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A Review of Acute Physical Activity Effects on Brain and Cognition in Children

Charles H. Hillman, Nicole E. Logan, and Tatsuya T. Shigeta

ABSTRACT

The prevalence of physical inactivity in children has become a global pandemic and has consequences for physical, as well as cognitive and brain, health. Single bouts of physical activity (PA), however, have shown a transient, positive effect on cognitive performance in preadolescent children. Acute bouts of moderate to vigorous PA have demonstrated benefits for cognition, including attention and executive function. These acute effects of PA on cognitive performance can be seen both immediately after and following a delay from the cessation of PA. Further, event-related potentials have been used to delineate real-time neural responses to behavioral tasks after PA interventions. A short bout of moderate-intensity aerobic PA serves to increase the allocation of attentional resources and improved cognitive processing and stimulus classification speed. As such, there are implications for evaluating the effect of PA within schools. Several neural mechanisms are suggested to explain the observed improvements in executive function after PA, such as the importance of brain-derived neurotrophic factor on synaptogenesis, the expression of human growth factors, the activated release of catecholamines, and increased blood lactate levels. The ensuing descriptive review demonstrates the current understanding of the effects of acute PA on childhood brain and cognition and may serve as a basis for understanding PA-induced improvements in academic achievement.

INTRODUCTION

In an era where physical inactivity has become a global pandemic (1), adverse effects have been observed not only for children's physical health (2) but also their psychosocial well-being (3). Only 1/3 of boys and 1/5 of girls in Western countries are physically active at the recommended levels to optimize their health (i.e., >60 min of daily moderate to vigorous physical activity (PA); (4)). The shift to a more sedentary lifestyle is contrary to our evolution as a physically active species; thus, our genetic makeup is maladapted to the sedentary lifestyle of today (5,6). As such, sedentary behavior represents a physiological disjunction from healthy (i.e., physically active) behaviors and has implications for poorer cognitive and brain health (7).

Although children in industrialized countries are growing increasingly inactive and unhealthy, the investigation of the effects of PA on cognitive and brain health during development has only recently been recognized. A recent meta-analysis observed that single bouts of PA had a small, positive effect on cognitive performance regardless of whether cognition was assessed during PA, immediately after PA, or following a delay after PA (8). Further, several factors moderated this effect, with PA intensity characterized as "moderate" to "very hard," a delay of 11–20 min after PA, PA bouts of at least 20 min in duration, and tasks that tap executive control engendering the largest effects on cognition. Several other meta-analyses (9–13) have corroborated the findings of Chang et al. (8). Collectively, these findings suggest that single bouts of PA promote transient benefits to cognition. To that end, the recent findings from the 2018 Physical Activity Guidelines Scientific Report (14) summarized this literature and indicated that strong evidence was available demonstrating that acute bouts of moderate to vigorous PA have a transient benefit for cognition, including attention, memory, crystallized intelligence, processing speed, and executive control during the postrecovery period after a bout of PA. The findings indicated that the effects are larger in preadolescent children and older adults relative to other periods of the life span (pp. F3–5; https://health.gov/paguidelines/second-edition/report/pdf/PAG_Advisory_Committee_Report.pdf).

The relatively recent advent of neuroimaging techniques has facilitated the investigation of the neural underpinnings of acute PA effects on cognitive processing. In particular, electroencephalography, and more specifically event-related potentials (ERP), has been used to delineate real-time neural responses to behavioral tasks after PA interventions (15,16). ERPs refer to patterns of neuroelectric activation that occur in response to, or in preparation for, a stimulus or response. This approach offers the requisite temporal resolution to gain insight into cognitive operations that occur between stimulus engagement and response execution, and it may be more sensitive in parsing the effect of PA on the various aspects of cognition relative to overt task performance measures. However, research using

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neuroelectric assessment after acute PA interventions, especially in children, was essentially nonexistent until the turn of the millennium. Since then, this field has prospered over recent years, as evidenced by the increasing number of publications focusing on the effects of a single bout of aerobic PA on brain and cognition using neuroelectric and behavioral techniques (see Fig. 1. of Pontifex et al. [16]). Accordingly, the ensuing descriptive review demonstrates the current understanding of the effects of acute PA on childhood brain, cognition, and academic achievement.

Acute PA, Brain, and Cognition

PA has increasingly been cast aside during children's school days, as they become more regimented toward preparation for standardized testing and examinations, although such a strategy has shown no improvements in grades and could even be detrimental to health (17). This trend is contradictory to evidence linking PA to academic achievement (18–20). Even short sessions of PA in the classroom can have a positive effect on academic behaviors, such as paying attention and staying on task (21–24). A recent study even showed that improvement in these behaviors can occur with as little as a 4-min "dose" of in-class PA (23). Such findings support the feasibility of implementing PA before learning, which could in turn foster performance in a learning environment. Cognitive function is a candidate mechanistic moderator in the relationship between PA and academic performance. Thus, investigating the transient effects of PA on cognition may be the first step in gaining a mechanistic understanding of this framework. Yet, this topic is still building a repertoire.

A study by Howie et al. (25) tested preadolescent children (9 to 12 yr old) in a classroom-based acute high-intensity PA intervention, which was delivered in the form of activity breaks that were not integrated with academics, and compared groups that underwent these PA sessions for 5, 10, or 20 min against a control group. Children were tested on a math problem set and cognitive battery after the PA session. The authors found that the 10- and 20-min PA groups outperformed the other groups in math, but there were no differences in the trail making test and digit recall performance, cognitive tasks that tap executive control. That is, the PA groups performed better on academic but not cognitive outcomes. This study, in isolation, suggests that acute PA may selectively affect academic but not cognitive performance. However, the lack of an effect of cognitive performance may be due to the cognitive tasks selected for assessment and the manner in which they are administered, which may not have the requisite sensitivity to reflect smaller changes in cognition as a result of acute PA. Therefore, testing the subtleties of the transient effects of PA may be better suited for laboratory paradigms. For instance, studies by Hillman et al. (26) and Pontifex et al. (27) showed that an acute bout of walking significantly enhanced both academic and executive control performance using computerized paradigms in preadolescent children. The ensuing narrative will further detail the particular effects that acute PA can have on cognitive function, particularly the multidimensional executive control construct, and highlights the value of PA as a valuable tool to aid in children's education and, in turn, bolster support for increasing opportunity of PA in schools.

Acute PA Effects on Executive Control

Executive control describes a subset of goal-directed, self-regulatory operations involved in the selection, scheduling, and coordination of computational processes underlying perception, memory, and action. The core cognitive processes collectively termed "executive control" include inhibition, working memory, and cognitive flexibility (28,29). Inhibition (often termed "inhibitory control" or "attentional control") refers to the ability to override a strong internal or external pull to appropriately act within environmental constraints (28). Working memory (sometimes distinguished into the terms "updating" and "working memory capacity") refers to the ability to hold information in mind and manipulate it. Working memory is also heavily involved in other executive control processes because it relates to the ability to represent internal goals and standards for the comparison of those goals, against current performance, to regulate behavior (28–30). Cognitive flexibility (also known as "mental flexibility" or "set shifting") is the ability to quickly and flexibly change perspectives, focus attention, and adapt behavior to execute goal-directed actions (28,31).

During maturation, executive control exhibits protracted development relative to other cognitive processes (32), with efficient and effective allocation of control occurring during the latter stages of adolescence. The protracted development exhibited for executive control is tied to the protracted development of the neural tissue that mediates such functions, namely, the frontal lobes and associated networks (33–37). Late childhood and adolescence represents a time of rapid development of the frontal lobes leading to greater functioning of the executive control system (38). Younger children, who possess immature frontal lobes, are more sensitive to interference from irrelevant stimuli and have greater difficulty focusing attention on relevant stimuli (39). With maturation comes the ability to manage interference via increased efficiency of executive control processes (38) and the ability to inhibit a response tendency while making an alternative response (40). Inhibitory processes develop drastically in children 3 to 5 yr old, with further development in executing tasks that require both inhibition and working memory in 5- to 8-yr-olds and continued refinement throughout childhood and adolescence (40).

A growing literature has demonstrated the beneficial effects of PA on cognition (7,8,10,13). In children and adults, this association appears disproportionately larger for tasks or task components that require extensive amounts of executive control (26,41,42). Relative to PA, the evidence, thus far, suggests that single bouts of PA may provide transient benefits to executive control in children, indicating that PA behaviors influence the neural underpinnings of executive control. The subsections below illustrate evidence that both support and discount the transient effects that acute bouts of PA can have on each facet of executive control in children.

Inhibition

Investigations into the transient effect of a single bout of PA on behavioral indices of executive control have predominately used tasks that tap aspects of inhibition (16). Findings have indicated that a short bout of moderate-intensity PA results in improvements in general aspects of cognition, with selectively larger improvements in performance for task components requiring greater amounts of inhibitory control (13,26,27,43–45). A recent meta-analysis by de Greeff et al. (46) reviewed studies of healthy children, 6–12 yr old, that assessed the effect of single bouts of PA on executive control. They further decomposed their investigation into the subgroup of studies that used inhibition tasks. A small to moderate positive effect of acute PA on inhibition was observed (Hedges' g = 0.28, 95% confidence interval = 0.01–0.56, P = 0.042), corroborating to previous meta-analytic findings that acute PA affects tasks of executive control (8,13) and specifically enhances inhibitory control (47).

Working Memory

An emerging literature has examined acute PA effects on working memory, with several studies detailing a beneficial effect of acute PA on working memory performance (48–51). However, these findings are less consistent relative to inhibitory control outcomes, as contrary results have been reported in meta-analyses, with some finding a null effect of acute PA on preadolescent children's working memory (Hedge's g = 0.27, 95% confidence

interval = −0.12 to 0.66, $P = 0.18$) (47). Although this apparent specificity of acute PA effects on inhibitory control, but not working memory, has been demonstrated in a previous meta-analysis (46), a more recent meta-analytic investigation indicated no such distinction between inhibition and working memory components, with a significant effect of acute PA across aspects of executive control (13). The inconsistency in these findings was addressed by Pontifex et al. (16), who reported that studies assessing the acute PA effects of inhibitory control greatly outnumber those assessing working memory (see Fig. 2 of Pontifex et al. [16]). Given this disparity, discounting a possible effect of acute PA on children's working memory is premature, and the field of must continue to accrue evidence before a determination of acute PA effects on working memory can occur.

Cognitive Flexibility

As with working memory, cognitive flexibility has received less attention in the acute PA literature relative to inhibition (16). Some meta-analytic investigations suggest that there is no effect of acute PA on cognitive flexibility (46,47), whereas others have shown a more general positive effect of acute PA on executive control with no differences between the various subcomponents (13). Despite these inconsistent findings, a growing empirical evidence base suggests that acute PA may improve cognitive flexibility in both healthy children and those with attention deficit/hyperactivity disorder (52–54). Specifically, Ludyga et al. (54) reported that cognitive flexibility improved after a bout of moderate-intensity aerobic PA compared with an inactive control condition. Using a crossover design, participants were randomized into PA and control conditions on separate days, and cognitive flexibility was assessed 15–20 min after the 20-min intervention (i.e., PA and rest). The results indicated that both typical children and those with attention deficit/hyperactivity disorder improved their cognitive flexibility performance after a bout of PA (54). Interestingly, their findings corroborate previous meta-analyses, indicating a general benefit for executive control 10–15 min after a bout of moderate PA (8, 13). These findings suggest that acute PA has transient effects on cognitive flexibility across multiple child populations. Such evidence illustrates a divergence from the aforementioned meta-analytic investigations (46,47), likely due to the scarce amount of research focusing on transient effects of PA on cognitive flexibility (16).

Acute PA Effects on Neuroelectric Indices of Executive Control

Neuroelectric methods provide further assistance in elucidating specific transient effects of PA on cognitive function. Several studies have incorporated neuroelectric (i.e., ERP) measures into the examination of the effects of a single bout of PA on executive control; however, the majority of the developing literature has focused on inhibitory control (16,26,27,43). Previous studies have examined the P3 component of the stimulus-locked ERP to understand alterations in stimulus processing. That is, the amplitude of the P3 is believed to index the allocation of attentional resources in the service of working memory during stimulus engagement, with larger amplitude indicative of greater resource allocation (55). The latency of the P3 is thought to index the speed of stimulus classification and evaluation with increased latency reflecting longer processing time (56). Findings from these investigations have suggested that a 20-min bout of moderate-intensity aerobic PA serves to increase the allocation of attentional resources (as indexed by larger amplitude of the P3 component) and improved cognitive processing and stimulus classification speed (as indexed by shorter latency of the P3 component), with a disproportionately larger effect for task conditions requiring greater inhibitory control after the PA bout (26,27,43). Further, these findings of enhancements in P3 after a 20-min bout of moderate-intensity PA (15) are corroborated by meta-analytic findings, indicating that the strongest effects on cognitive function also occur when assessed after a 10- to 15-min delay (8).

Neural Mechanisms of Acute PA Effects

Although neuroelectric findings provide a marker of brain function, cellular and molecular mechanisms underlying acute PA effects on cognition provide a more detailed understanding of neural alteration after PA. Previous research suggests that the effects of acute PA bouts on cognition are moderated by brain-derived neurotrophic factor (BDNF) (57). The effects of PA on BDNF levels and cognitive function in rodents have been well documented (58), whereas the human literature is less comprehensive (59,60). BDNF is essential to the maintenance of the healthy neuronal phenotype, as well as being important for cognitive function (61,62). Furthermore, BDNF is involved in three important neural functions (61), including the modulation of the presynaptic neurotransmitter release (63), modulating the evoked excitatory postsynaptic currents via TrkB receptors (64), and directly inducing neuronal depolarization (65). These important neural functions provide, in part, a mechanistic understanding of the increased neuronal growth, survival, and synaptogenesis detected because of the increased BDNF concentrations and subsequent cognitive benefits observed after PA. Importantly, Ferris et al. (61) noted that participating in acute PA significantly elevated BDNF levels in young adults, and this increase was intensity dependent. Specifically, after a graded maximal PA test, and also after an acute bout of high-intensity PA (but not low intensity PA), serum BDNF levels significantly increased from baseline. This increase in BDNF after acute PA sessions was also associated with increased Stroop task performance (a task of executive control) from pre- to post-PA, indicating improved cognitive performance. Furthermore, Dinoff et al. (66) suggested that changes in BDNF concentrations were also dependent on the duration of PA. They noted that BDNF levels were significantly increased after more than 30 min of PA, compared with PA durations of 30 min or less. Accordingly, high-intensity acute aerobic PA appears to modulate BDNF levels in humans, thus serving as a mechanism for executive control and brain function (66).

Further, two growth factors, insulin-like growth factor (IGF-1) and vascular endothelial growth factor (VEGF), have been shown to act in parallel with BDNF to moderate the effects of PA on the resultant cognitive and neuroplastic changes. In addition to changes in BDNF levels, Skriver et al. (67) also demonstrated changes in VEGF and IGF-1 after an acute bout of PA. Specifically, plasma concentrations of IGF-1 yielded a significant increase after high-intensity PA; however, this was not consistently observed in VEGF. The variation of human growth factor concentrations after PA is consistent with previous studies, yet some report no significant changes (68) and others report significant increases relative to baseline (67,69). Furthermore, the link between increased VEGF and IGF-1 plasma concentrations found in Skriver et al. (67) was not correlated with PA-related changes in acquisition or retention of a motor skills task, whereas an association with BDNF was observed. The changes in human growth factor expression observed post-PA occurs synergistically with changes to BDNF levels. Namely, circulating IGF-1 is thought to mediate PA-related BDNF mRNA expression in the brain, consequently stimulating neurogenesis, whereas VEGF expression leads to angiogenesis. Because of the synergistic nature of these factors on neuroplastic changes within the brain, it is thought that circulating growth factors act in a similar way to BDNF for enhancing cognitive function after acute bouts of aerobic PA. In addition, rodent studies have shown that blocking the function of these circulating growth factors may impair learning and memory, indicating that they have a role in cognitive behavior (70,71). However, the role of PA-related expression of circulating growth factors on human cognition remains unexplained.

Furthermore, another potential class of biomarkers that may account for enhanced cognitive function after PA include the release of catecholamines. Specifically, the activated release of epinephrine and norepinephrine after acute PA has also been reported to increase in humans (67). This is important to consider when assessing the effects of PA on cognitive function because the release of catecholamines may improve memory function by way of an increase in neural blood-glucose levels (12,72). Peripheral release of epinephrine and norepinephrine activates beta-adrenergic receptors, which project to higher areas of the central nervous system thought to be involved in the regulation of emotional memory, such as the amygdala and hippocampus (73,74). Therefore, increases in the concentrations of epinephrine and norepinephrine after acute aerobic PA should theoretically facilitate cognitive function, but additional study is needed (12,67).

Lastly, lactate has also been suggested as another metabolic compound that moderates neural function after acute PA. Skriver et al. (67) observed significantly enhanced lactate levels after an acute bout of high-intensity aerobic PA, in correlation with greater acquisition of skill retention and motor performance. The increase in lactate levels, observed alongside increases in peripheral plasma levels of IGF-1, VEGF, epinephrine, norepinephrine, and BDNF, suggests that these biomarkers have a specific role in the mechanistic formation of memory, learning and executive control after acute aerobic PA.

Summary

The current review illustrated the value that acute PA can have on children's cognition, which may serve as a valuable aid in the educational process. Building on demonstrations of PA benefits in the classroom, short bouts of moderate-intensity aerobic PA provide transient improvements in executive control and its neural underpinnings. These findings inform the optimal PA intensity, duration, and post-PA testing period for future studies assessing domains of executive control and provide the justification for evaluating the mechanisms responsible for these effects. Although the effects on cognitive processing vary depending on the nature of the PA intervention and the aspect of cognition studied, there is strong evidence that acute aerobic PA can enhance performance on tasks of executive control. However, although the above evidence provides a platform for understanding the dose–response effect of acute PA on inhibitory control, whether such findings translate to other aspects of executive control is unclear. Specifically, studies of acute PA on executive control have used a crossover design with an appropriate control condition. Few studies to date have used such a design to assess acute PA effects on working memory or cognitive flexibility, and none have done so in conjunction with neuroelectric outcomes in children. Data from acute PA studies suggest several possible mechanisms are at play, including the role of neurotrophins, human growth factors, catecholamines, and lactate, which influence brain health and cognitive function after PA. To that end, more research is needed to understand whether there are developmentally specific transient effects of PA on distinct executive control processes using neuroelectric techniques and methods sensitive to biomarkers of the underlying mechanisms.

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