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A Review of the Effects of Physical Activity on Cognition and Brain Health across Children and Adolescence

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Abstract

Physical activity (PA) can improve physical, mental, cognitive, and brain health throughout the lifespan. During preadolescent childhood, the benefits of PA for cognitive health have been widely studied, with evidence indicating enhanced executive control, improved academic performance, and adaptation in underlying brain structure and function. Across school age children, the predominant literature has focused on preadolescent children, with a comparatively smaller body of evidence in adolescent children. Yet, preliminary findings suggest improvements in verbal, numeric, and reasoning abilities as well as academic achievements. Further, benefits of PA are also rarely examined in preschool children. Consequently, lack of standardization across studies has led to various approaches in the measurement of PA and fitness. However, since implementing tools that objectively quantify active play, PA has been related to better executive function, language acquisition, and academic achievement. Despite evidence that PA promotes cognitive and brain health during development, a growing number of schools have minimized PA opportunities across the school day. The minimization of PA along with several other factors, including lack of active commuting to school, nutrition transition, and availability of electronic devices, for example, has reduced children's physical and mental health. Accordingly, today's children have become increasingly inactive, which affects public health and contributes to educational concerns. By dedicating time to active play, sports, physical education, and other forms of PA, children are best positioned to thrive in both the physical and cognitive domains.

Introduction

Despite recommendations and widespread health campaigns from the World Health Organization [1] and the 2018 Physical Activity Guidelines for Americans [2] aimed at improving health and wellness among youth, most children are not adequately physically active to derive the full health benefits. In fact, less than 24% of children aged 6–17 years engage in the recommended 60+ min of daily moderate-to-vigorous physical activity (MVPA) [3]. Physical activity (PA) behaviors during childhood track into adolescence and adulthood [4], which is concerning since physical inactivity has been linked to earlier mortality and greater morbidity associated with multiple chronic diseases [2]. Largely absent from these public health concerns is the effect of physical inactivity on cognitive and brain health. Further, many school districts have obviated PA from the school day due to budgetary constraints and an increased emphasis placed on standardized test performance. Although it may seem counterintuitive that spending less time in the classroom and more time engaged in PA might serve to improve cognition and learning [5], there is a growing literature detailing the beneficial effects of PA on brain health, cognition, and academic performance [6].

The current literature on the benefits of PA for brain and cognition differ across youth. Specifically, the majority of evidence exists among preadolescent children (6–13 years) [6], with comparatively less research in preschool children [7] and adolescents [8]. Although the extant findings overwhelmingly indicate benefits of PA on brain structure and function as well as cognition and academic performance, outstanding research questions remain. Accordingly, this article summarizes the current literature on the benefits of PA for brain health and cognition in youth, and highlights future areas of research needed to advance the state of the science.

Preschool Children

Early childhood is a critical period of motor, mental, and cognitive health development [2]. PA has been shown to act on and improve different health outcomes in children, but to date, physical health outcomes have been researched more commonly than mental and cognitive health outcomes in children younger than 6 years [7]. Considering the importance of this period of rapid growth, investigating the potential effects of PA on cognition and brain health in this population is imperative.

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Brain development begins in the first trimester of pregnancy, accelerates postnatally through the second year, and continues throughout the lifespan [9]. Cognitive health in children younger than 2 years is largely tethered to the achievement of behavioral milestones such as attending to faces, reacting to sounds in the environment, smiling, speaking, or playing with toys at appropriate time points of development [10]. PA for children under 2 years can be strengthening neck muscles to hold their head up, rolling over, stretching their legs and arms, and learning to sit up, crawl, and walk [10]. Although the quantifiable connection between cognitive health and PA in children under 2 years of age remains unknown, it is generally thought that novel experiences that promote motor skills, movement, and exploration enhance neuroplasticity and further cognitive growth [9].

In children between 3 and 5 years, the most prevalent form of PA is active play. Given that active play is naturally unstructured, standardization of PA measures in this age group is difficult to obtain [11]. In recent years, there has been a shift away from subjective reporting to using pedometers and accelerometers that capture objective daily PA (i.e., step counts) [11]. Using accelerometers, it has been suggested that young children who spend more time in MVPA during play showed improvements in self-regulation – an encompassing term used to describe integrated executive functioning capabilities such as inhibitory control, working memory, and cognitive flexibility [12]. More broadly, systematic reviews have concluded that young children who participate in greater amounts of PA have demonstrated improvements in executive function, language acquisition, and academic achievement [7].

Fitness is also challenging to measure in this demographic. The gold standard laboratory measure for fitness is a graded exercise ($\dot{V}O_{2\,max}$) test, during which a participant typically runs/walks on a treadmill or cycles on an ergometer until volitional exhaustion. $\dot{V}O_{2\,max}$ testing has been successfully completed in children as young as 4 years, but it is subject to physical limitations of the individual – children shorter than 125 cm may require a pediatric treadmill or cycle ergometer [13]. Additionally, there is debate whether children achieve a true $\dot{V}O_{2\,max}$, which occurs during a plateau of oxygen uptake [13]. Although $\dot{V}O_{2\,max}$ has been positively related to daily activity variables captured via accelerometry in children younger than 6 years, the relationship was only found in boys, contradicting previous studies in older children and adolescents [14].

The lack of standardized measures has yielded diverse approaches to quantifying fitness in young children. For example, isolated physical fitness measures such as muscular strength, running speed, balance, flexibility, and coordination are inconsistently measured and reported in this population [15]. Field-based fitness tests such as a shuttle run to measure aerobic fitness, obstacle courses to

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measure motor skills, and balance beams to measure dynamic balance have been associated with better attention and spatial working memory [16].

Additional efforts have been made to connect other easily measurable health indicators, such as weight status, to cognition in children. While the effects of obesity on brain health in children younger than 6 years are inconclusive, higher body fat percentage is associated with poorer executive control and academic achievement in youth slightly older than preschool children (6–8 years) [17].

Overall, current knowledge regarding the benefits of PA for cognition and brain health in preschool children suffers from variability of measurement, and given that the field is currently emerging, there are important considerations moving forward. Recent interest in this demographic has suggested that maintaining a healthy lifestyle, including engaging in regular PA and maintaining a healthy body mass, should be established early in childhood to capitalize on benefits for cognition and brain health across the lifespan.

School Age Children

Preadolescent Children

As PA continues to decrease throughout the lifespan, critical populations of interest include preadolescent and adolescent demographics. The physical inactivity epidemic is widespread, affecting not only US children. Comparably, European preadolescent children spend only 16 min/day (5%) in MVPA but 209 min/day (64%) engaged in sedentary activities [18]. Given that PA behaviors during preadolescent childhood track into adolescence and adulthood [4], early intervention is necessary to positively promote greater participation in PA across the lifespan, subsequently leading to the promotion of healthier lifestyles.

The benefits of PA intervention in preadolescent children are extensive, encompassing many aspects of physical, mental, cognitive, and brain health. For example, PA interventions are efficacious for enhancing mental health and wellness [19], increasing executive control [20–23], and improving academic performance [21, 23] in preadolescent children. In recent years, a move towards understanding the cognitive and underlying brain structure and function mechanistic relationship in response to PA interventions has emerged. PA dose-response relationships in preadolescent children have indicated that higher attendance in an afterschool PA program is associated with larger changes in neural indices of attention and processing speed, as measured by event-related brain potentials, and improved performance during tasks of executive control and academic performance (Fig. 1a, b) [21]. Specifically, children in the FITKids and FITKids2 clinical trials delivered a 2-h PA intervention during 5 school days per week for

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9 months (150 days), based on the Child and Adolescent Trial for Cardiovascular Health (CATCH) curriculum, which provided MVPA in an after-school noncompetitive environment. Children who were randomized to the PA intervention were compared before and after the test to children who were randomly allocated to the wait list control group. This control group was asked to maintain their regular after-school routine and were not contacted again until 9 months after testing.

Overall, when examining the preadolescent brain responses to PA, children demonstrated enhanced cognitive performance and brain function during tasks requiring greater amounts of executive control (i.e., tasks that modulated inhibition, working memory, and cognitive flexibility demands) at the 9-month post-test, relative to before the test, and this effect was absent for children assigned to the control group [20–22]. Moreover, the observed behavioral benefits coincided with interesting brain (i.e., event-related brain potentials) outcomes, such that children in the PA intervention exhibited a larger P3 amplitude (Fig. 1a), stability of the error-related negativity potential (Fig. 1c), and a larger initial contingent negative variation amplitude (Fig. 1d) compared to children in the control group 9 months after the test. Such findings suggest that the PA intervention was beneficial to brain functions underlying the allocation of attentional resources, conflict monitoring, and cognitive preparation processes during tasks that require executive functions, respectively. Lastly, increased aerobic fitness, which is associated with increased levels of PA, was found to correlate with tasks of inhibitory control and academic achievement [23].

Furthermore, recent evidence has suggested that PA is associated with increased white matter microstructure in the genu (the anterior bulbar end of the corpus callosum) [24]. Specifically, the 9-month FITKids trial demonstrated that children in the PA intervention showed increases in fractional anisotropy (the total magnitude of directional movement along axonal fibers) and decreases in radial diffusivity (a sensitive measure for axonal or myelin damage, defined as the magnitude of diffusion perpendicular to the tract) in the genu after the test compared to before the test – an observation which was not seen in the control group (Fig. 1e). Importantly, the genu of the corpus callosum is an area associated with the integration of cognitive, motor, and sensory information between the left and right hemispheres of the brain. Notably, the FITKids trial also revealed that children in the PA intervention showed decreased brain activation, as measured via functional MRI, in the right anterior prefrontal cortex, coupled with within-group performance improvements in an inhibitory control task (Fig. 1f) [25]. Collectively, functional MRI data suggest that PA and fitness are important lifestyle factors for cognitive and brain health in preadolescent children. The FITKids clinical trials further indicate that daily PA serves to increase

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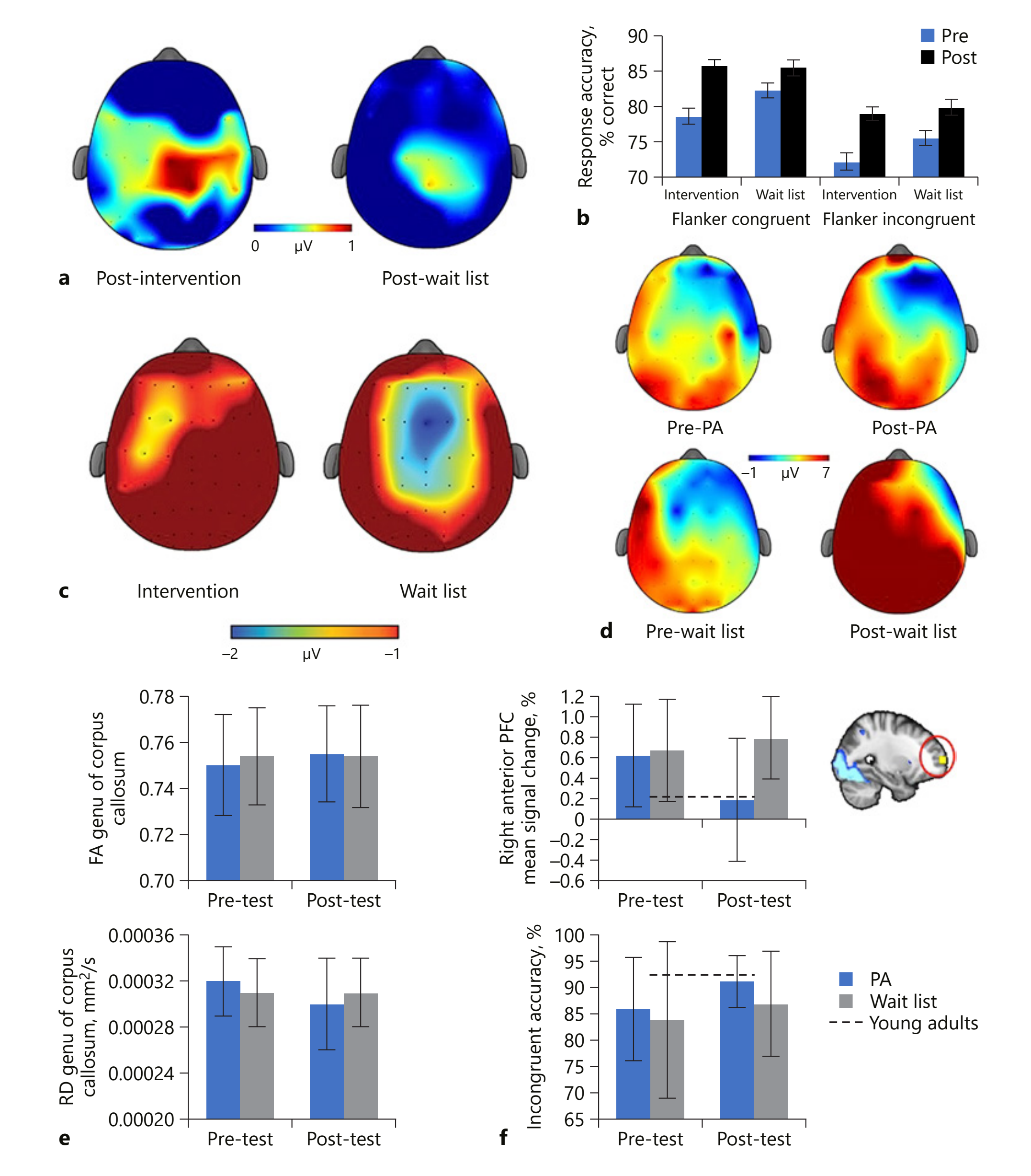
aerobic fitness alongside improvements in academic performance, executive function, and underlying brain structure and function. Meanwhile, such findings were not demonstrated in a control group of children following 9 months of typical development.



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Adolescent Children

In addition to research focused on child and preadolescent populations, the relationship between adolescent cognitive performance and brain outcomes in response to PA has recently attracted investigative focus; however, the field is relatively unexplored compared to the extant literature with preadolescent children. Specifically, cross-sectional studies have explored this relationship in adolescents, and data suggest that children who participated in PA during extracurricular leisure time had better cognitive performance on measures of verbal, numeric, and reasoning ability [26]. Further, apart from extracurricular activities, better cognitive performance across similar measures was observed in adolescent females who reported actively commuting to school (e.g., walking or biking) compared to nonactive adolescent female commuters (e.g., car, bus, or subway) [27]. These cross-sectional studies, which delve into cognitive responses to healthy PA behaviors, have initiated a framework for further investigation, and collectively provide evidence of a positive relationship between PA and cognitive function [8]. Evidently, there is a need for chronic PA interventions in adolescents, across the entire school day, to appropriately assess the effects of PA on brain and cognition.

Lastly, the effects of PA interventions on academic achievement have also been explored. Specifically, an in-school vigorous PA intervention over the course of 1 semester was associated with higher grades in academic achievement at the completion of the semester [28]. Notably, the increased grades were not observed in children who participated in moderate PA interventions, suggesting that this effect was only related to the PA of vigorous intensity [28]. Additionally, an acute in-school PA intervention in adolescents demonstrated increased performance in mathematical tasks, indicating that benefits may be observed immediately following the cessation of an exercise bout, as well as following prolonged exposure to PA behaviors. [29]. Collectively, these data suggest enhanced

Fig. 1. Data from the FITKids and FITKids2 trials illustrating cognitive and brain changes stemming from a 9-month PA intervention compared to a wait list control group in preadolescent children. **a** Topographic scalp plots demonstrating mean change in P3 amplitude (μV) during modified flanker and switch tasks for each group [21]. **b** Response accuracy (%) for the modified flanker task, and the homogeneous and heterogeneous conditions of the switch task for each group and time point [21]. **c** Topographic scalp plots depicting the mean change in error-related negativity amplitude (μV) during the modified flanker task for each group [20]. **d** Topographic scalp plots demonstrating an initial contingent negative variation amplitude for each group and time point [22]. **e** The ratio of fractional anisotropy (FA) and radial diffusivity (RD) for the genu of the corpus callosum (mm^2/s) for each group and time point [24]. **f** Mean percent change in the blood oxygen level-dependent signal for the right anterior prefrontal cortex (PFC) and incongruent flanker task response accuracy (%) for each group and time point [25].

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academic performance in response to PA interventions in both preadolescent and adolescent children. As school districts continue to move away from PA opportunities during the school day due to budgetary constraints and an increased emphasis on standardized test performance, these trends on the beneficial effects of PA for brain health, cognition, and academic performance of school-age children are important to consider [6].

Future Directions

There are certainly a number of important future directions that are necessary to advance the field of childhood PA, brain health, and cognition. Compared to preschool-age children (<6 years), efforts must be directed toward improving the precision of data collection both in terms of exposure variables, such as the measurement of PA behaviors, and in terms of the measurement of cognitive outcomes. That is, the field has yet to develop consensus on the best means for measuring PA in younger children. Further, there are a number of tests available to assess cognition during this period of development, yet much of the existing PA literature has lacked a theoretically guided approach, with little understanding of development and maturation. For example, given that preschool-age children are undergoing rapid maturation, research in this area should consider timing PA interventions with critical periods of development, a window during which the brain is most responsive (i.e., open to structuring and restructuring) to environmental exposures. Similar consideration for critical periods has been used with other behavioral interventions, such as for optimizing language acquisition [30]. It is plausible that brain and cognition may be especially amenable to PA intervention during specific critical periods affording greater opportunity to provide health benefits to preschool-age children.

Compared to school-age children (6–18 years), the study of PA on brain and cognition has developed more rapidly, with more sophisticated study intervention designs and measurement approaches to assess brain and cognition. However, considerably more research is necessary to unpack the underlying neural mechanisms that underpin cognitive enhancements. For example, we are just beginning to understand changes in neural networks, rather than single regions or areas of the brain, that are influenced by PA behavior. Future research will need to combine these neural network approaches to understanding modifications in the whole brain with randomized controlled trials that offer the sophistication and proper controls to afford causal evidence. The further ability to link PA-induced changes in neural networks that underlie academic performance is an additional future direction that is ripe for study.

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A final future direction that warrants further consideration is individual differences in PA effects on brain and cognition. That is, individual differences in response to PA intervention are common, but with respect to brain and cognition, little is known regarding what underlies differential responses. Previous findings in the literature indicate differential responses as a function of sex, genetic makeup, body composition, and disability/disease status, to name only a few. A systematic approach to understanding individual differences and their influence on the effects of PA on brain and cognition is imperative toward designing effective interventions aimed at improving public health.

Conclusion

The importance of PA on early cognitive and brain health and development in children is evident. Data suggest a beneficial relationship between the time preschool children spent in MVPA through active play (assessed by means of accelerometry) and greater improvements in measures of self-regulation. Additionally, the positive effects of PA on cognitive and brain health in older children are vast. PA interventions in preadolescent children have demonstrated greater improvements in neural indices of attention, conflict monitoring, motor preparation, and processing speed, as well as improved performance during tasks of executive control and academic performance. Neuroimaging data also indicate greater improvements in executive control tasks coupled with decreased activation in the right anterior prefrontal cortex.

Further, cross-sectional adolescent research has demonstrated the importance of considering the effects of PA on fitness and cognitive and brain outcomes. Importantly, adolescents who participate in greater amounts of PA demonstrate greater performance on measures of verbal, numeric, and reasoning ability. Meanwhile, in-school intervention data suggest vigorous PA over the course of just 1 semester is associated with better performance in academic achievement tasks. Collectively, both structured and unstructured PA throughout development is essential to promote cognitive and brain health in children.

PA is important to consider when evaluating and promoting the health and development of all children. Recently, many school districts have focused their curriculum toward spending more time in the classroom and less time engaged in PA. However, evidence suggests this may in fact be counterintuitive to the improvement in classroom-based learning, as PA positively promotes cognitive and brain health and academic performance. Consequently, restructuring classroom time to include regular bouts of PA throughout the school day is recommended. PA trends have also demonstrated that healthy behaviors during child-

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hood track into adulthood. Thus, implementing healthy behaviors early during development and throughout the school curriculum is likely to positively influence the adherence of PA across the lifespan. Habitual commitment to PA is therefore important for the public health of children as they develop into adulthood, as well as when considering the health behaviors of subsequent generations.

Conflict of Interest Statement

The authors declare no conflict of interest.

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