CHAPTER 17

EFFECTS OF PHYSICAL ACTIVITY ON COGNITION IN CHILDREN AND ADOLESCENTS

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As the global prevalence of sedentary behaviors and associated decrements in physical health attributes during childhood continue to increase, a greater understanding of the extent to which physical activity (PA) relates to brain health and cognition during development is of increasing importance. To better understand the association and effects of PA behavior and related attributes on cognitive function, investigations in this area have leveraged insights provided through neuroimaging techniques, such as electroencephalography (EEG) and magnetic resonance imaging (MRI).

In this chapter, we focus on such investigations as they relate to neural processes associated with memory and higher-level cognitive functions in children and adolescents, which have broad implications for academic achievement. We specifically focus our review of the present literature on the aspects of cognition, duration of PA, population characteristics, moderating factors, and modality of PA interventions that modulate the changes in cognitive function associated with habitual PA.

Although a growing number of investigations have examined the effects of PA on cognition, several challenges still exist in elucidating the enhancements in cognitive function sustained from engaging in habitual PA because these changes may take years to manifest. For example, the following remain unclear: the degree to which changes in aerobic fitness modulate cognitive function, whether the strength of the relationship between chronic engagement in regular PA differs across age groups, and the extent to which other health-related components of physical fitness beyond aerobic fitness relate to superior cognitive function. Within each of these domains, we call attention to critical limitations of the present literature with the express purpose of identifying future research directions to advance the field.

CHRONIC PHYSICAL ACTIVITY AND COGNITION

Aspects of Cognition Impacted by Physical Activity

Early research addressing the relationship between habitual PA and cognition initially focused on lower level cognitive processes, such as simple reaction time or finger-tapping tasks. It was found that elderly individuals who chronically engaged in PA demonstrated shorter reaction time and faster speed of movement relative to more sedentary elderly adults (Spirduso, 1975; Spirduso & Clifford, 1978). However, a seminal meta-analysis conducted by Colcombe and Kramer (2003) shifted the field toward investigating higher level cognitive processes (i.e., cognitive control) after finding that such aspects of cognition were impacted by chronic PA to a greater extent than other lower level cognitive processes.

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The construct referred to as *cognitive control* describes a subset of self-regulatory processes involved in maintaining control over actions, solving problems, and resisting temptations/distractions (Davidson, Amso, Anderson, & Diamond, 2006). Accordingly, the shift toward examining cognitive control revitalized research in this area because cognitive control has been demonstrated to underlie aspects of scholastic performance (Bull & Scerif, 2001; St Clair-Thompson & Gathercole, 2006). Failures in cognitive control, on the other hand, have been associated with symptoms of attention-deficit/hyperactivity disorder (Barkley, 1997), an increased risk of becoming obese (Graziano, Calkins, & Keane, 2010), and a higher likelihood of drug and alcohol abuse later in life (Nigg et al., 2006).

Within the literature, the term *cognitive control* is used synonymously with the terms *executive control*, *executive function*, and *central executive*. Whereas the terms *executive control* and *executive function* are more generally used in developmental and school psychology literatures, the term *central executive* originates from Baddeley's model of working memory (Baddeley & Hitch, 1974) and, thus, has been historically used in the attention and cognitive psychology literature. The more recent adoption of the term *cognitive control* bridges these diverse fields by drawing together the core constructs that modulate goal-directed interactions with the environment (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Meyer & Kieras, 1997).

Indeed, modern theoretical perspectives of cognitive control in adults suggest that this broad class of high-level cognition comprises three component processes: inhibition, working memory, and cognitive flexibility (Davidson et al., 2006; see also Chapter 16, this volume). However, in preschool-aged children, such component processes are not yet differentiated. That is, despite contextual differences in tasks corresponding to such a three-factor perspective, factor analysis of performance across a battery of cognitive control tasks in children 2 to 6 years old supports a unitary model (Wiebe, Espy, & Charak, 2008).

Accordingly, the maturation and differentiation of cognitive control processes occur in parallel to neural maturation in regions, such as the anterior cingulate cortex, prefrontal cortex, basal ganglia, and superior frontal sulcus, as well as the insular and parietal cortices (Bunge & Crone, 2009; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Travis, 1998). Thus, such a developmental time course helps to connect the various research domains, bridging the gap between the school psychology literature/measures that tend to treat executive function as a unitary construct and other literature/measures that attempt to isolate the core component processes of inhibition, working memory, and cognitive flexibility as functionally distinct.

Early conceptualizations for the reasons PA might impact cognitive control processes to a greater extent than other aspects of cognition posit that it was the result of cognitive reserve (Stern, 2002). The theory of *cognitive reserve* stems from the notion that individuals vary in the extent to which they are able to handle cognitive demands before cognitive deficits begin to manifest. Therefore, it has been suggested that individual differences manifest either as a result of functional differences in the use of strategic processes or structural differences in the integrity or integration of various brain regions, thus allowing the individual to be better able to handle increasingly demanding cognitive loads (Stern, 2002).

The supposition that follows is that individuals who are more physically active or have greater levels of aerobic fitness will have more cognitive reserve. With this greater reserve, they may be better able to optimize neural recruitment (i.e., bring online other neural systems/processes) or use alternative cognitive strategies to handle increasingly rigorous task demands (Chodzko-Zajko & Moore, 1994; Etnier, Nowell, Landers, & Sibley, 2006; Stern, 2002). Indeed, much of the work in this area has focused on elderly adults and preadolescent children, populations that exhibit poorer cognitive reserves as a result of age-related tissue loss or development. This process increases the likelihood of detecting modulations in cognition resulting from PA (Hillman, Erickson, & Kramer, 2008) because these populations exhibit lower levels of baseline performance, and their cognition may be more easily taxed.

Further support for this cognitive reserve perspective is provided by Pontifex et al. (2011), who found that lower-fit children engaged in less efficient cognitive strategies, resulting in a decreased ability to flexibly modulate cognitive operations to meet task demands. However, lower level cognitive processes that rely on neural regions, such as the basal ganglia, cerebellum, prefrontal cortex, and hippocampus, also appear particularly sensitive to the effects of PA and the associated attribute of aerobic fitness (Pontifex et al., 2014). Accordingly, a modern conceptualization suggests that the relation of PA and fitness to cognition also appears to depend on the specific network of neural regions underlying the cognitive process. Thus, if a task is not sufficiently challenging or does not rely on these specific neural networks, then the facilitative effects of PA and fitness on cognitive function may be attenuated (Pontifex et al., 2014).

Physical Activity Versus Aerobic Fitness

Much of early work used aerobic fitness as a proxy of chronic PA engagement and demonstrated the positive relation of childhood fitness to cognitive control (e.g., Chaddock, Erickson, Prakash, VanPatter, et al., 2010; Hillman, Buck, & Themanson, 2009) and academic achievement (e.g., Castelli, Hillman, Buck, & Erwin, 2007). In some ways, this approach is problematic in pediatric populations because there is only a small-to-moderate relationship between these constructs (Morrow & Freedson, 1994), with aerobic fitness and PA exhibiting independent associations for metabolic risk factors (Ekelund et al., 2007).

Aerobic fitness represents a physical health attribute related to the ability to perform prolonged strenuous exercise, whereas, in the broadest sense, PA refers to any voluntary body movement produced by skeletal muscles that results in an increased energy expenditure. Most studies in this area of research have used moderate-to-vigorous PA (MVPA) and examined the association between PA and cognition. Accordingly, for the purpose of this chapter, *PA* is defined here in the narrow sense as MVPA—as activities with an energy expenditure above three metabolic equivalents (METs), such as brisk walking and running.

Although recent several studies have examined the relation of MVPA to cognitive function and academic achievement, the findings have been equivocal because the existing evidence has shown either positive (Booth et al., 2014; Syväoja, Tammelin, Ahonen, Kankaanpää, & Kantomaa, 2014) or null (LeBlanc et al., 2012; Pindus et al., 2015) associations. Pindus et al. (2016) assessed both aerobic fitness and MVPA in preadolescent children (mean age ≈ 9 years) and indicated a positive relation of aerobic fitness to inhibitory aspects of cognitive control and academic achievement, with no such relationship being observed for MVPA engagement. Hansen, Herrmann, Lambourne, Lee, and Donnelly (2014) also found a positive association between aerobic fitness and academic achievement in preadolescent children (mean age ≈ 8 years) but not accelerometer-measured PA levels. Thus, it is likely that aerobic fitness relates more strongly to cognitive control and academic achievement than PA in children.

These findings provide evidence of a positive association between increased aerobic fitness and cognition during childhood, and highlight the need for further investigations assessing both aerobic fitness and PA. However, the critical issue remains: Are current methodological approaches for assessing PA—which rely on a 3- to 7-day period of accelerometer-based tracking—truly representative of chronic PA engagement? It instead may be necessary to conduct such assessments across a number of time points over a longer period (e.g., sampling PA four or six times a year) to adequately quantify habitual activity levels. Ultimately, the existing evidence coalesces to indicate that habitual PA and associated increases in aerobic fitness may be vital for the development, optimization, and preservation of cognitive health and effective function during childhood.

Insights Provided Through Neuroimaging

Beyond overt measures of behavioral performance, neuroimaging investigations have provided a greater understanding of the relationship between habitual PA and cognition. Although much of the research in this area has focused on older adult populations (see Erickson, Banducci, & Akl, 2012, for a review), there is marked similarity between the neural regions in older adult populations and those regions in pediatric populations sensitive to chronic PA. In particular, both preadolescent children and older adults with lower levels of aerobic fitness have exhibited smaller hippocampal volume and poorer hippocampal-dependent memory performance (Chaddock, Erickson, Prakash, Kim, et al., 2010;

Erickson et al., 2009). Similarly, the integrity of the prefrontal cortices relates to the level of aerobic fitness in older adults (Colcombe et al., 2004), with poorer aerobic fitness further relating to reduced activation of the prefrontal and parietal cortices in both preadolescent children and older adults (Chaddock et al., 2012; Colcombe et al., 2004). Aerobic fitness also appears to be related to greater volume of neural tissue in the basal ganglia across the lifespan (Chaddock, Erickson, Prakash, VanPatter, et al., 2010; Verstynen et al., 2012).

Evidence from several recent randomized controlled trials (RCTs) of the effect of increasing PA on cognition is consistent with these aerobic fitness-related findings. For example, the FITKids trial (Chaddock-Heyman et al., 2013; Hillman et al., 2014; Kamijo et al., 2011) examined the effects of a 9-month randomized controlled PA intervention aimed at improving aerobic fitness (5 days/week, > 70 min/day) on cognitive control in low-fit preadolescent children (mean age ≈ 9 years, mean percentile of maximal oxygen consumption [VO_2 max] ≈ 20th). Findings demonstrated that the FITKids intervention improved cognitive performance across all three domains of cognitive control: inhibition, cognitive flexibility, and working memory (Chaddock-Heyman et al., 2013; Hillman et al., 2014; Kamijo et al., 2011). Furthermore, those studies assessed brain activity using functional neuroelectric and neuroimaging techniques, such as EEG and functional MRI (fMRI). The results of those studies indicated that the FITKids intervention resulted in increased brain activity related to stimulus evaluation and cognitive preparation processes during cognitive control tasks (Hillman et al., 2014; Kamijo et al., 2011). At posttest, children assigned to the intervention group had similar brain activity patterns to a group of college-aged young adults (Chaddock-Heyman et al., 2013). Moreover, Hillman et al. (2014) showed that higher attendance rate in the FITKids intervention was associated with greater improvements in cognitive control measured by behavioral task performance and EEG. That result suggests a dose–response relationship between PA and changes in cognition.

This dose–response relationship between PA and cognition resulting from increased PA participation was observed by Davis et al. (2011). The researchers investigated the effects of an aerobic exercise intervention (≈ 13 weeks, 5 days/week) on cognitive control in sedentary and overweight preadolescent children (mean age ≈ 9 years). Participants were randomly assigned to one of three groups: no exercise control group, low-dose aerobic exercise group (20 minutes/day), or high-dose aerobic exercise group (40 minutes/day). Findings revealed that both exercise groups improved task performance on a cognitive control task, but this improvement was greater for the high-dose exercise group. Additionally, fMRI data indicated that the aerobic exercise intervention resulted in increased activation of the prefrontal cortex. More recently, fMRI studies further examined the effects of an 8-month aerobic PA program (mean number of days offered ≈ 140, 40 minutes/day) on brain activity and structures in obese preadolescent children (mean age ≈ 10 years; Krafft, Pierce, et al., 2014; Krafft, Schaeffer, et al., 2014; Schaeffer et al., 2014). Findings indicated that the PA intervention improved white matter integrity (Krafft, Schaeffer, et al., 2014; Schaeffer et al., 2014) and resulted in more mature and efficient resting state brain networks (Krafft, Pierce, et al., 2014). The white matter integrity and resting state brain networks are thought to be vital for supporting high-level cognitive operations (Gordon et al., 2011). Taken together, it appears that habitual aerobic PA engagement can change brain activity and structure, which, in turn, may result in functional improvement in cognitive control.

Duration of Activity to Obtain Cognitive Benefits

Interestingly, those longitudinal investigations in children have generally observed that changes in cognition are unrelated to changes in aerobic fitness. Such findings replicate those observed in older adult interventions (Etnier et al., 2006) and have been taken as further evidence that PA and physical health attributes (e.g., aerobic fitness) may differentially impact cognition. However, even well-designed PA interventions create small changes in aerobic fitness (Beets, Beighle, Erwin, & Huberty, 2009; Metcalf, Henley, & Wilkin, 2012). Given these small changes, it may take several years of chronic PA engagement to incur changes in aerobic fitness that are comparable with the extremes tested within cross-sectional investigations. Thus, although longitudinal RCTs provide strong evidence for the facilitative effects of increasing PA on enhanced cognition, it is irrational to discount the observations made in cross-sectional investigations, even if they are not yet supported by longitudinal evidence. Cross-sectional findings may reflect differences manifested over a much longer period or with more substantial changes in aerobic fitness. Therefore, further research is needed to enhance the understanding of how an increase in PA and aerobic fitness in combination differentially induce changes in cognition.

Further complicating the understanding of the relationship between PA and cognitive control is further evidence suggesting that there also may be a bidirectional association; superior cognitive control operations were implicated in predicting future higher levels of PA in children (Pentz & Riggs, 2013; Riggs, Chou, Spruijt-Metz, & Pentz, 2010). Although relatively little evidence exists on how long these effects persist following the cessation of a PA intervention, some insight has been provided by Alfini et al. (2016). The researchers examined changes in cerebral blood flow sustained from a 10-day exercise period of 12 master endurance athletes (mean age ≈ 61 years). Findings indicated that cerebral blood flow was reduced across a number of neural regions involved in the default mode network—associated with high-level cognitive operations and sustained task maintenance—and the hippocampus after just 10 days of not exercising (Alfini et al., 2016). Another neuroimaging study showed that 6 weeks of aerobic training (5 days/week, 30 minutes/day) increased hippocampal volume in young to middle-aged adults (mean age ≈ 34 years); this increase returned to baseline 6 weeks after the cessation of aerobic PA (Thomas et al., 2016). Accordingly, the evidence suggested that the more permanent enhancements in cognitive health and function associated with chronic PA may not be so permanent after all. Thus, in answer to the question about duration of PA to obtain cognitive benefits, it appears that lifelong PA is necessary to maintain the beneficial effects.

Age and Cognitive Benefits

One of the critical limitations of the present literature is that relatively little is known about the potential moderators that impact the strength of the relation of chronic PA and fitness to cognition. In particular, although it is uncertain whether the strength of the relation of chronic PA and fitness to cognitive function differs among age groups, it is likely that the positive relationship persists across the lifespan (Hillman et al., 2008; Hillman, Kamijo, & Pontifex, 2012). Although the vast majority of evidence exists in the gerontology literature, which focuses on people aged 65 years and older, and the developmental psychology literature, which focuses on preadolescent children, there is a positive association between chronic PA participation (resulting in improved aerobic fitness) and cognition for college-aged adult populations, as well as other developmental populations (e.g., adolescents).

Investigating modulations in cognition in college-aged adult populations can present a number of challenges, given this population’s high-functioning state, which makes it difficult to sufficiently tax neural systems, as well as potential confounds related to sleep deprivation (Frenda & Fenn, 2016) and substance use (Pope & Yurgelun-Todd, 1996; Zeigler et al., 2005). Nevertheless, cross-sectional evidence has revealed a positive association between aerobic fitness and a number of aspects of cognition, including cognitive control (Kamijo & Takeda, 2009; Themanson & Hillman, 2006), implicit memory, and long-term memory (Pontifex et al., 2014; Pontifex, Gwizdala, Parks, Pfeiffer, & Fenn, 2016).

Similarly, pubertal changes during adolescence are themselves related to modulations in behavior and cognition. Two recent investigations have attempted to use population-based samples to overcome such confounds while gaining insight into the relationship between aerobic fitness and cognition during this period. Åberg et al. (2009) used data gathered from a Swedish cohort study of more than 1.2 million men at age 18 years. It was revealed that aerobic fitness and changes in aerobic fitness from ages 15 to 18 years were positively associated with cognitive function as assessed by tests of logical performance, verbal knowledge, visuospatial/geometric perception, and technical/mechanical skills, which included mathematical/physics-related problems. Such findings were replicated by Pindus et al. (2015), who found a positive association between aerobic fitness and performance on an inhibitory control task in a sample of 5,515 adolescents (mean age ≈ 15 years). Taken together, it appears that aerobic fitness is positively associated with various aspects of cognitive function irrespective of age.

Other Potential Moderating Factors

Because the investigation into potential moderating factors of the relation of chronic PA and aerobic fitness to cognition is relatively new, limited information is available that elucidates which factors are truly important in this relationship. One factor that must be taken into consideration is the level of baseline performance. Much of the extant longitudinal evidence has used populations with relatively inferior cognition at baseline: individuals who were sedentary overweight/obese (Davis et al., 2011; Krafft, Pierce, et al., 2014; Krafft, Schaeffer, et al., 2014; Schaeffer et al., 2014) or exhibited low aerobic fitness (Chaddock-Heyman et al., 2013; Hillman et al., 2014; Kamijo et al., 2011).

Conceptually, those children who have the poorest performance at baseline have the greatest opportunity for improvement, whereas such an opportunity is limited in those children who are already performing a task at a very high level. Although Resaland et al. (2016) did not find beneficial effects of a PA intervention on academic achievement, their subgroup analyses indicated that the lowest tertile group of mathematic scores at baseline exhibited improved academic achievement. Thus, a key consideration for investigations in this area is in selecting cognitive tasks that provide a developmentally appropriate challenge with sufficient range so as to avoid potential ceiling effects. Future research should either probe the influence of baseline performance on cognitive benefits from PA participation or attempt to control for its potential influence.

Another potential moderator that influences the relation of chronic PA and aerobic fitness to cognition may be biological sex. In an examination of the relationship between aerobic fitness and working memory in preadolescent children across three separate studies (Study 1: $n = 97$; Study 2: $n = 95$; Study 3: $n = 84$), Drollette et al. (2016) found that a positive relationship between aerobic fitness and working memory performance was evident for boys but not for girls. In contrast, cross-sectional investigations of the relationships between fitness and performance on standardized tests of academic achievement have demonstrated a stronger association for girls than for boys (Eveland-Sayers, Farley, Fuller, Morgan, & Caputo, 2009; Van Dusen, Kelder, Kohl, Ranjit, & Perry, 2011). Although plausible explanations for such discrepant findings remain unclear, differences in the aspect of cognition assessed (working memory vs. academic achievement), differences in the assessment of aerobic fitness (VO_2 max test vs. FITNESSGRAM/1-mile test), or even the use of normalization procedures for the fitness and academic achievement measures may have inadvertently differentially biased males relative to females. Nevertheless, consistent with recent National Institutes of Health initiatives, future research is needed to elucidate the extent to which biological sex moderates the relation of chronic PA and fitness to cognition.

Fitness Components and Cognitive Benefits

Within cross-sectional investigations in this area, the focus has predominately been on how differences in aerobic fitness relate to various measures of cognition. Aerobic fitness, however, represents a singular component of a set of health- and skill-related attributes referred to as physical fitness. The extent to which other health-related components of physical fitness—such as muscular strength, muscular endurance, and flexibility—relate to superior cognitive health and function has received far less attention. In many ways this emphasis is not surprising, given that the extensive focus of pediatric exercise physiology remains on aerobic fitness and MVPA. Thus, investigations quantifying the components of muscular strength, muscular endurance, and flexibility in pediatric populations have generally relied on tests, such as the FITNESSGRAM, to provide an overall metric of physical fitness based on several subtests (see Chu, Chen, Pontifex, Sun, & Chang, 2016, for a more extensive review). The FITNESSGRAM is a valid and reliable field assessment (Welk, Morrow, &

Falls, 2002) to measure multiple aspects of health-related physical fitness, including PACER (aerobic fitness), push-ups and sit-ups (muscle fitness), sit and reach (flexibility fitness), and body mass index (body composition).

Using the FITNESSGRAM, Castelli et al. (2007) observed a positive association between physical fitness and performance on a state standardized achievement test, with higher academic achievement observed for children who had scores falling within healthy fitness zones. However, this relationship was largely influenced by performance on the PACER aerobic fitness test and body mass index (Castelli et al., 2007), with no such relationship being detected for push-up/curl-up based measures of muscular strength and endurance or for sit-and-reach measures of flexibility (Castelli et al., 2007). Conversely, other investigations using these same measures have observed positive associations between academic achievement and muscular strength/flexibility (Bass, Brown, Laurson, & Coleman, 2013; Coe, Peterson, Blair, Schutten, & Peddie, 2013; Van Dusen et al., 2011; Wittberg, Northrup, & Cottrel, 2009), yet these associations have not always remained consistent after controlling for aerobic fitness. One reason for these discrepant findings may be the limited capacity in which these aspects of physical fitness were assessed.

Kao, Westfall, Parks, Pontifex, and Hillman (2017) used a more comprehensive assessment of muscular fitness that quantified performance across a full-body battery of seven muscular fitness assessments of the upper body, lower body, and core. Their results revealed that a composite representation of full-body muscular fitness was associated with superior working memory independent of aerobic fitness quantified using VO_2 max. Beyond these physical health-related attributes, there is some evidence that emergent properties of the physiological system, such as agility and motor coordination (components that are at times more generally labeled as *skill attributes*), also may relate to cognitive function.

Specifically, Niederer et al. (2011) observed superior working memory performance in preschool children with high levels of agility and dynamic balance. A critical limitation in the investigation of the extent to which these physical attributes relate to cognition was found. The researchers needed to determine—conceptually and methodologically—appropriate assessments of these attributes for use in pediatric populations. Given that many such pediatric assessments are tailored for detecting the relatively large changes induced by maturation or motor dysfunction, existing tools appear to lack the sufficient sensitivity to quantify performance at a level necessary for detecting associations with cognition.

NEW DIRECTIONS IN FUTURE RESEARCH

Results of a growing number of studies have found a positive relation of PA and fitness to cognition in children and adolescents. Findings from these studies suggest that this association can vary based on several factors, such as aspects of cognition and fitness components. This assumption is based mainly on cross-sectional findings. Although, as discussed earlier, cross-sectional designs have several advantages to understanding the relation of PA and fitness to cognition, cross-sectional findings merely show the association but not their causality. Yet, evidence from high-quality RCTs, which are considered the gold standard for evaluating the efficacy of PA interventions, has remained scarce in this area of research.

The following three research questions are proposed that future RCTs should address:

- The public is interested in what types of PA are most beneficial for cognition during childhood and adolescence. To date, most RCTs have used aerobic PA. These studies indicate that PA interventions lead to increased aerobic fitness, which in turn leads to improved cognitive function (Chaddock-Heyman et al., 2013; Davis et al., 2011; Hillman et al., 2014; Kamijo et al., 2011; Krafft, Pierce, et al., 2014; Krafft, Schaeffer, et al., 2014; Schaeffer et al., 2014). Considering positive cross-sectional associations between muscular/agility fitness and cognitive control (Kao et al., 2017; Niederer et al., 2011), what types of PA other than aerobic exercise also can improve childhood cognition? Chen, Tseng, Kuo, and Chang (2016) indicated that a 3-month PA intervention, which resulted in improvements in muscular and flexibility fitness, improved cognitive control in obese adolescent children (mean age ≈ 13 years). Future RCTs should compare several types of PA to elucidate which changes in fitness components are most likely to contribute to cognitive health and development.

- As described earlier, Pindus et al. (2015, 2016) measured both aerobic fitness and PA levels, and found a positive association between aerobic fitness and cognitive function in children and adolescents but not PA levels. Furthermore, a recent longitudinal study found that larger increases in aerobic fitness over a 3-year period were related to greater improvements in task performance during cognitive control tasks in preadolescent children (mean age at baseline ≈ 8 years; Scudder et al., 2016). These findings suggest that improvements in physical fitness may be essential for the beneficial changes in cognitive function.

  However, van der Niet et al. (2016) examined the effects of cognitively engaging PA (e.g., tag games, football games; 22 weeks, 2 days/week, 30 minutes/day) on cognitive control in preadolescent children (mean age ≈ 9 years). Findings from that investigation indicated that the PA intervention improved task performance of cognitive tasks requiring inhibition and working memory, even though participants' physical fitness, including aerobic, muscular, and agility fitness, was unchanged. Thus, the cognitively engaging PA might make a greater impact on cognitive functioning than a "simple" PA, such as running. Given that this is mere speculation, further RCTs are needed to develop PA programs that effectively enhance cognitive function.
- In the reported RCTs that focused on the effects of PA on cognition, the length of interventions was relatively short (3–9 months). As discussed earlier, long-term interventions should be required for substantial improvement in fitness. Findings from cluster RCTs, in which the effects of PA interventions on academic achievement in preadolescent children were examined, provide some insight into the length of PA interventions. Specifically, 2-year (Mullender-Wijnsma et al., 2016) and 3-year (Donnelly et al., 2009) PA interventions improved academic achievement, whereas a 1-year intervention did not (Resaland et al., 2016). Although several methodological differences (e.g., participants' age) could be related to this inconsistency, it is reasonable to suggest that a relatively long intervention period, presumably more than 2 years, is essential for improvement in academic achievement. Future RCTs should conduct long-term PA interventions and assess fitness and cognitive function at several time points to clarify the length of time necessary to enhance childhood fitness and cognitive function.

PRACTICAL CONSIDERATIONS AND APPLICATIONS

Although a small number of studies have found a null relationship between PA and academic achievement (LeBlanc et al., 2012; Resaland et al., 2016), apparently no studies have shown a negative relation of PA and fitness to cognition during childhood and adolescence (Donnelly et al., 2016; Jackson, Davis, Sands, Whittington, & Sun, 2016). Stated differently, time spent being physically active, which is a vital contributor to health and well-being, has not been shown to impair academic performance. In contrast, as reviewed here, empirical evidence supports a positive relation of PA and fitness to cognition. Accordingly, it is plausible to surmise that regular PA, which results in a concomitant increase in fitness levels, is a key component for facilitating cognitive health and development during childhood and adolescence.

Although the number of studies that examined the relation of PA and fitness to cognition has grown rapidly in recent years, this research field is still considered to be in its infancy. At present, there is insufficient evidence regarding the frequency, intensity, time, and type of PA necessary for a PA program to induce changes in childhood cognitive function. This limits the extent to which effective programs can be proposed. Based on a dose–response relationship between PA and changes in cognition, which has been suggested in several RCTs (Davis et al., 2011; Hillman et al., 2014), greater amounts of PA may be more beneficial for cognitive function for children and adolescents.

Evidence from adult studies suggests that the cognitive enhancements resulting from chronic PA engagement may not be enduring attributes following the cessation of PA (Alfini et al., 2016; Thomas et al., 2016). Habitual PA during childhood and adolescence can substantially increase the probability of being active in adulthood (Telama et al., 2005). On the basis of the evidence obtained so far, it is reasonable to suggest that establishing a habit of regular PA during childhood and continuing PA throughout life (i.e., lifelong PA) are essential to improve and/or maintain cognitive functioning.

CONCLUSION

For more than a decade, accumulating evidence has demonstrated a beneficial effect of PA on cognition during childhood and adolescence. Most of these studies have focused on aerobic fitness and higher-level cognitive processes (i.e., cognitive control). On the basis of these findings, we can conclude at least that regular PA leading to increased aerobic fitness improves cognitive control in children and adolescents. It appears that the effects of PA on cognition may be modulated by aspects of cognition, duration of PA, population characteristics (e.g., age, sex, baseline performance), and modality of PA interventions. However, the mechanisms underlying this modulating influence remain unclear. It also is uncertain how much these factors affect changes in cognition associated with habitual PA engagement in children and adolescents. Clarifying these issues is necessary to advance the field. Ideally, such advancements should be targeted toward providing necessary evidence to promote changes in public policy that will ensure developmentally appropriate trajectories of brain health and cognition in children through empirically backed implementations of PA opportunities.

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