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Current Opinion in Behavioral Sciences

Physical activity, brain, and cognition

Kirk I Erickson[1], Charles H Hillman[2] and Arthur F Kramer[3]

In this brief review we summarize the promising effects of physical activity and fitness on brain and cognition in children and older adults. Research in children finds that higher fit and more active preadolescent children show greater hippocampal and basal ganglia volume, greater white matter integrity, elevated and more efficient patterns of brain activity, and superior cognitive performance and scholastic achievement. Higher fit and more physically active older adults show greater hippocampal, prefrontal cortex, and basal ganglia volume, greater functional brain connectivity, greater white matter integrity, more efficient brain activity, and superior executive and memory function. Despite these promising results, more randomized trials are needed to understand heterogeneity in response to physical activity, mechanisms, and translation to public policy.

Addresses
[1] Department of Psychology, University of Pittsburgh, 210 S. Bouquet St., Pittsburgh, PA 15260, USA
[2] Department of Kinesiology and Community Health, University of Illinois, 906 S. Goodwin Ave., Urbana, IL 61801, USA
[3] Beckman Institute for Advanced Science and Technology, University of Illinois, 405 N. Mathews Ave., Urbana, IL 61801, USA

Corresponding author: Erickson, Kirk I (kiericks@pitt.edu)

Current Opinion in Behavioral Sciences 2015, **4**:27–32

This review comes from a themed issue on **Cognitive enhancement**

Edited by **Barbara J Sahakian** and **Arthur F Kramer**

For a complete overview see the Issue and the Editorial

Available online 15th January 2015

doi:10.1016/j.cobeha.2015.01.005

The brain is inherently plastic; it is moldable, malleable, changes with experience and is never quiet. However, there are many factors that influence both the capability and range of brain plasticity throughout the lifespan and this is where the field of kinesiology merges with psychology and neuroscience. As will be described in this brief review, there is promising evidence that merely a modest amount of moderate intensity physical activity (PA) is necessary to take advantage of the brain's natural capacity for plasticity, resulting in improved cognitive performance, better academic achievement, and reduced risk for dementia. On the basis of the evidence described below, we argue for three overarching principles: Firstly, PA is an effective method of capitalizing on brain plasticity; secondly, the effects of PA on brain and cognition are not uniform; some brain areas and cognitive domains are more consistently influenced by PA than others; and finally, because of the widespread effects of PA on peripheral and central physiology, there is not just one single molecular mechanism by which PA improves cognitive function, but rather a host of different pathways involved in cognitive enhancement. Yet, despite strong evidence for these general principles, we still have much to learn about PA and brain health throughout the lifespan including knowledge of dose–response, application to developmental, neurologic, and psychiatric conditions, moderators of the effects, and a better understanding of the molecular, systems, and behavioral mechanisms of PA on cognition. Answers to these, and other related, questions will be critical for transitioning PA from the laboratory environment to more widespread clinical prescription and for promoting evidence-based changes in public policy to encourage increased PA for improving cognitive function throughout the lifespan.

Childhood physical activity effects on brain and cognition

Childhood PA effects on cognition and brain is a relatively recent line of inquiry, with the seminal publication appearing 10 years ago [1]. Before that report, the body of work was predominantly directed toward the relation of PA or physical education on standardized tests of academic achievement or measures supporting academic performance [2]. However, over the past decade, considerable research efforts have focused on the benefits of PA (or aerobic fitness) on brain structure and function, cognition, and scholastic performance with the goal of understanding how these health behaviors promote effective functioning within the context of learning.

Brain structure: Research on PA and brain structure in childhood is in its infancy. Specifically, only five studies have been reported, which have used cross-sectional or relatively small sample randomized controlled designs. A few studies used diffusion tensor imaging (DTI) to investigate structural integrity of white matter tracts. Findings indicated that children who received a PA intervention had greater integrity in the uncinate fasciculus compared to the control group [3], and that attendance in the intervention related to increased integrity of the superior longitudinal fasciculus [4]. Cross-sectional studies have investigated differences in aerobic fitness on white matter integrity and subcortical structures that are critical for learning and memory. For example, Chaddock and colleagues [5] reported that higher fit children had greater white matter integrity, as indexed by fractional anisotropy, than lower fit children in several white matter tracts including sections of the corpus callosum, corona radiata, and superior longitudinal fasciculus. Chaddock and colleagues [6,7] have also used voxel-based morphometry and observed greater gray matter volume in the hippocampus and basal ganglia (i.e., caudate nucleus, putamen, globus pallidus) in higher-fit children compared to lower-fit children. Further, higher-fit children exhibited better performance during tasks that tapped executive control and relational (i.e., associative) memory. Despite these interesting findings, the field is in need of growth to improve our understanding of PA on brain structure during development.

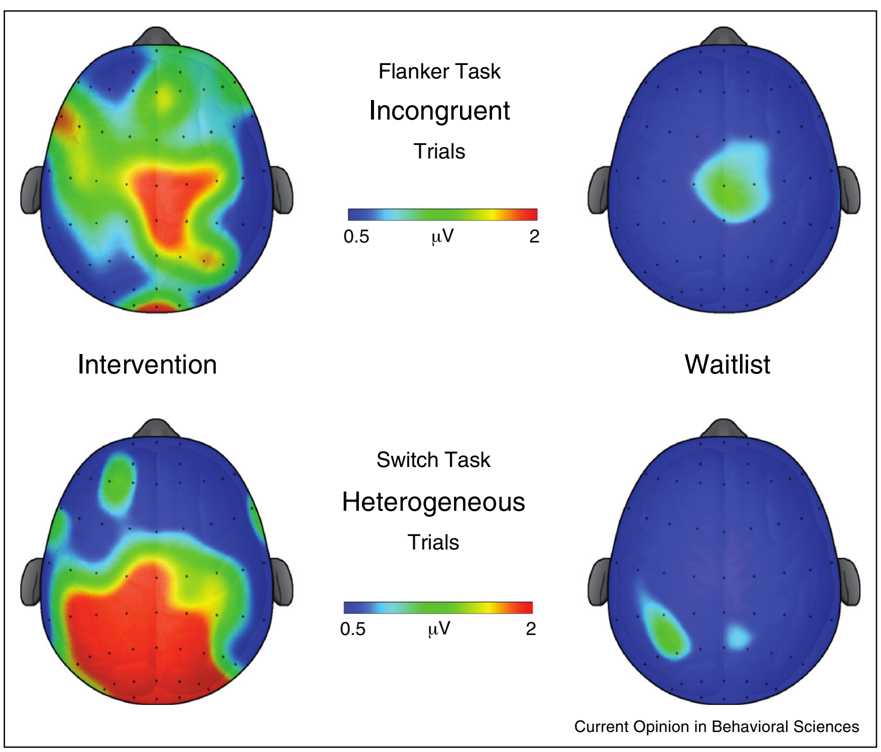
Brain function: Over the past decade, several correlational studies have demonstrated a relationship between PA or aerobic fitness and brain function using event-related brain potentials (ERPs) and functional magnetic resonance imaging (fMRI) techniques (e.g., [8••,9,10••]). However, more recently, randomized controlled trials have demonstrated the beneficial effects of extended participation in PA programs on brain function using fMRI [11,12••] or ERP [13••,14] measures. Importantly, these improvements in brain function have been accompanied by improvements in cognition, with executive control functions appearing especially susceptible to PA intervention [13••] — see Figure 1. Such findings are promising and indicate that prolonged PA participation relates to improved cognition and beneficial changes to underlying brain function.

Scholastic performance: One benefit to studying the relation of PA to childhood cognition is the applicability to real-world scholastic performance. Unlike adults, who lead idiosyncratic lives, virtually all children in western culture receive some form of formal education, which provides the opportunity to assess how PA (or other health behaviors) influences performance on scholastic assessments, including standardized academic achievement tests. Although there is a general lack of consensus, the vast majority of findings point to a beneficial relation of PA and aerobic fitness to scholastic performance, with higher marks observed for academic achievement tests and classroom-based assessments [15–17].

Effects of physical activity on brain and cognition in late adulthood

The examination of the effects of PA on brain and cognition in older adulthood is more established than that of younger age groups, with many of the seminal studies published between 1975 and 2000. Although results from several of these earlier studies were equivocal about the effects of PA on cognition, more recent

Figure 1



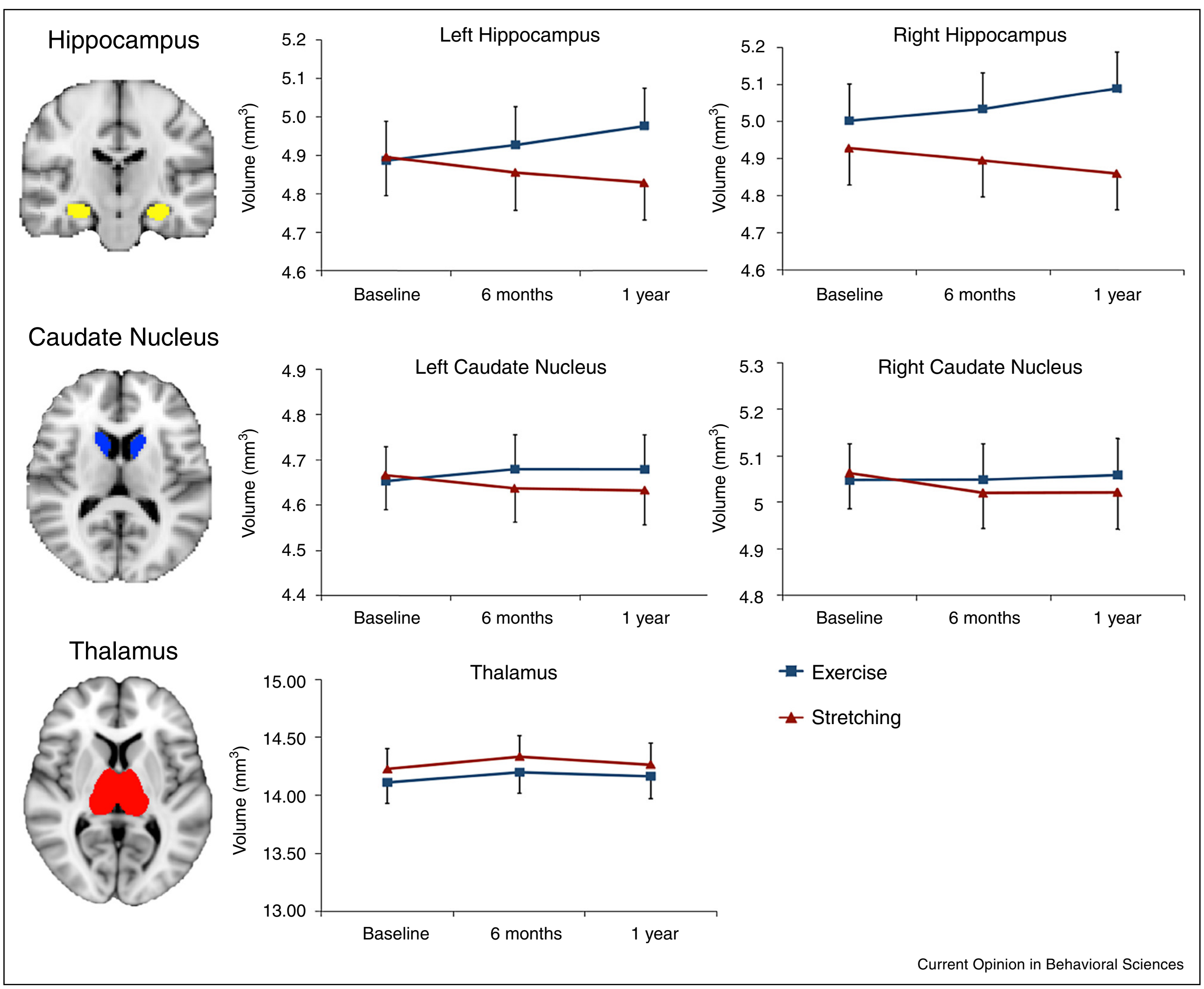
Topographic scalp distribution of the change in P3-ERP amplitude during a flanker task (top) and a switch task (bottom) for the intervention group (left) and waitlist group (right). P3 amplitude increased in the intervention group at post-test only for conditions requiring greater amount of executive control across both tasks.Adapted from Hillman *et al.* [13••].

meta-analyses and neuroimaging studies have shown convincing patterns that PA is an effective method for enhancing brain and cognition in late life.

Cognitive performance: Cross-sectional, observational, and randomized clinical trials of PA in late adulthood have demonstrated that engaging in PA may preserve and/or enhance cognitive function even in cognitively impaired individuals (e.g., [18]). Summaries of these studies can now be found in several meta-analyses, most of which confirm that PA positively influences cognitive function in late adulthood with small to moderate sized effects [19]. In a meta-analysis of 18 randomized PA trials, engaging in moderate intensity PA resulted in enhanced cognitive function across all cognitive domains examined, but with the largest effect sizes for indices of executive function [20]. Meta-analyses of longitudinal observational studies have also confirmed that self-reported engagement in PA is associated with nearly a 40% reduced risk of experiencing cognitive decline over several years [21]. These, and other studies, make a convincing argument that both continuing to engage in, and starting to engage in, PA in late adulthood may have a profound effect on maintaining cognitive health, improving function, and reducing the risk of developing cognitive impairment.

Brain structure: There have been now more than 30 published studies of PA or fitness on brain structure in older adults (>60 years) with the majority showing positive associations (see [22]). Such effects are important since increasing age is associated with brain atrophy and loss of volume, which precedes and predicts conversion to

Figure 2



A randomized physical activity intervention in 120 older adults demonstrated that moderate intensity walking exercise for one year increased the size of the hippocampus while the size of the hippocampus for the stretching and toning control group showed a slight reduction. There were no significant changes for the size of either the caudate nucleus or thalamus.Adapted from Erickson *et al.* [31••].

dementia. Higher aerobic fitness levels have been associated with larger gray matter volumes in older adults in several areas including the frontal cortex [23,24], hippocampus [25,26], and caudate nucleus [27]. Longitudinal observational studies have also shown that greater amounts of PA are associated with larger gray matter volumes in these regions, and greater volume is, in turn, associated with a reduced risk of cognitive impairment [28]. These cross-sectional and observational results in older adults are further supported by clinical trials that have shown that six-months to one-year of regular PA is associated with an increase in both frontal cortex [29••,30] and hippocampal volume [31••,32,33] — see Figure 2. These effects on gray matter volume are accompanied by differences found in white matter integrity. For example, several studies have reported that higher cardiorespiratory fitness levels and PA are associated with greater white matter integrity along several tracts linking frontal and subcortical areas [34–36] and that greater changes in fitness after an intervention was associated with an increase in white matter integrity [37]. In sum, there is now convincing evidence that PA and fitness influence brain structure, characterized by both gray matter volume and white matter integrity, in late adulthood.

Brain function: Both task-evoked fMRI and resting state studies of intrinsic brain connectivity have also been conducted in relation to participation in PA or fitness in late adulthood. These studies have found that higher fitness levels [38], greater amounts of PA [39], and randomized trials [40••,41] are associated with increased neural efficiency during cognitively challenging tasks. In addition, higher fitness levels and randomized interventions are associated with increased connectivity between hippocampal, prefrontal and cingulate regions [42,43•]. Importantly the changes that are observed in both task-evoked fMRI paradigms and in resting state paradigms are associated with improvements in cognitive performance, indicating that these changes are not meaningless by-products of engaging in exercise, but have behavioral relevance.

Conclusions and future directions

In sum, there is now substantial evidence that greater PA and higher fitness levels are associated with better brain and cognitive health for children and older adults. However, there are clearly a number of important gaps in the literature. For example, there is growing evidence that the benefits of PA may vary as a function of genetic factors [44,45•] and dietary factors [46], which may help explain heterogeneity in effect sizes in the literature. With regard to genetics several studies have reported that PA can reduce the potential detrimental effects of the APOE e4 allele on cognition and biomarkers for brain pathology [47•] but see [48]. However, most of these studies tend to have relatively small samples and focus on a single gene. Another important issue for future studies is how best to combine different cognitive training protocols or intellectual engagement activities with PA or exercise in an effort to enhance cognitive and brain health [49–51]. Additional animal research is needed to further elucidate the molecular and cellular mechanisms that underlie the beneficial effects of exercise on cognition and performance [52]. Finally, although a number of scientific and governmental organizations have made specific recommendations for PA and exercise for different populations, we generally do a poor job of meeting even the minimal amount of activity on a weekly basis [53,54]. Therefore, it will be important to continue to examine the factors that motivate and those that detract from maintaining recommended levels of PA [55].

Conflict of interest statement

None declared.

Acknowledgements

This manuscript was supported by grants from the National Institutes of Health to KIE (R01 DK095172), to CHH and AFK (R01 HD069381), and to AFK (R37 AG025667).

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