Review Article

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Influence of physical activity and cardiorespiratory fitness on brain structure and functioning: a review

Authors' Contribution:

A – Study Design
B – Data Collection
C – Statistical Analysis
D – Manuscript Preparation
E – Funds Collection

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Abstract

Positive correlations between physical activity and fitness with psychological benefits have been reported for many decades. Currently available novel neuroimaging techniques enable comparison and assessment of collected data, creating an opportunity to draw conclusions on the effectiveness of different types of exercise on improving brain functioning and health. There is a strong correlation between frequency of physical activity across the lifespan and benefits for brain functioning and volume. Aerobic physical activity, as the most thoroughly investigated type of exercise, comes out as the most beneficial for increasing brain volume and enhancing cognitive functions. It is also effective for raising the levels of cardiorespiratory fitness (CRF). However, sedentary lifestyle may diminish positive influence of physical activity and seems to be a crucial negative factor for maintaining brain health.

Keywords: *physical activity, fitness, brain structure, cognitive functioning, CRF, BDNF*

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INTRODUCTION

Neuroplasticity is a fundamental feature of the human brain. The brain changes in response to external stimuli and is subject to self-organization in conjunction with internal conditions. In addition, it constantly adapts to the environment during every moment of its existence. With development of sciences studying different aspects of the nervous system, scientists learn and understand more psychological, biological and behavioral factors and their effect on the brain. Carrying out the above processes enables a comprehensive approach which integrates neuroscience with other life sciences, such as different varieties of psychology, various branches of medicine and physical education, including rehabilitation or kinesiology.

In particular, the impact of processes and behaviors associated with kinesiology has been getting increasingly understood in the last decade. A growing number of research, review articles and meta-analysis is showing a positive correlation between physical activity, fitness or exercise, and length and quality of living across the lifespan in terms of mobility, cognitive functionality and psyche. All this novel data enables and encourages development of methods of contemporary physical education which will be on par with knowledge that we, as a civilization, already possess.

In context of this work, two crucial terms should be defined, which are: physical activity and physical fitness. Physical fitness, sometimes also called motor efficacy, can be understood as "a social category, showing the resourcefulness of human being during in solving motor tasks during play, work or daily activities" [1]. Level of physical fitness can be determined in at least three measures [2]:

- The ability to perform and maintain physical work;
- The performance expressed as the time that one needs to finish a task or as the upper limit of the possible weight that one can carry;
- Physiological variables, such as maximum heart rate or maximal oxygen uptake at rest or while performing a specific physical activity.

Physical activity is defined as "muscular effort inducing a set of repercussions in the body, which lead to energy expenditure greater than its level at rest" [3]. Measures of physical activity may include habitual patterns of energy expenditure during physical work, task performance or leisure, as well as questionnaires, interviews, observations or measurements with usage of specialized electronic equipment [2]. Physical activity and associated with its practice increased energy expenditure are sources of an excessive list of benefits on many levels for the human body in any age [4].

Often, in both scientific and non-scientific articles, a synonym of what is considered physical activity is "exercise". In fact, these two terms have a lot in common and they overlap in a significant extent. However, in professional literature exercise is most often referred to as a subcategory of physical activity and it is considered a more structuralized concept, composed of two additional elements, which are: planned, adequately specified and repetitive body movement, as well as the purposefulness aimed at improving or maintenance of physical fitness [5].

MATERIAL AND METHODS

Presented work is an analysis of 80 scientific articles found in Google Scholar by combining such phrases as: physical activity, fitness, brain, structure, volume, plasticity, cognitive functioning. Results were filtered by subjective criteria of usefulness, validity and publication date. Articles displaying data contrary to this works' thesis have been included as well.

RESULTS

Synaptic plasticity and cellular health

Positive effects of physical activity on brain health is partly associated with enhanced production of brain-derived neurotrophic factor (BDNF), a protein acting as a key growth factor in central nervous system (CNS) and peripheral nervous system (PNS). BDNF is an important mediator of the beneficial effects of intensive exercise, as it stimulates glucose transport and intracellular energetic biogenesis, therefore improving cellular bioenergetics and protecting neurons from inflammation and other disorders. According to contemporary studies, BDNF may be labeled as a brain's main energy homeostasis regulator [6]. Other important BDNF functions include: upregulating antioxidant enzymes production, enhancing damaged neuronal DNA restoration, balancing insulin sensitivity, promoting synaptogenesis and neurite outgrowth and modulating the efficacy of neurotransmitter release [7]. Studies reveal a correlation between aerobic exercise, such as running, and increased serum BDNF levels. Signals from muscle tissue seem to induce BDNF expression in neuronal cells by creating exercise-induced muscle protein, FNDC5, and its derivate protein fragment, irisin, which crosses the blood-brain-barrier and directly affects BDNF production [8].

Apart from BDNF, synaptic plasticity enhancement as a result of physical activity is associated with upregulation of molecules involved in synaptic transmission, including synapsin I, synaptophysin, synaptotagmin and syntaxin [7]. In addition, there is evidence of physical activity positively affecting glial cell integrity and functioning, as well as synaptic dendrite complexity and spine density [9]. Aerobic exercise is proven to affect the expression of genes encoding proteins responsible for synaptic plasticity, cellular bioenergetics, intracellular debris disposal and cellular stress resistance in almost all brain regions. Exercise-induced neurogenesis is a well-studied phenomenon. Studies have shown a clear increase of neuronal tissue in the dentate gyrus area of the hippocampus in the adult brain [10].

Studies reveal that BDNF gene and protein expression remain elevated up to two weeks either after short (2-7 days) or long (1-8 months) regular or alternating aerobic activity. Also, cellular and synaptic beneficial effects of physical exercise seem to be less effective in aging organisms in comparison to younger organisms [9].

Overall, the beneficial effects of physical activity on CNS seem to result from two key effects: intermittent energy challenging and muscle tissue protein production. In comparison to sedentary lifestyle, physically active lifestyle is associated with higher stress resistance, as well as stress resilience, both in neurobiological and behavioral approaches.

Brain volume and structure

Burzynska et al. [11] from their study on persons aging 60-78 drew conclusions concerning structural changes of the brain complementary to those presented in the previous section. As much as a weekly intervention in the form of repetitive low to moderate intensity physical activity indicates a positive correlation between the activity intensity and both integrity and density of white matter (WM) in the temporal lobe and parahippocampal area. The increase in thickness of frontal, temporal and parietal cortex [12], as well as in WM integrity [13] depending on CRF levels was indicated in the works of Colcombe et al. [14]. Aging-associated grey matter (GM) reduction was less visible in those persons who exhibited higher CRF levels.

Other studies show a positive correlation of CRF levels with volumes of such brain structures as the hippocampus [15, 16, 17], basal ganglia [18, 19], dorsolateral prefrontal cortex (DLPFC) [20], parahippocampal cortex [21], SMA and selectively other areas of frontal and temporal cortex [12]. It should be noted that this correlation was unnoticeable in a few groups, one of which were healthy persons in the study of Burns et al., [22] and the other was the young age group in the study of Colcombe et al. [13].

The frequency of performing aerobic physical activity in the periods prior to baseline check-ups correlated with the reduction of brain tissue loss in elderly population in many studies. The described areas involved particularly the medial temporal cortex [23], DLPFC and cingulate cortex [24, 25], hippocampus [16, 26], as well as the selected areas of occipital, frontal and entorhinal cortex [27]. Frequent aerobic exercise can be also associated with WM volume in the areas of corona radiata and parieto-occipial junction [28] and with increased fractional anisotropy (FA) in prefrontal, temporal and parietal cortex, which was exhibited by the results of DTI imaging in the studies of Voss et al. [29]. The advantage of aerobic exercise over stretching activities was indicated by the study of Nagamatsu et al. [30]. In addition, as described in the review paper by Voelcker-Rehage & Niemann [31] taking into account 18 studies aimed at exploring the positive correlation between frequency of physical activity performance and brain tissue volume, the areas most often reported as beneficiaries were part of: frontal cortex (67% of the studies), temporal cortex (50%) and motor cortex (28%) (Figure 1).

In the studies of Makizako et al. [32], in which higher physical fitness was determined by the longer distance reached in the 6-minute walking distance (6-MWD) test, it was shown in a positive correlation with the volume of left medial temporal gyrus (MTG), medial parietal gyrus (MPG) and the hippocampus formation. It is important to indicate that the volunteers taking part in the study consisted only of persons with diagnosed mild cognitive impairment (MCI).

On the contrary, there are studies with results inconsistent with these described above. Chaddock-Heyman et al. [33] describe in their study the inverse correlation between physical fitness and thickness of superior temporal, superior frontal and lateral parietal cortex in the brains of 9 and 10-year old children. Described children, however, have achieved higher marks in task performance involving such skills as mathematics. Results of this study can lead to a conclusion that cortex thickness can be inversely correlated with selected cognitive functions in young and elderly populations.

Functionality of the brain

One of the consequences of aging is weakening of functional connectivity in the brain, such as Default Mode Network (DMN) and Dorsal Attention Network (DAN). Data presented by Voss et al. [34] outline the relationship between the efficiency of these networks, particularly DMN [35], and cardiorespiratory fitness (CRF) level, expressed as maximal oxygen uptake

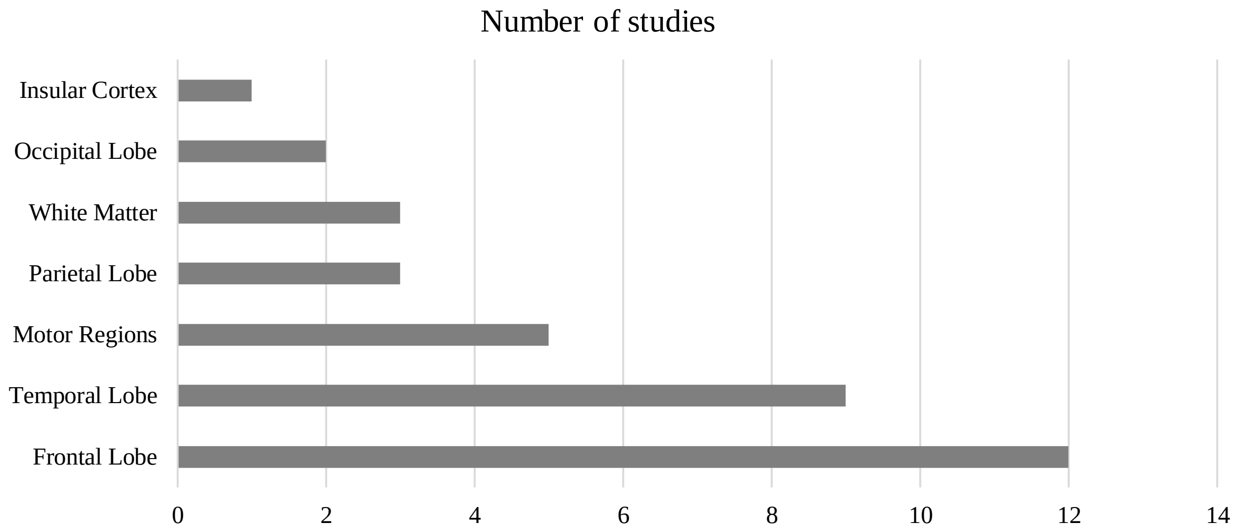

Figure 1. Number of studies describing areas that benefited form positive impact of metabolic exercise (18 studies in total). Adapted from Voelcker-Rehage C, Niemann C. Structural and functional brain changes related to different types of physical activity across the life span. Neuroscience & Biobehavioral Reviews. 2013;37(9):2268-2295.

(VO_2max). Effect was more visible in persons accustomed to physical activity of higher intensity. Voss takes into account the possibility of carrying out an effective exercise intervention in order to reverse negative effects of aging for the connectivity of DMN, DAN and other networks.

As a measure of functional integrity of the brain, Burzynska et al. [36] utilized in their study on persons aging from 60 to 80 the spontaneous variability of Blood Oxygenation Level-Dependent signal (SD_{BOLD}), associated with the resting state of the brain and recognized as a correlate of cognitive performance, especially in elderly population. Studies based on MRI scanning and diffusion tensor imaging (DTI) exposed a slight positive correlation between low intensity physical activity and SD_{BOLD} range. Moreover, SD_{BOLD} range exhibited as four times higher when the effect of moderate to high intensity physical activity was studied. However, this correlation was unnoticeable for sedentary lifestyle and high CRF level groups.

Nevertheless, CRF level can be associated with higher levels of activity in a number of brain areas. It was pointed out by Wong et al. [37] in their study using functional MRI (fMRI). They described a clear positive correlation of CRF levels with the intensity of activation in anterior cingulate cortex (ACC), supplementary motor area (SMA), somatosensory cortex, right motor cortex, right medial frontal gyrus (MFG), as well as deeper brain structures, such as thalamus and basal ganglia.

Cognitive processes

Kramer et al. in 1999 [38] proposed the hypothesis according to which the greatest neuronal beneficiaries of performing physical activity should be functions which are primarily related to frontal lobe activity and that they should benefit the most in elderly population. The frontal lobe, as the area most affected by tissue loss in the course of aging and in progress of a number of neurodegenerative diseases, is pointed by the researchers as the number one area that is positively affected by neuroprotective qualities of frequent physical exercise and high physical fitness.

Improvement of many executive functions can be associated with frequent aerobic exercise [39, 40, 41, 42, 43, 44, 45], in particular the explicit [46], spatial or short-term memory (STM) [16, 20, 47, 48]. In addition, CRF levels are positively correlated with the efficiency of declarative memory in children [18, 19, 49, 50] and adults [51], as well as the STM performance in the elderly [29]. Positive correlations also apply to the functions of attention management [52, 53]. Studies have shown reduced reaction time (RT) or higher correctness in the Stroop test among persons previously engaged in aerobic physical workouts [54, 55, 56, 57, 58] and those persons that exhibited high CRF levels [20, 53, 59, 60, 61]. A positive impact on executive functions was also associated with the performance of yoga [62].

Physical fitness proves to be a useful addition to the process of education of children and youth [63, 64, 65, 66, 67, 68, 69, 70], especially in the domain of arithmetic skills (Figure 2) [71, 72, 73]. An intervention in the form of increased physical activity could also reduce attention deficit hyperactivity disorder (ADHD) symptoms in children [74].

Aerobic physical activity, especially including dancing [75], seems to diminish negative aging effects in the cognitive domain [16, 25, 76]. In most studies similar correlations have not been proven for the resistance training [67]. However, there is at least one exception [77].

Developing an active lifestyle and obtaining high physical fitness in adulthood can unfortunately have limited benefits for cognitive functioning, as indicated by the studies of Madden et al. [78] and Belsky et al. [79]. It can be concluded that those persons who exhibit high intelligence (measured by IQ levels or other measures) and who obtained good education in childhood will in their future make better decisions concerning their health and physical fitness. Persons with low intelligence and worse education could live during their adulthood and senility in a less healthy manner, therefore obtaining lower scores in tests of cognitive abilities.

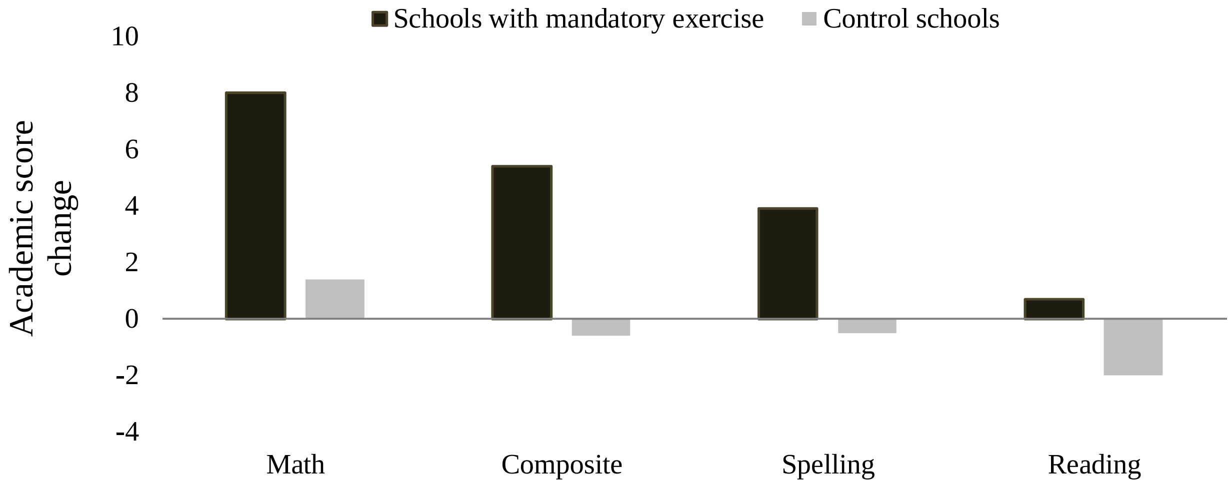

Figure 2. Academic score change after 3 years in comparison to baseline PAAC (n = 117). Schools with mandatory exercise (N=117): 45 to 75+ min/week of exercise. Control schools (N=86): no mandatory exercise. Adapted from Donnelly JE, Greene JL, Gibson CA, et al. Physical Activity Across the Curriculum (PAAC): a randomized controlled trial to promote physical activity and diminish overweight and obesity in elementary school children. Prev Med. 2009;49(4):336–341.

Beneficial effect of physical activity performance on a number of cognitive aspects of everyday functioning, although not very significant or only short-term, were also demonstrated in the groups consisting of young subjects. Younger participants seem to be a neglected group in brain and physical activity studies in comparison to adult or elderly populations [80].

DISCUSSION

Data presented in previous sections allow to reason that a late in-life intervention in the form of increased frequency of physical activity, regardless of its type or intensity, results in a limited amount of benefits in comparison to performing regular physical training since the early childhood. One of the most recent meta-analysis studies presents a more extreme perspective. Its authors prove that even a frequent and intensive physical exercise does not overcome the negative health effects of many daily hours of static or sedentary lifestyle [80].

CONCLUSIONS

According to the accumulated data, an undoubted advantage over other types of workout is exhibited by the aerobic exercise. It may be due to the fact that this is the most popularly studied form of physical training. Its intensity can also be relatively accurately regulated and translated into the improvement of CRF levels. The CRF level itself, however, correlates positively with functional and structural brain changes rather rarely and usually in a less significant manner than the frequency of physical activity.

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