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Research Summary:

Exploring the Link between Physical Activity, Fitness and Cognitive Function

Prepared for the Illinois Enhance Physical Education Task Force
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This research review describes how cognitive functioning and academic achievement are associated with physical activity and fitness level. It was prepared by the Illinois Public Health Institute (IPHI) to inform the work of the Illinois Enhance Physical Education (PE) Task Force, which is charged with revising the state learning standards for physical development and health based on neuroscience research. This document organizes the neuroscience research by the relevant Illinois learning standards on Movement Skills (Goal 19) and Physical Fitness (Goal 20). The review includes discussion of the residual effects of acute exercise on cognition, which suggests that sequencing physical activity before difficult learning tasks may be beneficial. In preparing this summary, IPHI received input and guidance from subject matter experts including Darla M. Castelli, Ph.D., who has extensively reviewed the literature on this topic and generously shared many references, as well as neuroscientist Charles H. Hillman, Ph.D., and author of *Spark* John J. Ratey, M.D.

There is substantial evidence of a relationship between physical activity, fitness and improved cognitive and executive functioning and executive control. Executive functioning refers to the cognitive processes necessary for goal-directed cognition and behavior which develop across childhood and adolescence (Best, 2010). Executive control refers to a division of goal-directed, self-regulatory processes involved in the selection, scheduling, and coordination of computational processes underlying perception, memory, and action. Specific tasks include scheduling, planning, working memory, multi-tasking and dealing with ambiguity (Hillman et al., 2008), as well as working memory, response inhibition, mental flexibility (Hillman et al., 2009).

ILLINOIS STATE GOAL 19: Movement Skills - Acquire movement skills and understand concepts needed to engage in health-enhancing physical activity.

Research supports an emphasis on aerobic exercise and motor skills, including motor activities that are bimodal and complex, to facilitate enhanced cognitive and executive functions and executive control. This neuroscience research has been corroborated by multiple studies that found positive associations between physical activity and academic performance in school-age children. Aerobic exercise is physical activity that requires increased heartbeat and harder breathing.

- Moderate-intensity aerobic activity: heart rate is raised, break a sweat. (e.g., fast walking, playing doubles tennis)
- Vigorous-intensity aerobic activity: even higher heart rate; break a sweat, hard to speak without pausing for a breath. (e.g., jogging, running, singles tennis, basketball, soccer) (CDC, 2011).

Physical Activity and Cognitive Function

As noted by the Centers for Disease Control and Prevention (CDC), research has shown that physical activity can affect the physiology of the brain by increasing cerebral capillary growth, blood flow, oxygenation, production of neurotrophins, growth of nerve cells in the hippocampus (center of learning and memory), neurotransmitter levels, development of nerve connections, density of neural network, and brain tissue volume. These changes may be associated with improved cognitive functions including attention, information processing, storage, and retrieval, enhanced coping, enhanced positive affect, reduced sensations of cravings and pain (Trudeau et al. 2008, Rosenbaum et al, 2001, as cited by CDC 2011).

Best (2010) explains that cognitive function, and specifically executive functioning, is enhanced through aerobic physical activity. To date, most studies examining these topics have analyzed the impact of acute exercise bouts because of cost and participation benefits. In a review of eight studies (two chronic exercise studies and six acute exercise studies), he finds that chronic and acute aerobic exercises affect cognition differently and that each component of cognitive functioning can be impacted uniquely depending on where an individual is developmentally. For instance, in one study of chronic exercise, running programs that became more physiologically demanding over time were found to enhance mental flexibility and divergent thinking[1] associated with executive functioning in children in 4th-8th grade (Tuckman and Hinkle, 1986; Hinkle et al., 1993; as cited by Best, 2010).

[1] Divergent thinking includes thought processes used to generate creative ideas by exploring many possible solutions.

Children in acute exercise studies were found to have improved concentration, response accuracy, reading comprehension, task accuracy and task completion.

Another such study by Hillman et al. (2009) found that acute bouts [20 minutes of walking at 60% of max heart rate (HR)] of exercise are associated with larger amplitude and shorter latency levels of P3 (an event-related potential component elicited in the process of decision-making), which improves cognitive processes central to problem-solving and goal-oriented action, including response speed and accuracy. Specifically, acute, moderately-intense exercise, like walking, has a positive effect on inhibition (a process of the prefrontal, temporal, and parietal cortices) and ability to focus. As stated by Hillman, the "ability to inhibit attention to task irrelevant or distracting stimuli is central to the ability to sustain attention and allow control over one's actions" (p. 1045). These data suggest that single bouts of exercise affect specific underlying processes that support cognitive health and may support effective functioning across the lifespan. Similarly, Ellemberg & St. Louis Deschênes (2010) demonstrated that boys (7-10 years old) who participated in 30 minutes of aerobic exercise at moderate intensities showed significant improvement in cognitive function, as demonstrated by simple reaction response time (tapping low level sensori-motor functions associated with primary visual and motor cortices) and choice response time tasks (cognitive task involving decision making processes that tap executive functioning), compared to those who watched TV.

Further, limited research suggests there may be cognitive benefits to participation in cognitively-engaging exercises. For instance, Budde et al. (2008) found acute 10-minute bouts of complex coordination exercise (bimanually coordinative) with moderate aerobic intensity require more executive functioning, which enhanced prefrontal neural functioning in adolescents aged 13-16. Specific results revealed better task accuracy and completion of task time when compared to 10-minute bouts of repetitive motor movements, like running/treadmill, in adolescents. Researchers controlled for heart rate to isolate the impact of the complex coordination activity.

Physical activity continues to have positive cognitive benefits over a lifetime. Findings from Ratey and Loehr (2011) show how physical activity positively impacts cognition throughout adulthood. This conclusion suggests that learning the basic skills necessary to engage in physical activity at a young age will be beneficial for future cognitive functioning.

Building on the significant and compelling body of research demonstrating a link between physical activity and cognitive functioning in youth, research on the brain neurochemistry of mice suggests that there may be additional cognitive benefits that have not yet been observed in youth. Such studies show that light to moderate physical activity lead to increased brain-derived neurotropic factor (BDNF) levels in the brain due to stimulation of the hippocampus, a part of the prefrontal cortex that houses executive control functions (Berg, 2010). Although this has yet to be demonstrated in children, it has been shown that higher-fit children show greater bilateral hippocampal volumes and superior relational memory task performance compared to lower-fit children, leading to enhanced memory performance (Chaddock, et al., 2010b) and that childhood aerobic fitness is associated with less behavioral interferences on a selective attention paradigm tool, greater basal ganglia volume and superior task performance, and greater dorsal striatal volumes, leading to enhanced cognitive control (Chaddock et al., 2010a). Additional physical activity is also beneficial.

Researchers have also found that the "dose" of physical activity influences the effect on cognitive function. The previously mentioned study by Davis et al. (2007) also demonstrated that higher doses of physical activity (40 minutes) was associated with significantly better cognitive performance than lower doses (20 minutes), as measured by their standard scores for Planning (a test of executive functioning).

Physical Activity and Academic Performance

There is a growing body of evidence that physical activity is associated with improved academic performance. Aerobic training in the form of group games requiring more complex motor activities (e.g., running games, modified basketball, soccer) increased activity in the prefrontal cortex and improved performance on tasks requiring executive functioning as well as having a marginal positive effect on mathematics achievement (Davis et al. 2007). Another study demonstrated that a substantial dose of regular, vigorous exercise for overweight children (HR>150 bpm) can positively affect executive functioning scores and math achievement (Davis et al. 2011). In a longitudinal study of K-5 students, girls enrolled in higher amounts of PE (70-300 min/week) were observed to have a small but significant academic benefit in reading and mathematics achievement, compared with girls enrolled in less PE (0-35 min/week); however, there was no significant finding among boys in the study (Carlson, et al. 2008).

Physical activity throughout the school day has also been shown to have positive benefits on academic achievement. A study by Donnelly et al. (2009) demonstrates the effectiveness of Physical Activity Across Classrooms (PAAC) on BMI and academic achievement over a three year longitudinal study. PAAC promoted 90 min per week of MVPA delivered by classroom teachers. Results include increased academic achievement, smaller increases in BMI, and increased energy expenditure in the students where ≥75 minutes of PAAC per week was delivered compared to <75 min. Further, students in the PAAC program were shown to spend more time in and out of school participating in MVPA. Increased activity on the weekends is thought to be due to a change in attitude fostered by the PAAC program, but is not definite. While some research suggests a positive association between physical activity and academic performance, it should be noted that not all studies have found statistically significant associations; for a more comprehensive review please reference CDC's publication: The Association Between School-Based Physical Activity, Including Physical Education, and Academic Performance (CDC, 2010).

Residual Effects on Cognition: Time course effect of acute aerobic exercise

Research suggests that due to the residual effects of acute aerobic physical activity on improved executive functioning, physical activity should be scheduled in advance of other academic courses such as reading and mathematics. A study by Joyce et al. (2009) found that the beneficial effects of acute steady-state moderate intensity exercise on cognitive performance can be maintained 30 minutes post exercise and can last for up to 52 minutes after exercise cessation in 13-14 year old students. The findings suggest the 30 minutes of exercise performed at moderate intensity (40% of heart rates close to 130 BMP) will yield such results. Increases in cognitive performance are due to response inhibition improvement; as described above, acute aerobic exercise affects inhibition, which is associated with cognitive processes central to problem solving and goal-oriented behavior.

Studies have found shorter P3 latency and larger P3 amplitude following acute exercise on tasks requiring cognitive control during inhibitory tasks. The findings were observed 25 minutes after the cessation of exercise (Hillman et al., 2009), and 48 minutes after exercise (Hillman et al., 2003). Further, Hillman et al. (2009) and Pontifex et al., (in press) both show improvements in academic achievement during the 1 hour (approximately) period following the cessation of the acute bouts of exercise.

This recent evidence lays a strong foundation for the assertion by Kubesch et al. (2009), whose study showed that a single 30 minute PE program led to an improvement in the ability focus, that physical education should be scheduled "before important subjects like mathematics and not at the end of the school day" (p. 240).

Gallotta, et al. (2012) found that different types of exertion contributed to students' (ages 8-11) immediate attentional performances. Generally, children showed higher working speed and concentration scores after each of three types of controlled lessons (traditional physical education lesson, corresponding to physical exertion; coordinative physical education lesson, corresponding to a mixed cognitive and physical exertion; and school curricular lesson, corresponding to cognitive exertion). The authors propose that children showed higher attention levels at the end of physical education lessons versus the beginning due to the arousal hypothesis [see Budde, 2008], which relates attention to increases in cerebral blood volume and excited cerebellum and frontal cortex.

Raviv (1990) found that levels of concentration and attention were lower later in the school day because of the efforts required by the learning process.

ILLINOIS STATE GOAL 20: Physical Fitness - Achieve and maintain a health-enhancing level of physical fitness based upon continual self-assessment

Cardiorespiratory fitness is a measure of how well the body is able to transport oxygen to its muscles during prolonged exercise, and of how well the muscles are able to absorb and use the oxygen. It is measured through $VO2_{max}$ testing (maximum oxygen consumption). Research demonstrates a correlation between physical fitness and improved cognitive functioning. This neuroscience research has been further corroborated by multiple studies that found positive associations between fitness and academic performance in school-age children.

Fitness and Cognitive Function

Cardiorespiratory fitness appears to relate to the ability to successfully engage executive control strategies to optimize task performance across the lifespan. Pontifex et al. (2011) found that higher-fit preadolescent children ($VO2_{max}$ above the 70th percentile) demonstrated higher P3 amplitude and shorter latency compared to lower-fit preadolescent children ($VO2_{max}$ below the 30th percentile). This suggests that "lower levels of cardiorespiratory fitness relate to deficits in the flexible allocation of cognitive control to meet task demands" (p. 1341), indicating that lower-fit children have general impairments when performing tasks requiring more cognitive control.

Further, Hillman et al. (2005) also found that high-fit children had greater P3 amplitude and shorter P3 latency compared with low-fit children, as well as high- and low-fit adults. High-fit children had faster reaction time than low-fit children suggesting that fitness was positively associated with neuroelectric indices of attention and working memory, and response speed in children. Hillman cites additional studies that link enhanced math and reading abilities to the same brain regions and concludes that similarities exist in the neural networks that underlie both cognitive functioning and academic achievement (p. 1045). In a randomized control study, Kamijo et al (2011) found that a physical activity afterschool program designed to increase cardiorespiratory fitness of preadolescent children lead to improved Sternberg task performance, which tests working memory demands. These results further exemplify that cardiorespiratory fitness is positively associated with improvements in executive control of working memory.

Lastly, a consistent relationship occurs between cardiorespiratory fitness and cognitive performance. Aberg, et al. (2009) found significantly higher intelligence test scores in male subjects, whose cardiovascular fitness improved between 15 and 18 years old, indicating that changes in cardiovascular fitness are associated with improved cognitive performance in adolescence, even though causal relationship could not be established.

Fitness and Academic Performance

Research on the association between fitness and academic achievement seems to corroborate the mechanisms proposed by neuroscience research. Extensive research on the association between fitness and academic achievement conducted in China, Illinois, Massachusetts, California, and Texas shows a connection between increased levels of physical fitness, as measured by fitness tests such as the FITNESSGRAM®, and academic achievement (Chih & Chen, 2011; Castelli et al., 2007; Chomitz et al., 2009; London & Castrechini, 2011; Roberts et al., 2010; Van Dusen et al., 2011). For instance, Van Dusen, et al. (2011) found that all FITNESSGRAM® variables except body mass index (BMI) were positively associated with academic performance; measures of cardiovascular fitness were found to have the highest connection to cognition. Further, each additional unit of cardiovascular fitness across quintiles was associated with improved performance on a standardized test, specifically the Texas Assessment of Knowledge and Skills. Also using the FITNESSGRAM® test, preliminary results presented at the American College of Sport Medicine conference by Bass et al. (2010) suggest that students in the healthy fitness zone for cardiorespiratory fitness were six times more likely to meet or exceed the Illinois Standardized Achievement Test (ISAT) reading test requirements and over two and a half times more like to meet or exceed ISAT math test requirements than students who were not in the healthy fitness zone. In addition, Srikanth et al. (2010) found that when comparing the effect of social support, self-esteem and cardiorespiratory fitness on middle school students' reading and math tests, cardiorespiratory fitness was the only factor correlated with higher scores.

A consistent relationship between fitness and academic achievement is also exemplified by Grissom's research (2005). His results indicate that a relationship exists between fitness and academic achievement, in that as one improved, so did the other. Results from a study by Cottrell et al. (2007) show that there is a significant relationship between children's cardiorespiratory risks such as fitness index and blood pressure, as well as weight, and their reading/language, arts, mathematics, and science test scores. These results suggest that there is value in implementing surveillance programs to evaluate weight risks, fitness, risk for diabetes, and/or high blood pressure.

Lastly, P.E. should be fun:

Much brain research suggests that cognitive input to the executive function networks is more likely when stress is low and lessons are stimulating and challenging, passing though the reticular activating system (a lower brain filter that focuses attention on changes perceived in the environment) (Willis, 2007). Willis specifies that pleasurable classroom activities release dopamine, a neurotransmitter that stimulates the memory, as well as promotes the release of acetylcholine, which increases attention.

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