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Review

A review of chronic and acute physical activity participation on neuroelectric measures of brain health and cognition during childhood

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ABSTRACT

Background. A growing body of research has detailed the beneficial relation of chronic participation in—and acute responses to—physical activity on aspects of cognition that underlie scholastic achievement. Here, we review the relevant neuroelectric findings on this beneficial relation in children, providing support for the influence of physical activity on specific cognitive processes that comprise academic performance.

Method. A review of studies examining physical activity and neuroelectric concomitants of cognition during childhood is described. When applicable, research involving adult populations is also described to better inform on this relationship in children.

Results. Collectively, the data support a beneficial relation of chronic and acute participation in physical activity to brain health and cognition. The results suggest more effective allocation of cognitive processes involved in stimulus engagement and action monitoring during tasks requiring variable amounts of cognitive control in children.

Conclusion. Physical activity may influence brain health and cognition in children, leading to enhanced scholastic performance and greater overall effective functioning across the lifespan.

Contents

In recent years, children in industrialized nations have become increasingly inactive, resulting in a greater prevalence of being overweight and unfit (DHHS and DOE, 2000). Inactivity during early childhood increases the likelihood of remaining sedentary across the lifespan and has been related to several chronic diseases (e.g., cardiovascular disease and type-2 diabetes) during adolescence and adulthood. However, absent from public health concerns is the impact that physical inactivity may have on brain health and cognition. Many school districts have obviated physical activity opportunities from the school day despite a growing literature indicating the benefits of physical activity to cognitive and scholastic performance (Castelli et al., 2007; see CDC, 2010 for review). Such educational practices are growing in popularity due to budgetary constraints and an increased emphasis placed upon student performance on standardized tests. It is counterintuitive that spending less time in the classroom and more time engaged in physical activities might improve cognition and learning (Sallis, 2010), yet human and non-human animal research is consonant (see Hillman et al., 2008 for review) in suggesting that physical activity benefits brain health and cognition.

Recent studies have illuminated the positive relation of aerobic fitness to brain health and cognition in preadolescent children using a

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number of measures that assess task performance (i.e., reaction time [RT] and response accuracy; Hillman et al., 2006), brain function (i.e., event-related brain potentials [ERPs]; Pontifex et al., 2011), and brain structure (i.e., magnetic resonance imaging [MRI]; Chaddock et al., 2010a,b) across a slew of cognitive tasks. More recently, a major component of this research has focused on cognitive control (i.e., goal-directed cognitive processes underlying perception, memory, and action), because it is well established that aerobic fitness-related improvements in cognition are disproportionately larger for tasks or task components that require extensive amounts of cognitive control in adult populations (Colcombe and Kramer, 2003; Hillman et al., 2006; Kramer et al., 1999). Although a relatively smaller literature has explored the relationship of fitness to brain health and cognition in preadolescent children, these studies have lent support for the importance of fitness toward cognitive development and provided a basis for maximizing scholastic performance (Ahamed et al., 2007; Castelli et al., 2007; Chomitz et al., 2009; Coe et al., 2006). Clearly, one advantage of examining the relation of fitness to cognition in children is the ability to link basic laboratory measures of cognitive performance with externally-valid assessments of scholastic performance. Accordingly, this manuscript will review the fitness and cognition research that is ongoing in our laboratory and elsewhere, which has implications for scholastic performance, but more broadly, cognitive health and function.

Aerobic fitness and cognition

Table 1 provides a summary of all studies described in this section. Early work in our laboratory examined the relation of fitness to inhibitory aspects of cognitive control (i.e., the ability to ignore distraction and focus on relevant aspects of the environment). In one of our initial studies, Buck et al. (2008) assessed the relation of aerobic fitness to inhibitory control using a paper-and-pencil version of the Stroop color–word task in a group of 7–12 year old children. This task necessitates multiple cognitive processes including selective attention, response inhibition, interference control, and speeded responding through the manipulation of task parameters. Specifically, in the word condition, participants were instructed to read aloud color words (e.g., RED and YELLOW) printed in black ink. In the color condition, participants were instructed to name aloud the color of the ink in which arrays of symbols (e.g., XXXX printed in blue ink) were printed. In the incongruent condition, participants viewed incongruent word–color pairs (e.g., BLUE printed in green ink) and were instructed to name the color of the ink in which the word was written. Successful performance requires individuals to inhibit their prepotent response to read the word and instead activate a less frequent response to name the color in which the word is printed, thus resolving interference associated with word reading (Buck et al., 2008). The results indicated that beyond the relationship of demographic factors (i.e., age, sex, IQ, education, etc.) to task performance, greater aerobic fitness was related to better performance across all conditions of the Stroop task, regardless of the amount of inhibitory control required. Thus, early findings from our laboratory suggested that fitness had a general relation with cognition across tasks requiring variable amounts of cognitive control. Intrigued by this initial finding, we developed a program of studies using various neuroelectric measures to examine covert aspects of the stimulus–response relationship to better understand, which aspects of cognition were beneficially influenced by fitness.

Interactions within the stimulus environment

Several of our studies investigating the fitness–cognition relationship have focused on processes underlying stimulus engagement. In particular, neuroelectric measures, including the P3 (P300 or P3b) of the human ERP, have been especially useful in teasing apart the various processes subserving stimulus engagement. Briefly, ERPs reflect covert aspects of information processing, and have provided insight into the mechanisms underlying cognitive function beyond that of overt behavior. Due to its high temporal resolution, the advantage of the ERP approach is that it can provide information regarding a subset of processes occurring between stimulus encoding and response execution. The P3 is a positive-going component observed in the stimulus-locked ERP waveform and is believed to represent the updating of memory once sensory information has been analyzed (Donchin, 1981). The amplitude of this component is proportional to the amount of attentional resources during stimulus engagement (Polich, 2007) with larger P3 amplitude reflecting increased attention toward a stimulus. The latency is considered a measure of stimulus classification speed or stimulus evaluation time (Duncan-Johnson, 1981), with shorter latency indicating faster cognitive processing speed. Accordingly, in the current context, the

Table 1
Summary of the discussed studies designed to evaluate the relation of fitness on cognitive performance in children.

Author(s)	Sample	Measures	Task	Findings
Buck et al. (2008)	74 children (33 fem.), ages $M = 9.3$	Fitness — PACER test, task performance	Stroop task	Greater aerobic fitness was associated with better Stroop performance.
Castelli et al. (2007)	259 (127 fem.) third- and fifth-grade students	Fitness — PACER test, academic achievement	ISAT (Illinois Standards Achievement Test)	Physical fitness was positively associated with better math and reading achievement.
Chaddock et al. (2010a)	21 (11 fem.) higher-fit and 28 (18 fem.) lower-fit 9 and 10-year old children	Fitness — indirect calorimetry using a treadmill, task performance, brain volume — MRI	Item and relational memory paradigm	Higher-fit children showed greater bilateral hippocampal volume and better accuracy on the relational memory task.
Hillman et al. (2005)	24 preadolescent children ($M = 9.6$ years), 12 (5 fem.) higher-fit and 12 (6 fem.) lower-fit	Fitness — PACER test, task performance, ERPs (P3)	Visual oddball	Higher-fit children had greater P3 amplitude, shorter P3 latency, and faster RT compared to low-fit children.
Hillman et al. (2009a)	19 (9 fem.) higher-fit and 19 (9 fem.) lower-fit $M = 9.4$	Fitness — PACER test, task performance, ERPs (P3, ERN)	Modified flanker task	Higher-fit children had greater P3 amplitude, reduced ERN amplitude, and better response accuracy compared to low-fit children.
Pontifex et al. (2011)	48 preadolescent children ($M = 10.1$ years), 24 (13 fem.) higher-fit and 24 (10 fem.) lower-fit	Fitness — indirect calorimetry using a treadmill, task performance, ERPs (P3, ERN)	Modified flanker task	Lower-fit children had decreased accuracy in the incompatible condition, whereas higher-fit children maintained task performance. Higher-fit children had greater P3 amplitude, decreased P3 latency, and reduced ERN amplitude. Higher-fit children were also able to upregulate P3 and ERN amplitude in the incompatible condition.

ERP = event-related potential; MRI = magnetic resonance imaging; ERN = error-related negativity.

P3 allows for inferences into the beneficial relation of fitness to cognitive function.

Several studies conducted in our laboratory have employed the P3 to assess the fitness–cognition relationship in children. Specifically, Hillman et al. (2005) compared the P3 component between higher-fit and lower-fit children ($M = 9.6$ years) during an oddball task. This task had participants respond to rare target stimuli (i.e., oddballs), which are presented within a train of frequent non-target stimuli that do not require a response. During this task, a clear P3 component emerges following target stimuli, and is thought to represent an increase in the allocation of attentional resources toward the updating of an individual's mental representation of the stimulus environment (Donchin, 1981). Hillman et al. (2005) indicated that higher-fit children exhibited larger P3 amplitude and shorter P3 latency with better task performance compared to their lower-fit counterparts. Such a finding suggests that higher-fit children may be able to recruit a greater amount of attentional resources toward the stimulus environment and process information more quickly, which in turn may underlie the production of quicker and more accurate responses.

In a second study (Hillman et al., 2009a), 9–10 year old children were examined to extend our initial findings through the use of a modified flanker task (Eriksen and Eriksen, 1974). This task requires variable amounts of inhibitory control—one aspect of cognitive control—for successful task completion. The flanker task consists of arrays of congruent and incongruent stimuli, with the instruction to respond based on the central (i.e., target) stimulus and ignore flanking stimuli. Incongruent, compared to congruent, trials require greater amounts of cognitive control to inhibit interference generated by the flanking stimuli due to the activation of the incorrect response mapping. Hillman et al. (2009a) indicated that higher-fit children exhibited more accurate responses and larger P3 amplitude compared to lower-fit children across the flanker conditions. This study suggested that fitness benefited cognition during tasks requiring variable amounts of cognitive control in preadolescent children, and more specifically, that greater fitness related to an increase in the allocation of attentional resources during stimulus evaluation. Collectively, these studies (Buck et al., 2008; Hillman et al., 2005, 2009a) imply that aerobic fitness may be positively related to overall cognitive function in preadolescent children during tasks that require variable amounts of attention and cognitive control.

By contrast, other findings have corroborated those of Colcombe and Kramer (2003), who observed that fitness had both a general and selective relationship with cognition in older adults. Specifically, Colcombe and Kramer (2003) found a general relationship between fitness-training and cognition; however, the effects were selectively and disproportionately larger for tasks or task components requiring greater amounts of cognitive control. Neuroelectric support for this finding in children ($M = 10.1$ years) was observed in Pontifex et al. (2011), wherein the fitness–cognition relationship was examined through manipulation of stimulus–response compatibility (i.e., cognitive flexibility) during a flanker task. Such a manipulation upregulates cognitive control requirements and necessitates greater variability in the allocation of cognitive control across the multiple conditions. Specifically, in the incompatible stimulus–response condition, participants were instructed to press a button that opposed the direction of the central target arrow, which differs from the compatible condition in which the stimulus and response were consonant in directionality. This manipulation has been shown to necessitate greater flexibility in the modulation of cognitive control for incompatible relative to compatible stimulus–response conditions (Friedman et al., 2009).

Relative to fitness, higher-fit children were able to maintain their response accuracy irrespective of stimulus–response compatibility conditions, whereas lower-fit children exhibited decreased accuracy with increases in task difficulty (i.e., less accuracy for incompatible relative to compatible conditions; Pontifex et al., 2011). Interestingly, these behavioral findings were supported by the P3-ERP component, as higher-fit children exhibited overall larger amplitude (replicating Hillman et al., 2005, 2009a), but more importantly, they exhibited modulation of the P3 component with greater amplitude for incompatible compared to compatible conditions. Such a finding was not observed for lower-fit participants, who exhibited overall smaller amplitude with no modulation across stimulus–response compatibility conditions. Further, higher-fit participants had shorter P3 latencies, indicating faster cognitive processing speed relative to their lower-fit peers (Pontifex et al., 2011). This pattern of results suggests that higher-fit children are better able to maintain task performance through the flexible regulation of cognitive control, which was reflected by their increased capacity to modulate attentional resource allocation based on task difficulty. Accordingly, the findings from these cross-sectional studies (Buck et al., 2008; Hillman et al., 2005, 2009a; Pontifex et al., 2011) suggest that higher aerobic fitness may promote better cognitive and brain health through improvements in a host of cognitive control functions that support goal-directed behavior.

Action monitoring

Two of the studies described above (Hillman et al., 2009a; Pontifex et al., 2011) also examined neuroelectric indices of action monitoring, which is another important aspect of cognitive control. That is, for the organization of goal-directed behavior, individuals must continuously monitor their correspondence between intended and executed actions, and correct response errors during subsequent environmental interaction in order to maintain performance and respond appropriately. It has been well established that the action monitoring system is indexed by an ERP component known as the error-related negativity (ERN; Gehring et al., 1993; or error negativity: N_e; Falkenstein et al., 1991). The ERN is a negative-going waveform observed in response-locked ERP averages (i.e., ERPs that occur in response to the execution of an action) that is often elicited by commission errors during a cognitive task. The ERN is maximal over fronto-central recording sites, and has been localized to the dorsal portion of the anterior cingulate cortex (ACC; Carter et al., 1998; Dehaene et al., 1994; Miltner et al., 2003; van Veen and Carter, 2002), which is part of the neural circuit involved in action monitoring (Carter et al., 1998). The ERN is believed to relate to either the detection of errors during task performance (Gehring et al., 1993; Holroyd and Coles, 2002; Scheffers et al., 1996) or more generally to the detection of response conflict (Botvinick et al., 2001; Yeung et al., 2004), which oftentimes is engendered by the commission of an error.

Interestingly, several studies have suggested fitness-related modulation of action monitoring processes across children (Hillman et al., 2009a; Pontifex et al., 2011), young (Themanson and Hillman, 2006; Themanson et al., 2008), and older (Themanson et al., 2006) adults. In children, Hillman et al. (2009a) indicated that higher-fit participants exhibited smaller ERN amplitudes relative to lower-fit participants during a task requiring a rapid response. The conflict monitoring theory proposes that the ACC serves to evaluate for the presence of response conflict and provides a signal to other areas of the brain, such as the dorsolateral prefrontal cortex, which act to flexibly regulate cognitive control in support of subsequent environmental interaction (Botvinick et al., 2001; Carter and van Veen, 2007). That is, this theory holds that reduction in conflict due to increased cognitive control is evidenced by a relative decrease in ACC activation, as denoted by smaller ERN amplitude. Based on this theory, and coupled with the finding that higher-fit children exhibited greater response accuracy relative to lower-fit children on trials following an error, it is plausible that the decreased ERN amplitude in higher-fit children might indicate reductions in task-related response conflict due to increased cognitive control during task execution. As such, greater aerobic fitness may be associated with increased cognitive control, resulting in a lower threshold for detection and signaling of conflict (decreased ERN) and greater response accuracy on subsequent trials.

In a follow up investigation, Pontifex et al. (2011) again observed that higher-fit children exhibited smaller ERN amplitude compared to lower-fir children, suggesting a decrease in response conflict during environmental interaction. However, when manipulation of stimulus–response compatibility was considered (as described above), the fitness-ERN relationship was observed for the compatible, but not the incompatible, condition. In other words, higher-fit children had smaller ERN amplitude in the compatible condition compared to their lower-fit peers, which replicated the findings of Hillman et al. (2009a). Alternatively, during the incompatible condition, which necessitates greater amounts of cognitive control, higher-fit children exhibited a significantly larger ERN potential that did not differ from lower-fit participants, but differed significantly from the ERN response that they exhibited during the compatible condition. This pattern of results suggest that higher-fit children have a greater capacity to flexibly modulate action monitoring processes based on cognitive control demands to optimize behavioral interactions within the task environment. The modulation of ERN across conditions with greater amounts of fitness is also consistent with the above-mentioned P3 amplitude findings (Pontifex et al., 2011).

When considered together, a greater understanding emerges for the role of fitness on the cognitive control of environmental interaction. That is, the pattern of neuroelectric activation exhibited by higher-fit children suggests greater allocation of attentional resources during stimulus engagement (P3 amplitude) and decreased activation of resources toward the monitoring of their actions (ERN amplitude). Alternatively, lower-fit children appear to allocate fewer resources toward stimuli in their environment and instead rely more heavily upon an action monitoring strategy. However, under more demanding task conditions, this latter strategy appears to fail as lower-fit participants perform more poorly under conditions of greater conflict; whereas higher-fit participants appear to have the capability to flexibly and effectively regulate cognitive control, resulting in an increase in both the allocation of attentional resources toward external (i.e., P3 amplitude toward environmental stimuli) and internal (i.e., ERN amplitude toward response monitoring) aspects of the stimulus–response relationship. At an overt level, such a strategy results in the maintenance of a high level of task performance under a variety of conditions that place variable demands upon cognitive control.

Acute exercise and transient changes in cognition

Table 2 provides a summary of all studies described in this section. Recent meta-analyses (Lambourne and Tomporowski, 2010; Sibley and Etnier, 2003) and literature reviews (Tomporowski, 2003; Tomporowski et al., 2008) have reported that single bouts of exercise provide benefits to task performance aspects of cognition in youth. Accordingly, there is growing interest regarding not only the relationship of chronic exercise participation on cognition, but also the transient effects of a single bout of exercise. In contrast to the above mentioned studies that examined the relation of aerobic fitness to cognitive control, most acute exercise research has been less focused on a single aspect of cognition, and instead has investigated changes in cognition as a result of the exercise stimulus, including exercise duration and exercise type. In addition, it is difficult to reach consensus on this literature, as seemingly every study employed a different cognitive task and a different age group, rendering little possibility of drawing conclusions across multiple studies.

For instance, early research explored the relationship between single bouts of exercise and cognition using mathematical tests. Specifically, Gabbard and Barton (1979) had second-grade children complete a 2 min mathematical computation test prior to (i.e., pre-test), and following 20, 30, 40, and 50 min of participation in a physical education class, and afterwards (i.e., post-test). Classes comprised standardized relay activities that were performed in a cyclical manner. They noted that math scores following the 50 min physical education class were significantly higher relative to the pre-test, whereas no differences were observed between the pre-test and following other durations (i.e., 20-, 30-, and 40-min exercise) or the post-test. The authors concluded that a longer duration of physical exertion was necessary to induce an increase in cognitive performance, but that none of the conditions were detrimental to cognition (Gabbard and Barton, 1979).

Similarly, McNaughten and Gabbard (1993) investigated single bouts of exercise in sixth-grade children by having them walk the outer perimeter of a basketball court while maintaining a heart rate between 120 and 145 beats per min (bpm). Bouts of exercise lasted 20, 30, and 40 min in duration, and occurred during their normally scheduled physical education class at three different times: 8:00 a.m., 11:50 a.m., and 2:20 p.m. on separate days. Participants performed 90-sec mathematical computation tests immediately after each bout of exercise. Results indicated that children's scores following 30 and 40 min of exercise were significantly higher than following 20 min of exercise at 11:50 a.m. and 2:20 p.m., while no such differences were observed at 8 a.m. Since they did not compare test performance following exercise to a pre-test (i.e., baseline), it is unclear whether 20 min of exercise influenced cognitive function.

Findings from these two previous studies infer that longer duration exercise may be advantageous in preadolescent and adolescent children. However, other research has observed that fourth-grade children performed better on the Woodcock–Johnson Test, which assesses cognition, scholastic achievement, and general cognitive ability, after only 15 min of aerobic walking and stretching when compared to a control group consisting of non-aerobic classroom activity (Caterino and Polak, 1999). It should be noted though that second- and third-grade students did not differ as a result of the exercise manipulation. Collectively, these early studies, though pioneering in their efforts, were inconsistent in their findings, likely due to differences in the exercise mode, intensity, and duration, as well as the age of the study participants and aspects of cognition examined. As a result, early findings posed more questions than answers. Regardless, these studies do suggest that single bouts of aerobic exercise result in positive changes or no changes in cognition, suggesting that at the very least, time spent engaged in physical activity is not detrimental to scholastic performance.

More recent research has investigated the effects of different types of exercise on cognition. Budde et al. (2008) investigated the effects of 10 min of coordinative exercise or a ‘normal sports lesson’ on concentration and attention during physical education classes in adolescent children (13–16 years). The coordinative exercise required different bilateral skills (e.g., bouncing two balls using both hands simultaneously), while the normal sports lesson consisted of moderate exercise without any specific coordinative requirements. Concentration and attention were assessed using the d2-test, in which participants were required to differentially mark the letter “d” within a string of “d” and “p” letters. Participants conducted the d2-test immediately after a normal school lesson (control condition) and after either 10 min of coordinative exercise or a normal sport lesson on separate days. The results indicated that task performance was improved following 10 min of exercise for both groups compared to the control condition, and that further improvements were observed for the coordinative exercise group relative to the normal sports lesson group, despite the fact that exercise intensity (M = about 120 bpm) and duration (10 min) did not differ between the two conditions. However, it should be noted that the condition order was not counterbalanced in this study; thus, findings attributed to exercise participation may also have included practice/learning effects. Regardless, these recent findings raise questions concerning the potential differential influence of various types of exercise on cognition in youth.

Table 2
Summary of the discussed studies designed to evaluate the transient effects of physical activity on cognitive performance in children.

Author(s)	Sample	Task and measures	Exercise stimulus	Findings
Budde et al. (2008)	99 adolescent children (19 fem.), ages 13–16 years	d2-test/task performance	10 min of coordinative exercise or a 'normal sports lesson' (M = 120 bpm)	Task performance was improved following 10 min of exercise for both groups compared to the control condition. Further improvements were observed for the coordinative exercise group relative to the normal sports lesson group.
Caterino and Polak (1999)	54 second-, 71 third-, and 52 fourth-grade boys and girls	Woodcock–Johnson Test/task performance	15 min of aerobic walking and stretching	Fourth-grade children performed better on the Woodcock–Johnson Test following exercise compared to a control group consisting of a non-aerobic classroom activity. Differences were not observed in second- and third-grade children.
Gabbard and Barton (1979)	106 second grade boys and girls	2-min mathematical computation test/task performance	20, 30, 40, and 50 min of participation in a physical education class composed of standardized relay activities	Math scores following the 50 min physical education class were significantly higher relative to the pre-test.
Hillman et al. (2009b)	20 preadolescent children (M = 9.5 years; 8 fem.)	Modified flanker task/task performance, ERPs (P3)	20 min of seated rest and aerobic walking at 60% of estimated heart rate max (M = 125 bpm)	Children had greater response accuracy and larger P3 amplitude following exercise relative to seated rest, with selectively larger effects observed for the incongruent flanker condition.
McNaughten and Gabbard (1993)	120 sixth-grade boys and girls	90-sec mathematical computation test/task performance	20, 30, and 40 min of aerobic walking (120–145 bpm) at three different times: 8:00 a.m., 11:50 a.m., and 2:20 p.m.	Scores following 30 and 40 min of exercise were significantly higher than following 20 min of exercise at 11:50 a.m. and 2:20 p.m., with no differences observed at 8 a.m.
Pesce et al. (2009)	52 children, ages 11–12 years	Free-recall memory task/task performance	40 min of aerobic circuit training or team games (M = 140 bpm)	More words were remembered during the delayed recall following both aerobic training and team games compared to the control condition. During the immediate recall, more words were remembered following only the team games relative to the control condition.
Schneider et al. (2009)	11 preadolescent children, ages 9–10 years	n.a./EEG and standardized low resolution brain electromagnetic tomography (sLORETA)	15 min of aerobic bicycle exercise (M = 165 bpm)	Following exercise, children exhibited increased alpha activity in the precuneus and decreased beta activity in left temporal areas of the brain, suggesting a shift towards an overall state of physical relaxation, which may increase concentration.
Stroth et al. (2009)	33 children, ages 13–14 years	Modified flanker task, Go–NoGo task/task performance, ERPs (P3)	20 min of seated rest and aerobic cycling (M = 165 bpm)	There were no observed differences in task performance or the P3 component following exercise when compared to rest.

EEG = electroencephalography; ERP = event-related potential; n.a. = no tasks were administered; bpm = beats per minute.

Other research has focused on effects of single bouts of exercise on memory performance (Pesce et al., 2009). Specifically, children (11–12 years) performed a free-recall memory task following aerobic circuit training, team games, and any other lesson (i.e., no exercise control condition). For the free-recall memory task, participants were required to memorize 20 words and to write down as many words as possible 100 s (immediate free-recall) and 720 s (delayed free-recall) after the memorization period. Exercise duration (about 40 min) and intensity (M = about 140 bpm) were held constant between the two exercise conditions, with only the mode differing. The results indicated that a greater number of words were remembered during the delayed recall following both aerobic training and team games conditions compared to the control condition, whereas a greater number of words were remembered during the immediate recall only following the team games condition relative to the control condition. These findings suggest that memory processes in children may be aided by single bouts of exercise, and perhaps more so for exercise that incorporates cognitive activation through different cognitive and social interactions. Thus, the two previous studies which manipulated exercise mode (Budde et al., 2008; Pesce et al., 2009) imply that the beneficial effects of acute exercise on cognition may differ based on the types of exercise in which children participate.

Accordingly, despite the observance of a beneficial relation of single bouts of exercise to cognition, the field has yet to emerge in such a manner as to provide a comprehensive understanding of either the necessary characteristics of the exercise dose (i.e., mode, duration, and intensity) to enable cognitive benefits, nor a comprehensive characterization of the beneficial cognitive change following a single bout of exercise. As such, significantly more research is necessary to fully understand the relationship of single bouts of exercise to acute changes in cognition. Research in our laboratory has begun to examine this issue from a neuroelectric perspective.

Neuroelectric studies

Recent research examining single bouts of exercise in children has utilized electroencephalography (EEG) and ERPs to reveal the underlying positive effects of acute exercise on brain and cognition. Schneider et al. (2009) examined whether a single bout of aerobic exercise influenced EEG activity in children. Although earlier work (e.g., Dustman et al., 1990) had studied this question in adult populations, Schneider et al. (2009) was the first to extend this research question to children. Preadolescent children (9–10 years) performed 15 min of aerobic exercise ($M=165$ bpm), and EEG was recorded during rest before and immediately after exercise. Source analyses (standardized low resolution brain electromagnetic tomography) indicated that children exhibited increased alpha activity in the precuneus (a region of the superior parietal cortex involved in visuospatial processing, memory, awareness, and conscious self perception) and decreased beta activity in left temporal areas of the brain following aerobic exercise. They speculated that this increase in alpha activity in the precuneus may reflect an overall state of physical relaxation, which may increase concentration. Furthermore, decreases in beta activation in brain regions responsible for aspects of memory and language may lead to improvements in cognitive performance by altering available processing capacity (Schneider et al., 2009). The authors suggested that such changes in EEG following exercise reflect neuroplasticity that may underlie cognition and scholastic performance (Schneider et al., 2009).

Research conducted in our laboratory has focused on the effects of single bouts of exercise on cognitive control processes that may underlie scholastic achievement. Similar to our work examining the relation of fitness to brain health and cognition, our acute exercise paradigm is aimed at understanding component cognitive processes involved in information processing that are transiently altered by exercise participation. To that end, Hillman et al. (2009b) investigated the effects of acute exercise on cognitive control using the P3 component during a modified flanker task. Preadolescent children ($M=9.5$ years) performed the task following 20 min of seated rest and aerobic exercise ($M=125$ bpm) on separate days, counterbalanced across participants. The results indicated greater response accuracy and larger P3 amplitude following exercise relative to seated rest, with selectively larger effects observed for the incongruent flanker condition, which required larger amounts of cognitive control. These findings suggest that children may devote more attentional resources (i.e., reflected by larger P3 amplitude) during task conditions necessitating greater amounts of inhibitory control, which result in more accurate task performance following exercise. Further, following the completion of the flanker task, scholastic achievement was tested using the Wide Range Achievement Test (3 rd edition), which examines reading comprehension, spelling, and mathematics performance. Findings from this test indicated that children also had higher academic achievement following exercise. When the individual academic tests were examined separately, improvements were observed on the reading comprehension assessment following exercise, while no differences were observed for spelling and mathematics (Hillman et al., 2009b). However, the spelling and mathematics tests were administered more than 1 h after the cessation of the acute bout, thus it is not clear whether the single bout of exercise selectively improved reading comprehension or if the initiation of the spelling and mathematics tests occurred after the transient benefits of exercise had subsided. This remains an open question. Regardless, these findings are especially interesting as they suggests that single bouts of moderate exercise (i.e., walking) may improve performance on externally-valid measures of academic achievement, and has implications for how physical activity may be administered during the school day to improve scholastic performance.

However, it should be noted that other researchers have not observed the same positive effects of a single bout of exercise to cognition. Stroth et al. (2009) examined the relation of fitness and a single bout of aerobic exercise to cognitive control in 13–14 year old children using ERPs. Participants performed a modified flanker/Go–NoGo task, which taps attention and inhibition, after 20 min of aerobic cycling at 60% of individual maximal heart rate, and compared their performance to a resting baseline condition. The findings revealed that P3 amplitude was not modulated by either fitness or a single bout of aerobic exercise (Stroth et al., 2009). However, it is important to note that the P3 component was measured at electrode sites overlying the lateral portions of the central scalp region, rather than over the midline-parietal region where a robust literature has indicated P3 achieves its topographic maximum (see Polich, 2007 for review). Further, a number of ERP studies exploring the relation of exercise (i.e., fitness-differences and single bouts of physical activity) to cognition have observed modulation of the P3 component at midline-parietal sites, suggesting a beneficial influence of exercise to stimulus engagement aspects of cognition (e.g., Hillman et al., 2009b, 2003; Kamijo et al., 2004; Kamijo et al., 2007; Polich and Lardon, 1997). Accordingly, the findings of Stroth et al. (2009) are not representative of the overall body of literature on exercise and P3 indices of cognition.

Further support for the beneficial relationship of single bouts of exercise to P3 indices of cognition may be garnered from research in adult populations, where a significantly greater literature-base may be found. Specifically, early work in our laboratory (Hillman et al., 2003) had 20 young adults ($M=20.5$ years) exercise on a treadmill at a pace of 'somewhat hard' (13) to 'hard' (15) on the Borg ratings of perceived exertion (RPE) scale (Borg, 1970), which equated to an intensity level of 83.5% of maximal heart rate during a 30 min bout of exercise. Participants were then attached to an EEG and performed a modified flanker task once their heart rate returned to within 10% of their resting level (approximately 45 min following the cessation of exercise). On a separate day, participants sat quietly for the same duration, with the two conditions counterbalanced across participants to minimize learning effects. Results indicated that P3 amplitude was larger following exercise across both conditions of the flanker task, suggesting a general increase in the allocation of attentional resources toward external events in the stimulus environment. Further, P3 latency was selectively shorter during incongruent trials, suggesting faster cognitive processing speed during tasks requiring greater amounts of cognitive control (Hillman et al., 2003). The findings suggested that single bouts of exercise serve to enhance cognition through increased effective engagement with the stimulus environment.

Additional research has examined differential exercise intensities on the modulation of P3 amplitude (Kamijo et al., 2004). That is, adults (22–33 years) exercised on a cycle ergometer at low (RPE = 7–9), moderate (RPE = 12–14), and high (volitional exhaustion) intensities, with a control condition composed of seated rest. Participants performed a Go–NoGo task following each of the counterbalanced sessions. On average, participants exercised for 18 min during each session and results indicated greater P3 amplitude after exercise following the moderate intensity condition (Kamijo et al., 2004). In a similar study, Kamijo et al. (2007) examined the P3 component following 20 min bouts of cycling at light (RPE = 11), moderate (RPE = 13), and hard (RPE = 15) intensities. ERPs were collected during a modified flanker task, with findings replicating previous studies (Hillman et al., 2003; Kamijo et al., 2004). In other words, relative to a resting baseline, P3 amplitude was larger following moderate intensity exercise, and P3 latency was shorter for incongruent trials regardless of exercise intensity. Furthermore, P3 amplitude also increased after light intensity exercise, while no such effect was observed for the hard intensity condition (Kamijo et al., 2007). From these findings it was concluded that the intensity of aerobic exercise may possibly follow a curvilinear relationship with cognition, such that moderate intensities produce the greatest improvements in processes subserving stimulus engagement.

In its entirety, research has supported the notion that participation in a single bout of exercise has favorable consequences for cognitive function in both child and adult populations. It is apparent that acute exercise effects differ based on participants' age, exercise duration, modes of exercise, and cognitive requirements of the task. However, given the relatively small literature-base, a detailed understanding of this relationship remains unclear in children. Turning to the adult literature, a greater understanding of the effects of acute exercise on cognition differ based on (1) the intensity and duration of exercise,

(2) the nature of the cognitive task, (3) the time at which the cognitive task is administered relative to the acute exercise bout, and (4) the fitness of participants (Kamijo, 2009). Accordingly, these findings need to guide future investigations in children to best determine the complex relationship between single bouts of exercise and cognition.

Summary

In summary, there is increasing public interest in the relation of children's health to scholastic performance (CDC, 2010; Datar and Sturm, 2006). Externally-valid measures of scholastic achievement are often complex, constituting a diverse assortment of cognitive functions. Research in our laboratory has pursued aspects of this complex relationship, focusing on a collection of cognitive processes that support cognitive control. We have implemented neuroelectric measurement into our experimental protocols to further understand covert aspects of information processing to better identify those specific processes occurring between stimulus engagement and response execution, which are influenced by chronic differences in aerobic fitness and single bouts of physical activity. This program of research has suggested that physical activity may influence the integrity and flexibility in which attentional resources are administered within the external world, and the extent to which individuals monitor and adjust their actions in response to external demands. Future research must continue to identify aspects of cognition that are influenced by physical activity participation and better determine the relationship to scholastic performance. The overall goal of this line of research is to improve scholastic performance, maximize health, and enhance the overall functioning of individuals as they progress through the human lifespan.

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