Cognitive plasticity in older adults: effects of cognitive training and physical exercise

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Cognitive training, physical activity, and exercise have often been reported to improve cognitive performance in older adults. This paper reviews some seminal and recent studies using these approaches to improve cognition and physical functioning in healthy older adults and in patients suffering from non-neurological chronic medical conditions. Results from cognitive training studies suggest that despite performance improvement in trained tasks, transfer effects appeared very limited. Surprisingly though, computerized dual-task training has been shown to improve balance and postural control in tests of physical functioning, suggesting that broad transfer can sometimes be observed. Physical exercise intervention studies generally found significant and large improvements in physical capacity, in some cognitive domains, and in quality of life. The benefits seem to be equivalent between frail and nonfrail participants. Overall, results reviewed here support the notion that cognitive plasticity for attentional control, as induced by cognitive training or physical activity and exercise, is preserved in late adulthood. Moreover, results of studies with patients at risk of cognitive decline also suggest that cognitive training and exercise interventions are promising nonpharmaceutical tools to help improve cognition in older at-risk individuals.

Keywords: cognitive aging; cognitive plasticity; physical activity; exercise; cognitive training

Introduction

Aging is an inevitable process that has an overwhelming societal impact. One quarter of the population worldwide will be 65 years and over in the 2020s, and the fastest growing segment of the population is composed of those over 85 years. Although this demographic change brings with it great hope, it also presents a challenge in managing health care, as aging is associated with physiological and psychological changes. For instance, nine out of ten individuals aged 60 years and older have at least one cardiovascular risk factor, and when cumulating two or more of these factors, individuals are more likely to show cognitive deficits, especially in the attention and executive control domains. Such declines are associated with a higher risk of developing certain types of dementia, and it is now well established that they can precede memory decline by approximately 3 years.

There is no cure for aging, but many examples of successful aging, both cognitive and physical, have motivated the search for the perfect lifestyle that would protect us against cognitive decline and dementia as we age. Determining this perfect lifestyle is a major endeavor and continues to drive many research questions. Related neuroscience research is focused on harnessing the potential of the brain at any given age and understanding the fundamental mechanisms by which the brain adapts and evolves through stimulation and experience. Over the last decade, this endeavor to delay cognitive decline has regained interest in a somewhat different and renewed approach in which researchers have shown that the brain seems to maintain an impressive level of plasticity throughout life, even at a very advanced age and despite reduced physical condition. This wonderful plasticity potential has unknown capacities and brings with it great hope for those suffering...
from brain insults or developmental diseases. Brain plasticity refers to the brain’s capacity to change and adapt, physically and functionally, throughout life. Evidence suggests that some activities of daily life are more favorable for inducing brain plasticity, such as regular engagement in physical exercise and cognitive stimulation. In this context, music and, by extension, music-associated activities, such as dancing, have been studied for their potential for inducing plasticity. However, neurocognitive stimulation has been more extensively studied through other sources of lifestyle-related activities. In this paper, I emphasize two approaches that have gained impressive popularity over the last decade, namely, computerized cognitive training and physical exercise. In both approaches, results from experimental study designs and clinical trials at a preliminary level will be reviewed and discussed, leading us to envision their potential synergetic benefit. I will conclude by touching on some of the unresolved issues and challenges in the study of cognitive stimulation and exercise as a means to maintain and enhance cognition in older adults and those at risk of cognitive decline.

**Cognitive aging**

Cognitive aging is a heterogeneous process in many ways. First, heterogeneity can be observed across cognitive functions, with knowledge-based processes being mainly spared in normal aging (e.g., nonpathological aging processes, such as dementia), while process-based functions are more easily impaired as we age. Cognitive slowing, mainly assessed through psychomotor tests, occurs as early as in one’s fifties. Working memory, or the ability to maintain and consciously manipulate information, is also highly age sensitive, and age-related differences are more likely to be observed in tasks that require executive control processes, such as inhibition, updating, and manipulation, and even greater if the memory load (i.e., the number of items to be maintained) is high. Episodic memory also tends to be sensitive to age, as older adults often show reduced recall in all episodic memory tasks (e.g., verbal or visual)—a decline that has been associated with poor encoding strategies, less use of environmental support, and deficits in binding new information with existing knowledge during encoding. Recent advances in structural and functional brain imaging techniques have provided insight into potential brain mechanisms of aging. Changes in brain volume, especially in prefrontal regions and the hippocampus, have been suggested to potentially account for the age-related cognitive changes often observed in memory and executive functions. Recent studies have questioned the relationship between brain volume and functions, and more advanced techniques are now being used to better understand the complexity of the interconnection between brain structure and function.

Cognitive aging is also characterized by an interindividual heterogeneity. In fact, although many individuals will experience some form of physical and cognitive decline as they age, examples of individuals who seem to be immunized against the aging process abound. One such example is Doris Lessing, who was, in 2007, at the age of 88 years, the oldest writer to receive the Nobel Prize in Literature (she died at 94 years). Even more recently is the 82-year-old Canadian writer Alice Munro who received the 2013 Nobel Prize in Literature for her work as “master of the contemporary short story.” Some individuals show protected physical capacity; for example, Olga Kotelko, at 94 years old, was still traveling the world to compete in 11 track and field sports in her age range (she died at 95 years old). She had collected 750 gold medals and broken 26 world records. One last example, not the least, is another Canadian, Ed Whitlock, who broke his first world record in marathon distance in 2004 in the 70-year-old-plus category, with a time of 2 h, 54 min, and 48 seconds. He then ran a marathon at an average speed of 14.5 km/hour. He set another mark at 80 years in Rotterdam with a time of 3 h, 25 min, and 43 s—much faster than many younger competitors. These are a few individuals, among many, for whom time seems to be the very last concern. At least from an outside perspective, these great elders inspire us to strive for understanding how lifestyle choices can help one adapt to the aging process and protect the brain from age-related cognitive decline. It is generally assumed that at least four factors could play a critical role in the way we adapt to age: social interaction, nutrition, cognitive stimulation, and physical activity. In the next section, I will present evidence from intervention studies conducted in our laboratory that suggest that at least two types of intervention—cognitive training and physical activity—can lead to significant cognitive enhancement.
Cognitive training

Cognitive training intervention, usually using in-house computer-based training software or more recently commercialized packages, is one way by which insight can be gained on how the brain adapts to new challenging situations. In some instances, and this is the case in the studies presented later, the protocol has been designed to target one or several specific cognitive processes. For instance, and as previously mentioned, executive control functions, as used when we have to coordinate multiple tasks at once, tend to be very sensitive to normal aging and to chronic physical conditions, such as vascular diseases and diabetes, or even reduced physical functions. In a series of studies conducted with colleagues at the Beckman Institute for Advanced Science and Technology at the University of Illinois, we observed that cognitive plasticity for executive control processes were preserved in older adults and that improvement could be generalized to new task conditions, suggesting improvement above and beyond learning of a specific task setting. Attentional control training can also be used in a clinical setting: for instance, it has been recently observed that it could help reduce postsurgery cognitive deficits when used in the context of cognitive rehabilitation following coronary artery bypass graft surgery. This study was innovative by showing that a transfer effect could be observed in clinical neuropsychological tests used to document clinically significant deficits. Moreover, cognitive improvement after dual-task training comes with an observable pattern of changes in brain activation. In fact, using the same dual-task training, Erickson et al. showed specific patterns of brain activation changes induced by the training program (i.e., increased activation in the left ventrolateral prefrontal cortex (VLPFC) and decreased activation in the right VLPFC and bilateral dorsolateral prefrontal cortex (DLPFC)), suggesting that improved efficiency and compensatory mechanisms in older adults’ brain functions can help manage multiple-task situations. In other studies, cognitive training in healthy aging individuals has shown structural changes, such as increased brain volume, cortical thickness, and density, and coherence of white-matter tracts. At the functional level, task-related brain activation (using functional magnetic resonance imaging (fMRI) and positron emission tomography (PET)) was also found, showing patterns of increased and decreased task-related activation. Further studies are required to generalize these findings to larger groups and to investigate more diverse training protocols.

A very important question regarding cognitive training effects is whether the benefits translate to other untrained situations. The so-called transfer effect has shown mixed results and, in many cases, the transfer is most likely to be observed if the testing conditions are very close in design from the training situation. With regard to dual-task training, it was found that if the response and/or the stimulus modality of the tasks changed from the training condition to the testing conditions, training effects as indexed by improved attentional dual-task costs are reduced compared to the improvement observed in the training task. However, the training effect does seem to generalize to some extent to untrained tasks. More impressively, dual-task training can also lead to improved balance and postural control, as assessed with single- and dual-support balance, with and without cognitive load. This suggests that computerized attentional control training can lead to significant functional benefits for older adults.

Overall, the results reported here suggest that cognitive training can help improve attentional control in older adults and that it can be used as a therapeutic and rehabilitation tool in clinical populations to alleviate cognitive symptoms. While transfer effects are still debated, it seems that functional benefits, such as improved balance and postural control, can be expected after training. These reports, together with supporting evidence from brain imaging studies are encouraging, but further studies are needed to assess the reliability of cognitive training, its clinical validity, and the associated neuroplasticity mechanisms.

Physical activity and exercise

While the use of cognitive training now has a history of one or two decades in the cognitive aging literature, its influence has recently been partly shadowed by impressive advancements from exercise intervention studies. Although care should be taken here due to the large variability of interventions and the rather unrestricted and sometimes slack or vague definition of physical activity, results remain quite impressive with respect to the cognitive boosting effects. In fact, very striking results
have been published showing longitudinal observations that strongly support the protective effect of physical activity. For instance, Sofi et al.\textsuperscript{12} compiled the results of 15 prospective studies, merging more than 30,000 participants worldwide, and showed a decreased risk factor for dementia of up to 38\% for those individuals engaged in vigorous exercise more than three times per week. This meta-analysis supports past findings from another meta-analysis of intervention studies\textsuperscript{13} that showed that exercise can lead to a significant improvement in cognition, with larger effects on executive control functions if the training involved a significant dose of aerobic exercise and lasted over 6 months. In a recent set of studies, it was observed that only 3 months of well-structured and supervised exercise is associated with a significant improvement in attention and executive functions.\textsuperscript{14} Moreover, the improvement in executive control observed in the training group correlated with the improvement observed in the maximum level of oxygen consumption (VO\textsubscript{2} max).\textsuperscript{15} Another related issue is to what extent participants’ baseline fitness level and extreme negative physical condition, such as frailty, would limit the extent of training that can be performed by the participant in order to induce benefits on cognitive profile. This is not trivial, however, as frailty is known for its negative impact on cognition. A recent intervention study answered this question by showing that after a 3-month exercise program composed of combined aerobic and strength-training exercise, moderately frail older adults showed improved physical functions together with enhanced cognition in several domains, namely speed of processing, executive control, and working memory.\textsuperscript{16} Even more impressive were the results obtained with a severely frail woman who also showed physical, psychological, and cognitive benefits following a 3-month exercise intervention in a geriatric setting.\textsuperscript{17}

It is no surprise that such impressive and conclusive results have launched the quest for finding the brain plasticity mechanisms that would account for the benefits of physical activity and exercise on cognition. The benefits most likely occur at two levels, indirectly and directly. Indirect effects could involve improved health conditions (e.g., stress, sleep, diet) and reducing chronic diseases (e.g., coronary heart diseases, metabolic syndrome) that impact neurocognitive functions. But more direct effects of exercise on the brain have been reported using animal models (mostly rodents) and involved training-induced angiogenesis, neurogenesis in the hippocampus in elderly rats, and synaptogenesis. These changes would be supported by exercise-induced changes in molecular growth factors, such as brain-derived neurotrophic factor (BDNF; neuroplasticity and protection) and increased production of insulin-like growth factor 1 (IGF-1; neurogenesis and angiogenesis). Evidence of transient and permanent changes at the structural and functional levels in humans has been reported after a variety of exercise intervention programs.\textsuperscript{18} Even more impressive are recent findings that link these changes to an actual cognitive-enhancing effect of exercise. For instance, in a recent fitness intervention study, Erickson et al.\textsuperscript{19} showed that an increased volume of the anterior portion of the bilateral hippocampus mediates the effect of exercise on spatial memory in older adults.

To conclude, several studies converge to support the notion that physical activity and exercise have protective effects against age-related cognitive decline by lowering the risk of cognitive deficits and dementia by up to 38\%.\textsuperscript{12} Intervention studies also confirm this by showing improved cognitive performance in participants who completed a structured exercise program, and supporting evidence from brain imaging studies suggest that the improved performance is predicted by changes in brain structure and function. Although these results are rather convincing, several unresolved issues call for further exploration of the link between exercise and brain plasticity. For instance, no previous study allows us to draw conclusive results on the dose–response relationship, the ideal mode of exercise to induce greater changes, and whether the benefits can be maintained and for how long following the exercise program. Another major and hopefully very promising question is whether exercise interventions can be combined with cognitive training programs to further boost brain function in older adults and clinical populations. To address this issue, a recent study looked at the effect of a combined intervention program involving physical exercise training biweekly and cognitive training once per week for 3 months. The study went further in trying to dissociate the effect of aerobic training compared to
nonaerobic stretching exercise and cognitive dual-task training, and to a placebo computer condition (learning to surf the internet). Against all odds, preliminary results suggest that combining both do not fare better than fitness or computer dual-task training alone.20 Of course, the fact that the intensity of each individual intervention had to be reduced, as compared with previous studies using the same interventions alone, might explain the lack of synergistic effects of the combined treatment. Perhaps future studies would benefit from using exercise interventions that naturally involved cognitive stimulation. This hypothesis is now being tested by comparing a dance intervention treatment with aerobic exercise, in order to assess whether cognition and exercise can be combined in a single activity to further boost cognition in older adults.

**Conclusion**

As the world population is aging at an unprecedented rate, the quest for lowering the negative impact of age on cognitive functions is underway. For more than a decade or two, researchers have tried to identify lifestyle factors and intervention programs that maintain cognitive functions and even enhance cognitive performance in older adults. Cognitive stimulation, achieved through computer software or a physical activity program, seems to momentarily enhance cognition and may lead to benefits in real-life situations. However, future studies are needed to better understand how brain plasticity can be enhanced in order to significantly lower the risk of developing age-related cognitive decline and ideally reduce the incidence of neurodegenerative diseases. As this fascinating field of scientific investigation is still in its infancy, relatively speaking, innovative approaches are starting to emerge combining multiple interventions or more complex interventions that intermix emotion, stress management, exercise, and cognitive stimulation, such as dance, dance movement therapy, and yoga. Together with recent advancement in cognitive neuroscience on how to image brain structure and function, these innovative approaches lay the ground work for promising discoveries in the years to come.

**Conflicts of interest**

The author declares no conflicts of interest.

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