to promote tailored strategies (eg, walking programs, integrated work breaks, comprehensive population health and performance programs) to increase physical activity and improve employee health and performance. Companies can also provide meaningful incentives and awards (eg, financial incentives, health insurance benefits) to promote ongoing participation in health risk assessments and physical activity programs /16/.

In a comprehensive meta-analysis summarizing health and physical activity behavior outcomes associated with workplace wellness programs, Conn et al /14/ reviewed nearly 150 reports including more than 38,000 participants. Significant improvements were observed for physical activity behavior, fitness, lipids, anthropometric measures, work attendance, and job stress (**Figure 4**). Other systematic reviews reported that wellness programs are effective for improving weight loss and BMI /106–107/. Taken together, studies of population health and performance programs provide evidence that workplace interventions can successfully increase the physical activity behavior of employees. Moreover, these programs can provide significant benefits in terms of employee health and productivity. Although wellness programs generally do not assess cognitive function as an outcome measure, the growing body of literature that connects

physical activity with cognition suggests that workplace programs that promote engagement in physical activity may also promote improved cognitive performance among employees.

Workplace wellness programs have significant benefits for employers as well as employees. A meta-analysis evaluating the costs and savings associated with workplace wellness programs showed that medical costs decrease by about \$3.27 for every dollar spent on wellness programs and that absenteeism costs decrease by about \$2.73 for every dollar spent /17/. Thus, integrated population health and performance programs that promote physical activity provide gains for employees and employers through improvements in worker health and performance and financial returns for the company. In light of the increasing evidence that improved cognitive performance is one of the many benefits related to physical activity, workplace interventions that promote physical activity are likely to have lasting benefits on employees' physical fitness and cognitive productivity.

Conclusion

Extensive evidence suggests that physical activity beneficially influences brain function and executive cognitive processes in particular. The effects of physical activity on cognition are exerted at the systemic, molecular, and cellular levels and are associated with changes in brain volume, cerebral blood flow, and growth factor availability and signaling cascades. Published studies suggest that physical activity in adulthood has a significant, lasting impact on cognition. Not only does acute exercise improve executive cognitive performance but regular physical activity in midlife has a protective effect against cognitive decline in later adulthood. Recommendations for maximizing the lasting benefits of movement and physical activity on cognition in adulthood include bouts of intense exercise, avoidance of prolonged periods of sedentary behavior (ie, sitting), engagement in leisure activities, and participation in workplace wellness programs. Population health and performance programs that promote physical activity may provide lasting benefits for employees in terms of physical health and brain function, translating into improved employee performance and increased financial returns for the company. In summary, humans were designed to move. Movement improves cognitive performance and delays age-related cognitive declines through multiple neural mechanisms that support improved

brain function. Additional insights from future studies will continue to clarify the beneficial effects of physical activity—and the detrimental effects of inactivity—on cognitive performance throughout adulthood.

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Table 1. Physical Activity During Midlife Preserves Cognition in Later Adulthood

Study	Participants	Assessments	Results
Andel et al /86/	264 seniors with dementia and 2870 controls enrolled in the HARMONY study, which included members of the Swedish Twin Registry who were aged 65 years and older in 1998	Assessment of dementia occurred an average of 31 years after assessment of exercise in the following: 1) regular exercise involving sports; 2) light exercise such as walking or gardening; 3) hardly any exercise.	Compared with participants who reported getting hardly any exercise, those who reported regular exercise or light exercise had significantly reduced odds of developing dementia 31 years later.
Bosma et al /87/	830 adults aged 49 to 81 years without dementia who participated in the Maastricht Aging Study	Participants with no engagement vs at least 1 h/wk of engagement in physical activity were tested at baseline and at follow-up 3 years later on 6 cognitive tests (Stroop color-word incongruent task, Rey Auditory Verbal Learning Test, Letter Digit Coding Test, Word Fluency Test, and MMSE).	Compared with inactive participants, those who reported at least 1 h/wk of physical activity had less cognitive decline over 3 years on the Stroop and Letter Digit Coding Test tasks.
Geda et al /88/	198 adults (median age, 83 years) with MCI and 1126 adults (median age, 80 years) with normal cognition who participated in the Mayo Clinic Study of Aging	Participants reported their level of physical exercise (light, moderate, or vigorous) during midlife (aged 50–65 years). A battery of neuropsychological tests was administered to determine whether participants had MCI in 1 or more cognitive domains (memory, executive function, language, visuospatial skills).	Participation in moderate exercise during midlife was associated with significantly reduced odds of developing MCI in late life; exercise reduced the risk of MCI by 39%.
Hassing et al /89/	1152 adults, including 312 with dementia and 181 with Alzheimer's disease, from the Swedish Twin Registry who participated in a BMI survey in 1963 and were aged 45–65 years in 1963	Participants were screened for dementia, including Alzheimer's disease, over a follow-up period of 40 years. Correlation analyses were conducted to determine whether being overweight in midlife (BMI ≥ 26.5 kg/m ²) increased the risk of developing dementia.	Being overweight during midlife significantly increased the risk of developing any dementia (59% greater risk) or Alzheimer's disease (71% greater risk).

Richards et al /90/	1919 adults enrolled in the Medical Research Council National Survey of Health and Development (the British 1946 birth cohort)	Participants reported their level of physical exercise (eg, aerobic activities, sports) and spare-time activities (eg, social activities) at age 36 years. Verbal memory was assessed at ages 43 and 53 years using a word-learning task.	Engagement in physical exercise and spare-time activity at age 36 years was significantly associated with better verbal memory at age 43 years. In addition, participants who reported engaging in physical exercise at age 36 years had a significantly slower rate of decline in memory from ages 43 to 53 years. Moreover, protection against memory decline was evident in participants who reported engaging in physical exercise at age 43 years (either new or continuing exercisers) but not in participants who gave up exercise after 36 years, suggesting that continuing physical exercise after age 36 years was important for protection of cognition.
Rovio et al /91/	1449 adults, including 117 who developed dementia and 76 who developed Alzheimer's disease, in the Finnish CAIDE study who had assessments at midlife (mean age, 51 years) and follow-up (mean age, 72 years)	Participants reported their level of physical activity and were categorized as active (participated in leisure-time physical activity at least twice a week) or sedentary (participated in leisure-time physical activity less than twice a week). Correlation analyses were conducted to determine whether engagement in physical activity decreased the risk of developing dementia or Alzheimer's disease.	Compared with the sedentary group, participants who reported engaging in physical activity at least twice a week during midlife had a significantly reduced risk of developing dementia (52% lesser risk) or Alzheimer's disease (60% lesser risk).
Sabia et al /92/	5131 civil servants in London who participated in the Whitehall II study	BMI was self-reported or measured at age 25 years (early adulthood), early midlife (mean age, 44 years), and late midlife (61 years). Cognition was assessed at late	Being obese (BMI ≥ 30 kg/m ²) at late midlife was associated with poorer cognition on all measures (MMSE, memory, and executive function tests). In

		midlife using a battery of tests and categorized as measuring global cognition (MMSE), memory (20-word free recall test), and executive function (Alice Heim 4-I test of inductive reasoning and tests of verbal fluency).	addition, cumulative obesity (being obese at 2–3 of the study time points) was associated with lower MMSE, memory, and executive function scores, suggesting that the effect of obesity on cognition accumulates over the adult life course, examined over a mean duration of 36 years in this study.
Singh-Manoux et al /84/	10,308 civil servants in London who participated in the Whitehall II study, a prospective, occupational cohort study that began in 1985, when participants were aged 35–55 years	Participants reported their level of physical activity (low, medium, or high) at study baseline and other time points. Cognitive function was assessed from 1997 to 1999, when the participants were aged 46–68 years, using a battery of tests that included measures of fluid intelligence (ie, Alice Heim 4-I test of inductive reasoning) and verbal fluency.	A low level of physical activity at study baseline was significantly associated with poorer performance on a measure of fluid intelligence (which involves short-term memory, abstract thinking, creativity, ability to solve novel problems, and reaction time) 11 years later, when workers were aged 46–68 years.

BMI, body mass index; CAIDE, Cardiovascular risk factors, Aging and Incidence of Dementia; MCI, mild cognitive impairment; MMSE, Mini-Mental State Examination.

Table 2. Recommendations for Maximizing the Benefits of Physical Activity on Physical and Mental Health

Recommendation	Rationale
Engage in focused periods of physical activity and rest	<ul style="list-style-type: none">• Exercise intensity is related to information processing speed, memory, mental flexibility, and overall cognitive function /83,68/.• Taking frequent physical activity breaks (ie, avoiding prolonged periods of uninterrupted sitting) has important health benefits /97/ that may promote preservation of cognitive performance.• Participation in mental, social, and physical activities preserves cognitive function /78,87,90,103/ and improves emotional satisfaction and health-related quality of life /104–105/.
Participate in workplace wellness programs	<ul style="list-style-type: none">• Participation in wellness programs that promote physical activity improves worker health and productivity /14–15,106–107/.• Financial gains for employers include decreased medical costs and reduced absenteeism costs /17/.

Figure Captions

Figure 1. Exercise exerts systemic, molecular, and cellular effects to mediate executive cognitive function. At the systems level, electrophysiologic and neuroimaging studies have shown that physical activity improves cognitive performance by increasing neuroelectric activity, brain volume, and blood flow in brain networks that mediate attention, learning, and memory. At the molecular level, physical activity increases the availability of neurotrophins and growth factors in the brain. Signaling cascades induced by these factors regulate cellular effects that support brain function, including synaptic plasticity, neurogenesis, and angiogenesis. BDNF, brain-derived neurotrophic factor; FGF-2, fibroblast growth factor-2; IGF-1, insulin-like growth factor-1; VEGF, vascular endothelial growth factor.

Figure 2. Increased CBV in the hippocampal dentate gyrus in adults who participated in a 12-week exercise training program. a) Relative CBV (rCBV) in the dentate gyrus selectively increased after exercise training, whereas exercise did not significantly affect CBV in other hippocampal subregions. b) A high-resolution MRI taken after exercise training in 1 of the adult participants shows the hippocampus (left image) with depiction of individual subregions (middle image). Higher CBV (indicated by warmer colors) is evident in the dentate gyrus (right image). CA1, *Cornu Ammonis* 1; CBV, cerebral blood volume; DG, dentate gyrus; EC, entorhinal cortex; Sub, subiculum. Figure

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Figure 3. Improved executive function after exercise intervention. The mean performance on various tasks of executive function improved after a 10-week exercise program in young (a, b) and middle-aged (c, d) adults. Across all 4 groups, regardless of age or sex, significant improvement was observed after the exercise intervention on all tasks except the Visual Reproduction memory task. Data are reproduced with permission from Young /75/. Reproduced from the *British Journal of Sports Medicine*, Young RJ, Volume # 13, pages 110–7, copyright 1979 with permission from BMJ Publishing Group Ltd.

Figure 4. Meta-analytic findings of effects of workplace physical activity interventions on physical activity behavior, health, and work-related outcomes. A meta-analysis of the effects of workplace physical activity interventions reported significant benefits on physical activity behavior, fitness (oxygen consumption), work attendance (derived from company records), job stress (self-reported), anthropometric measures (body mass index, weight, abdominal girth, and percent body fat), lipid measures (total cholesterol,

high-density lipoproteins, or the ratio of total cholesterol to high-density lipoproteins), and diabetes risk (fasting glucose or insulin levels). Data are reproduced with permission from Conn et al /14/. This article was published in the American Journal of Preventive Medicine, Volume # 37, Conn VS, Hafdahl AR, Cooper PS, Brown LM, Lusk SL. Meta-analysis of workplace physical activity interventions. Pages 330–9. Copyright Elsevier 2009.