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REVIEW ARTICLE

# Exercise and Children's Intelligence, Cognition, and Academic Achievement

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**Abstract** Studies that examine the effects of exercise on children's intelligence, cognition, or academic achievement were reviewed and results were discussed in light of (a) contemporary cognitive theory development directed toward exercise, (b) recent research demonstrating the salutary effects of exercise on adults' cognitive functioning, and (c) studies conducted with animals that have linked physical activity to changes in neurological development and behavior. Similar to adults, exercise facilitates children's executive function (i.e., processes required to select, organize, and properly initiate goal-directed actions). Exercise may prove to be a simple, yet important, method of enhancing those aspects of children's mental functioning central to cognitive development.

**Keywords** Exercise · Physical activity · Children · Intelligence · Cognition · Academic achievement

Since the time of the ancient Greeks, there has been an implicit belief that physical activity is linked to intellectual abilities. However, the relation between exercise and children's mental function has not, until relatively recently, been systematically evaluated. A historical overview provided by Kirkendall (1986) sheds light on why this is the case. His review of research published prior to 1985 revealed that a number of studies on the psychological benefits of physical activity were conducted during the 1950s and 1960s; however, there was a precipitous decline of publications in the 1970s and 1980s. The reduced interest reflected, in Kirkendall's opinion, educators' shift of research priorities toward the physical benefits of exercise and away from potential mental benefits.

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The health and wellness movement in the 1980s, along with the emergence of academic degree programs specializing in exercise psychology, led to a renewed interest in evaluating the effects of exercise on psychological processes (Tomporowski 2006). A number of influential theory-based papers directed researchers toward the study of the impact of exercise on mental health (Folkins and Sime 1981; Plante and Rodin 1990), affect (Morgan 1981; Morgan *et al.* 1970), and cognition (Tomporowski and Ellis 1986). A substantial literature has emerged over the past two decades that focuses on the impact of physical activity on the processes of aging. Comparatively less research has been conducted to assess how exercise influences children's mental development. Several recent experiments conducted both with adult humans and animals (Colcombe *et al.* 2004a, b; Pereira *et al.* 2007) provide evidence that exercise performed on a regular basis for several weeks alters brain functions that underlie cognition and behavior. Physical activity results in a host of biological responses in both muscles and organs that, in turn, modify and regulate the structure and functions of the brain (Dishman *et al.* 2006). Given that children respond to exercise in a fashion similar to adults, exercise experiences would have important implications for their education.

The purpose of the present review is to evaluate published studies that have examined the effects of physical activity and exercise on children's intellectual function, cognitive abilities, and academic achievement—three outcome measures often targeted by educators as indices of children's mental function. The review consists of three parts: first, an overview of contemporary cognitive theory directed toward exercise; second, a description of cross-sectional and experimental studies conducted with children; and third, an examination of methodological issues and recommendations for future research.

## The Executive Function Hypothesis

Cognition is a general term that reflects a number of underlying mental processes. Colcombe and Kramer (2003) conducted a theory-driven meta analysis of 18 studies designed to assess the impact of physical activity on older adults' cognitive performance. Tasks used in these studies were coded in terms of four specific types of mental processing: executive function, which involves scheduling, response inhibition, planning, and working memory; controlled processing, which requires the automatization of response sequences (Chodzko-Zajko and Moore 1994); visuospatial processing, which involves perceptual learning (Stones and Kozma 1989); and speeded processing, which places demands on simple reaction time (Spirduso and Clifford 1978). Their analysis revealed that aerobic exercise resulted in a moderately large effect on overall cognitive performance (Effect Size (ES)=0.47). Further, the strength of effect was related to the type of test employed. Greatest gains were found for tests of executive function (ES=0.68), followed by tests of controlled processing (ES=0.46), visuospatial processing (ES=0.42), and speeded processing (ES=0.27). These results were interpreted as evidence for a causal link between fitness level and brain vitality and, further, they indicated that the link is particularly strong when the effects of exercise training are evaluated with cognitive tests that tap into executive function. Similar conclusions were drawn by Hall *et al.* (2001) review of research.

Executive functions are involved in planning and selecting strategies that organize goal-directed actions (Das *et al.* 1994) and stand apart from processes involved in basic information processing; e.g., encoding, stimulus evaluation, response selection, and response execution (Kramer *et al.* 1999a, b). There is a general consensus among researchers that executive functioning is not a unitary process; rather it is a number of more elemental underlying processes. Evaluation of adults' performance on tests of executive function reveals three variables which, while moderately correlated, are clearly separable: set-shifting, which requires individuals to disengage processing operations of an irrelevant task and to engage operations involved in a relevant task; updating, which is closely linked to working memory and the need to monitor mental representations; and inhibition, which involves the deliberate suppression of a prepotent response (Miyake *et al.* 2000).

Strong support for the executive function hypothesis has been provided through research conducted with older adults. Kramer *et al.* (1999a, b) assessed the impact of aerobic exercise training on both executive and non-executive cognitive processes in older adults. Participants in this study were assigned to either a 6-month aerobic training program or a non-aerobic toning program. A battery of cognitive tests was administered to participants prior to and following interventions. Clear post-training differences were observed. Individuals who participated in aerobic exercise training performed tests that required executive function (i.e., a category switching task, a flanker task, and a countermanding task) more rapidly and more efficiently than non-exercisers. Importantly, treatments had negligible influence on older adults' performance of tasks that did not emphasize executive-type mental processes (e.g., pursuit rotor task, spatial attention task, digit–digit matching task). More recently, Colcombe *et al.* (2004a, b) used magnetic imaging techniques (fMRI) to assess the brain functions of 29 sedentary older men prior to and following a 6-month aerobic walking program. Physical activity modified brain function in the anterior cingulate cortex, a prefrontal cortical area implicated in the regulation and control of behavior. Men who exercised were able to perform a complex decision task more rapidly than those who did not exercise.

The empirical data obtained with research conducted with adults confirm predictions derived from the executive function hypothesis. It is plausible that the executive function hypothesis can be extended to predict exercise-related improvements in children's cognitive function. Advances have been made relatively recently that provide an understanding of children's brain development and the relation of specific brain regions to performance on cognitive tasks (Amso and Casey 2006; Casey *et al.* 2000; Diamond 2002). There is evidence for a dramatic increase in gray matter volume in infancy and early childhood, which is followed between age 7 and young adulthood by decreases in gray matter in the frontal cortex and a protracted increase of myelination and connectivity (Giedd *et al.* 1999; Sowell *et al.* 1999, 2004). Children's cognitive test performance parallels these changes, suggesting that the prefrontal circuits become increasingly specialized with development and that increased myelination of axons enhances processing speed (Amso and Casey 2006; Casey *et al.* 2005; Gogtay *et al.* 2004). The refinement of prefrontal cortical networks correspond to changes in children's continuous improvement in speed of processing, strategy utilization, working memory, and response control into early adulthood (Diamond 2002). Exercise is known to affect a number of factors that influence neurological development (Nelson 1999, 2000). Physical activity leads to the production of neurotrophins that regulate the survival, growth, and differentiation of neurons during development (Barde 1989; Vaynman and Gomez-Pinilla 2006), synaptogensis that occurs concurrently with myelination (Huttenlocher 1994; Huttenlocher and Dabholkar 1997), and angiogenesis that influences glucose and oxygen distribution (Black *et al.* 1990). While the precise effects of these exercise-related changes in brain functions have yet to be determined, some researchers have suggested that systematic physical activity will produce more global changes in children's brain function than those observed in adults (Hillman *et al.* 2005).

Children's development of executive function has been viewed for some time as the cornerstone for the emergence of both psychological processes and social behaviors.

Several clinical disorders that are characterized by lack of behavioral control, attention, and judgment (e.g., attention deficit hyperactivity disorder and autism) have been explained in terms of ineffective executive function (Lyon 1996; Naglieri 2003). Executive functions may influence the emergence of children's ability to understand when to apply knowledge, and then to act when it is most advantageous to do so. A child who cannot effectively plan, update working memory, shift from one mental set to another, and inhibit impulsive behavior is unlikely to be able to stay on task in the classroom and excel academically (St Clair-Thompson and Gathercole 2006). Moreover, the ability to control or inhibit responses is purported to underlie children's capacities to develop imagination, experience empathy, act creatively, and to self evaluate thoughts and actions (Barkley 1996). We describe in the next section the results of exercise studies conducted with children and evaluate them in light of the executive function hypothesis.

## Research Review

The intent of this review is to examine closely the child exercise literature with a view toward better understanding linkages between physical activity and specific types of cognitive functioning. The review expands upon a meta-analytic review of research studies conducted by Sibley and Etnier (2003) in which they identified 44 studies that yielded 125 comparisons for analysis. The overall effect size of 0.32 indicated that physical activity was significantly related to improved cognition in children. The type of exercise training did not appear to matter; positive effects were found following resistance training, motor skills training, physical education interventions, and aerobic training programs. The effect of physical activity was greatest for middle school and young elementary age children (ES=0.40). Further, physical activity's effect on cognition was task dependent. Effect size was largest for tests of perceptual skills (ES=0.49), followed by IQ (ES=0.34), achievement (ES=0.30), and then math tests (ES=0.20) and verbal tests (ES=0.17). Sibley and Etnier (2003) acknowledged that their review was limited in that only nine of the studies evaluated were reported in peer-reviewed journals and the methodological rigor of many studies was questionable. While the evidence suggests a causal relation between physical activity and children's cognition, a theory-based evaluation of studies may be useful in elucidating mechanisms that underlie the relation between physical activity and children's mental functioning.

The present review is limited to published correlational and cross-sectional studies and randomized experiments that evaluate the impact of chronic exercise or habitual physical activity on measures of children's mental function. Chronic exercise interventions are designed specifically to improve participants' physiological functioning (e.g., cardio-respiratory function, metabolism, muscular strength) via repeated training sessions that last several weeks or months (Wilmore and Costill 2004). These studies stand apart from studies that assess the effects of individual or acute bouts of exercise on cognition (See Tomporowski 2003a, for a review). Studies reporting correlations between children's mental function and participation and/or involvement in specific sports were excluded from review as they suffer from selection biases and fail to provide indices of children's level of physical activity. The studies evaluated were identified from citations in previous literature reviews and by key-word searches of select data bases (PsycINFO, MEDLINE, Pub-Med, and ERIC). A summary of the prospective and experimental studies reviewed is shown in Table 1 and a summary of the correlational studies reviewed is shown in Table 2.

**Table 1** Summary of Findings of Prospective and Experimental Studies Performed to Assess the Chronic Effects of Exercise on Children's Intelligence, Cognition, and Academic Achievement

| Author(s) | *n* | Sample | Design | Exercise intervention | Duration | Tests | Results |
|---|---|---|---|---|---|---|---|
| Exercise and children's intelligence | | | | | | | |
| Corder (1966) | 8 | 12–16 years, MR | R | Balance and coordination | 20 days | WISC | Inconclusive |
| Brown (1967) | 40 | 12 years, MR | R | Strength training | 6 weeks | Stanford–Binet | Improvement |
| | | | | | | Vineland | Improvement |
| Ismail (1967) | 142 | 10–12 years | R | Enhanced school PE | Academic year | Otis | No effect |
| Exercise and cognition | | | | | | | |
| Tuckman and Hinkle (1986) | 154 | 9–12 years | R | Aerobic running | 12 weeks | Perceptual-motor | No effect |
| | | | | | | Creativity | Improvement |
| Hinkle *et al.* (1993) | 42 | 13–14 years | R | Aerobic running | 8 weeks | Creativity | Improvement |
| Zervas *et al.* (1991) | 26 | 11–14 years | R | Aerobic exercise | 6 months | Design matching | Inconclusive |
| Davis *et al.* (2007) | 30 | 8–10 years | R | Aerobic exercise | 10–15 weeks | CAS: executive | Improvement |
| | | | | | | Non-executive | No effect |
| Exercise and academic achievement | | | | | | | |
| Ismail (1967) | 142 | 10–12 years | R | Enhanced school PE | Academic year | SAAT | Improvement |
| Shephard *et al.* (1984) | 546 | First–sixth grade | NR | Enhanced school PE | Academic year | Class grades | Inconclusive |
| Dwyer *et al.* (1983) | ~500 | Fifth grade | NR | Aerobic exercise | Academic year | ACER | No effect |
| | | | | | | GAP | No effect |
| Sallis *et al.* (1999) | 759 | K-fifth grade | NR | Enhanced school PE | Academic year | MAT | Inconclusive |
| Coe *et al.* (2006) | 214 | Sixth grade | R | Enhanced school PE | 4 months | TN | No effect |

*n* number of participants, *MR* mental retardation, *R* Random assignment, *NR* Non-random assignment, *WISC* Wechsler Intelligence Scale for Children, *CAS* Cognitive Assessment System, *SAAT* Stanford Academic Achievement Test, *ACER* ACER Arithmetic Test Form C, *GAP* GAP Reading Comprehension Test, *MAT* Metropolitan Achievement Test, *TN* Terra Nova Test

Studies were grouped on the basis of three outcome measures: intelligence, cognition, and academic performance. IQ tests provide a single global score and, sometimes, subscale scores that reflect performance on a variety of items that require memory, spatial organization, vocabulary, and problem solving (Cunningham 1987). Cognitive tests evaluate mental function at more molecular level of analysis than do traditional IQ tests. Tests developed by cognitive researchers are based on contemporary views; for example, those of attention (Kahneman 1973), information-processing (Sanders 1998), working memory (Baddeley 1986), and executive function (Miyake *et al.* 2000). Academic achievement is often assessed by standardized tests, academic grades, and teacher evaluations. As described below, each of these three measurement approaches used to assess the effects of exercise on children's mental function has strengths and weaknesses.

**Table 2** Summary of Findings of Correlational Studies Performed to Assess the Relation Between Physical Fitness and Children's Academic Achievement

| Authors | *n* | Sample | Measures | Results |
|---|---|---|---|---|
| Castelli *et al.* (2007) | 259 | Third and fifth grade | Fitnessgram[a] academic achievement[b] | Positive association |
| California Department of Education (2005) | 1,036,386 | Fifth, seventh, and ninth grade | Fitness battery academic achievement[c] | Positive association |
| Dwyer *et al.* (2001) | 7,961 | 7–15 years | Fitness battery teacher ratings | Positive association |
| Tremblay *et al.* (2000) | 6,856 | Sixth grade | Self-report fitness academic achievement[d] | No association |

*n* number of children

[a] Cooper Institute for Aerobics Research

[b] Illinois Scholastic Achievement Test

[c] California Standards Test

[d] New Brunswick Department of Education

## Exercise and children's intelligence

Three experiments, all conducted in the 1960s, employed global IQ measures to assess the effects of exercise training. While historically dated, the studies are important as they were the first to focus directly on the impact of routine physical activity on children's mental function. Two researchers evaluated the effects of exercise on children with mental retardation. People with developmental delays have been hypothesized to be more sensitive to the effects of interventions designed to affect mental function than individuals who are not developmentally delayed (Ellis 1969). Corder (1966) used the Wechsler Intelligence Scale for Children (WISC) in a study conducted to evaluate the effects of 20 days of physical fitness training on boys ranging between 12 to 16 years of age who were diagnosed with moderate mental retardation (Mean IQ=66). Twenty-four children, matched on IQ, were randomly assigned either to a 60-min exercise intervention comprised of calisthenics, sprint runs, and 400-yard runs, an activity-control condition that involved recording the daily training performance of children in the exercise group, or a non-exercise group. Compared to children in the non-exercise condition, physical activity resulted in improvements in the children's WISC Full Scale IQs (exercise ES[1]=0.92; non-exercise ES=0.30) and Verbal Scale (exercise ES=1.22; non-exercise ES=0.02). There were no group differences in Performance IQ. Importantly, IQ gains obtained by children who exercised did not differ from gains obtained by children in the activity control group, suggesting that the attention children obtained, rather than physical activity per se, led to improved IQ-test performance.

Brown (1967) assigned 40 12-year old boys (Mean IQ=35) randomly to either a 6-week exercise isometric program or an attention-control condition. The exercise program consisted of a series of 12 yoga-like activities that required the child to exert muscle tension to maintain body position. The Stanford–Binet Intelligence Test and the Vineland

[1]Unless otherwise noted, Effect Sizes (ES) provided in this section were calculated as recommended by Thalheimer and Cook (2002). Within-group ES was calculated when sufficient data were provided to determine a pre-post intervention test difference score that could be divided by the pooled standard deviation; between-group ES was calculated from available F-test statistics.

Social Maturity Scale were administered by evaluators unaware of children's treatment assignment. Children who participated in an exercise program, compared to those who did not exercise, improved on both the IQ test (exercise ES=0.54; control ES=0.13) and the social scale (exercise ES=0.86; non-exercise ES=0.08). Because the exercise tasks required the children to attend, use memory and reasoning processes, and control motor movements, Brown hypothesized that exercise-related improvements were due to the mental demands experienced by children.

Generalization of the results obtained by Corder (1966) and Brown (1967) are restricted due to the relatively small sample size employed in both studies, differences in the level of intellectual function of participants, and the type of exercise intervention employed. A historically important large-scale study by Ismail (1967), addressed these aforementioned methodological shortcomings. One hundred forty-two fifth- and sixth-grade (age range= 10–12 years) boys ($n$=66) and girls ($n$=76) matched on IQ, sex, and health status were assigned randomly to an exercise program that involved a special daily physical activity program or a control condition in which they participated in the standard school physical activity classes. The study was conducted throughout an entire academic year. Experiences gained from the enhanced exercise program did not influence children's performance on the Otis IQ test. The strengths of the study include a large sample size, stratification procedures, and the length of the exercise program. However, the conclusion that routine exercise has little effect on children's mental function is qualified by the lack of sufficient information concerning the exercise programs. It is not possible to determine the intensity of physical activity performed in either the special exercise or standard exercise programs, nor is it clear what instructional methods were employed by physical education teachers.

A plausible explanation for researchers' failure to detect the effects of exercise on children's intelligence is that IQ tests provide only global measures of functioning, which may not be sensitive enough to detect subtle changes in specific aspects of cognitive functioning brought about by exercise training. As discussed previously, there is a growing consensus among contemporary researchers that exercise may differentially benefit specific components of cognitive processing (Brisswalter *et al.* 2002; Kramer *et al*. 2000; Tomporowski, 2003a, b). Indeed, the processes that are central to executive function are difficult to isolate via traditional IQ tests. In the next section, we describe studies that measure specific components of cognition.

## Exercise and children's cognitive processes

Cognitive science is characterized by the study of mental processes (Ellis and Hunt 1993). Researchers in this field typically employ a componential-analysis approach to assess the operations of the mind (e.g., perception, attention, memory, information processing). Cognitive scientists usually employ theory-based tests and attempt to isolate and evaluate how various factors influence brain structures and mental processes. Several exercise scientists have assessed the impact of exercise training on specific components of children's mental function.

Reaction time measures and electroencephalography (EEG) were used by Hillman *et al.* (2005) to contrast the mental functioning of low and high physically fit children (Mean age= 9.6 years) and low and high physically fit young adults (Mean age=19.3 years). Brain activity was measured while participants performed a visual discrimination task. Children performed the discrimination task more slowly than did young adults; however, high-fit children's response times were significantly faster that those of less-fit children. Further, EEGs revealed that high-fit children evidenced P3 latency measures that indicated faster cognitive processing speed and P3 amplitude measures that indicated greater allocation of attention than lower-fit children. These fitness-related differences in performance are similar to those obtained in studies that examine fitness-related differences in young (Hillman *et al.* 2006) and older adults (Dustman *et al.* 1994). This study provides evidence that children who are physically fit display greater cortical activation and corresponding cognitive performance than less fit children.

A study conducted by Zervas *et al.* (1991) explored the possibility that exercise training would prepare children to perform a matching-to-sample task given immediately following an acute bout of physical activity. Nine pairs of twin boys, 11–14 years of age, participated in the study. One twin from each pair was randomly assigned to a 6-month aerobic exercise program that was conducted 3 days/week. The exercise program consisted of a 15-min warm-up period of stretching followed by 60 min of sprinting runs and continuous running. Exercise intensity was adjusted based on measures of the child's anaerobic threshold. The other twin was assigned to a standard school physical education program. An additional group of eight age-matched boys was assigned to a standard physical education program. Following treatments, boys assigned to the aerobic training program and boys assigned to the physical education program performed a computerized design-matching task that recorded accuracy and speed of responding before and 15 min after a physically demanding 25-min treadmill run. Treadmill speed was determined for each child on the basis of a test of $VO_{2max}$. The average treadmill speed was 13.01 km/h for children in the aerobic training program and 12.96 km/h for children in the standard exercise program. Non-twin children assigned to a standard exercise condition performed the cognitive task before and following a non-exercise period. Analysis of response times following the treadmill run revealed that children's speed of processing increased, regardless of their treatment condition. Analyses of children's response accuracy before and following exercise revealed that boys in the aerobic exercise training program and in the physical education program improved significantly (aerobic exercise group ES=2.01; standard exercise group ES=1.33); additionally, the response accuracy for children in the two exercise conditions was significantly higher that of boys in the control condition.

Improvements in children's response times and accuracy following an acute bout of exercise in the Zervas *et al.* (1991) study are consistent with findings obtained with adults (McMorris and Graydon 2000) and children (Tomporowski 2003a). The increased level of arousal induced by physical activity is believed to mediate increased response speed and accuracy (Davranche and Audiffren 2004). Interpreting the impact of exercise training on children's mental performance is less straightforward, however. Prior to the acute bout of exercise, children's performance on the matching-to-sample task did not differ as a function of exercise conditions, suggesting that exercise training had little effect on the processes involved in performing the task. Further, there was no evidence to suggest that an intense aerobic exercise training regimen better prepared children to perform mentally demanding tasks following intense physical activity than did a standard education class.

Several other studies do, however, provide evidence that chronic exercise training alters children's cognitive function. Tuckman and his colleagues conducted a series of experiments that employed a battery of cognitive tests to assess children's mental function prior to and following aerobic exercise training. Tuckman and Hinkle (1986) assigned 154 fourth-, fifth-, and sixth-grade children randomly to either a 12-week aerobic running program or a standard school physical education class that met 30 min at a time, three times per week. The exercise program consisted of sprinting, relays, and distance runs that were gradually made more physiologically demands over the course of training. The regular exercise program consisted of ball games and occasional jogging. An analysis of covariance was performed on post-test scores to assess differences between experimental and control groups, boys and girls, and the three grade levels. Tests of physical function revealed that children in the aerobic training program were faster in an 800-m run, but not a 50-m dash, than children in the control condition. Tests of cognitive function revealed that aerobic training did not influence children's performance on tests that measured perceptual-motor skill (Bender–Gestalt test) or visual-motor coordination (Maze Tracing Speed Test). Children in the aerobic exercise program did, however, perform better on a test of creativity (Alternate Uses Test) than did children in the standard exercise program. The Alternate Uses Test is measure of divergent thinking, that involves naming an object (e.g., hammer) and asking the respondent to describe as many appropriate uses of the object as possible.

A subsequent experiment conducted by Hinkle *et al.* (1993) provided similar results. Eighty-five eighth-grade children were assigned randomly either to an 8-week aerobic running program that met five times weekly or to a standard physical education class. The aerobic exercise program and standard exercise program were identical to those used in their prior research. A multiple analysis of variance was performed on children's pre-post treatment gain scores of physical and mental function. As in the earlier study, the students in the aerobic program completed an 800-m run significantly faster than did children in the standard exercise program. Also, those who exercised aerobically performed better on the Torrance Test of Creative Thinking, which measures verbal and figural divergent thinking. Tuckman (1999) summarized the results of several studies and concluded that chronic exercise training has little impact on children's intelligence or cognitive skills, but it does facilitate creativity. Most cognitive researchers consider that the tests of creativity reflect executive function (Lezak *et al.* 2004; Naglieri and Kaufman 2001). The Torrance Test of Creative Thinking, for example, provides an index of creative figural fluency, flexibility, and originality. As such, the results of the experiments conducted by Tuckman and his colleagues reported here are taken as support for the executive function hypothesis.

Clear evidence for a selective facilitation effect of aerobic exercise on children's executive function was obtained in a recent randomized clinical trial experiment conducted by Davis *et al.* (2007). The study assessed the impact of 10–15 weeks of exercise training on the cognitive functioning of 94 overweight children who ranged in age from 7 to 11 years. The children were randomly assigned to one of three experimental conditions: no exercise control, 20-min exercise, or 40-min exercise condition. Children participated in physical training games 5 days/week after school. The program consisted of games (e.g., running games, jump rope, soccer) designed to maintain average heart rates of above 150 bpm and to exert a vigorous physical challenge on children. A standardized test of cognitive function, the Cognitive Assessment System (CAS) (Naglieri and Das 1997), was administered to each child before and after the intervention period. The CAS provides four scales of cognitive functioning: Planning (which assesses executive function; i.e., cognitive control, utilization of processes and knowledge, intentionality, and self regulation), Attention (which assesses focused, selective cognitive activity and resistance to distraction), Simultaneous (which assesses spatial and logical processing of nonverbal and verbal material), and Successive (which assesses processing of sequential information). Analysis of covariance performed on post-test scores revealed that exercise influenced the Planning scale. Children in the high dose exercise group improved their Planning scale scores significantly more than did children in the control group (ES=0.30). No effects of the exercise intervention were observed on remaining CAS scales. There were no differences in the CAS performance of children who performed 20 min of daily exercise and those children in the control condition, suggesting that positive effects may accrue only with a large amount of vigorous physical activity.

In summary, the results of cross-sectional studies indicate that children who are physically fit perform cognitive tasks more rapidly and display patterns of neurophysiological activity indicative of greater mobilization of brain resources than do less fit children. Several large-scale experiments provide evidence to suggest that exercise training exerts specific, rather than global, effects on children's cognitive function. Following aerobic exercise training, children's performance improves exclusively on tests that involve executive function.

## Exercise and academic achievement

The majority of published research that has examined the effects of exercise on children's mental function has focused on academic achievement as an outcome measure (Keays and Allison 1995). The interest in academic behaviors has been motivated by an assumption that children who participate in physical activities that promote cooperation, sharing, and learning to follow rules learn skills that transfer to classroom settings (Taras 2005).

*Correlational studies* Several large scale correlational studies have been conducted that examine the strength of the relation between physical activity and academic achievement. Dwyer and his colleagues evaluated a sample of almost 8,000 Australian children ranging between 7 and 15 years of age selected from 109 schools (Dwyer *et al.* 2001). Measures of children's physical fitness (situps, pushups, long jump, hand grip, etc), cardiorespiratory efficiency (50-m sprint, 1.6 km run, and sub-maximal measure of $VO_2$), and general activity (self report questionnaire) were correlated with ratings of scholastic achievement provided by school personnel. Small but significant positive associations were found between scholastic achievement and physical fitness measures and general activity measures.

Data gathered by the California Department of Education in 2004 provided the basis for an evaluation of over one million children's scores on a standardized test of physical fitness that measured aerobic capacity, body composition, strength, and flexibility and the California Standards Test, which provides indices of language arts and mathematics proficiency (California Department of Education 2005). Physical activity scores of children in grades 5, 7, and 9 were strongly positively correlated with both measures of academic achievement, with girls evidencing a stronger relation than boys.

Correlational studies with smaller numbers of children also yield positive associations between fitness and academic performance. Castelli *et al.* (2007) measured 259 third- and fifth-grade children's physical fitness via a standardized field test (Fitnessgram) (Welk *et al.* 2002) that provided measures of aerobic performance, flexibility, and muscular strength. Regression analyses were conducted to determine the relation between physical fitness scores and standardized tests of academic achievement that yielded scores for mathematics, reading, and total academic achievement. Aerobic physical fitness was significantly positively associated with reading achievement ($\beta$=0.40), mathematics ($\beta$=0.42), and total academic achievement ($\beta$=0.43). Other measures of physical fitness were not associated with academic achievement.

Juxtaposed to these findings, Tremblay *et al.* (2000) reported no relation between the self-reported physical activity of 6,923 sixth grade Canadian children and their performance on standardized reading, mathematics, science and writing tests. One explanation for the weak statistical relation obtained in this study is the use children's self-reported physical activity, which is known to lack reliability (Pate *et al.* 1994).

*Longitudinal studies* Three large-scale longitudinal studies have used indices of academic achievement to assess the impact of physical activity on children's mental functioning. The Three Rivers Project conducted in Quebec, Canada in the mid-1970s evaluated 546 children as they progressed through grades 1–6 (Shephard *et al.* 1984). Children assigned to an activity condition performed 5 h of training per week while children assigned to a control condition performed 40 min of physical education activities per week. Physical activities during first and second grade focused on basic motor skills; cardiorespiratory and muscular fitness during the third, fourth, and fifth grade; and vigorous team sports during the sixth grade. Analysis of children's academic grades revealed that those who were active performed better than control children throughout grades 2 through 6, with girls evidencing greater improvements than boys.

The South Australian Project was conducted in two phases (Dwyer *et al.* 1983). The first phase, which was begun in 1978, evaluated the impact of 14-week exercise training programs on children's health and academic performance. Over 500 fifth grade children were assigned to 75-min classes that focused on physical activities that elicited elevated heart rate levels or to 75-min classes that focused on game skill development. Classes met each school day. Children assigned to a control-condition class met for 30 min, three times per week, and focused on game skills. Post-treatment measurements revealed that all three groups' endurance fitness improved, with children who participated in physical activity training making the greatest gains. There were no differences among the three groups' performance on standardized measures of children's mathematics and reading abilities, however. The seven schools participating in the study continued the physical activity training program as part of its regular curriculum. The second phase of the study assessed the impact of the maintenance of the school-based exercise program on children's health and academic performance. Measures of the health and academic performance of 216 fifth-grade children enrolled in 1980 were compared to those of children who participated in the first phase of the study. Children enrolled in 1980 evidenced greater endurance fitness and lower Body Mass Index scores than children from the 1978 cohort. Measurements of children's academic achievement, which were limited to arithmetic performance, did not reveal differences between the two cohorts. The fact that children's health was improved and their academic performance was not adversely affected by reductions of 45 min of daily formal academic teaching was interpreted by Dwyer and his colleagues as supporting the benefits of regular physical activity programs in school settings.

The effect of 2 years of regular physical activity training on the academic achievement of 759 children enrolled in kindergarten through the fifth grade was assessed by Sallis and his colleagues (Sallis *et al.* 1999). Children in different schools were provided a physical activity program designed specifically to enhance fitness and skill (Sports, Play, and Active Recreation of Kids—SPARK). Each session of the exercise program was 30 min long and the program was carried out 3 days/week throughout the school year. Classes were instructed either by exercise specialists or by classroom teachers trained to implement the SPARK program. Children in a control group followed their school's standard physical education program. An analysis of changes in percentile scores obtained on a standardized test of academic achievement revealed decreases in performance for the three treatment groups. The scores of children who participated in physical activity training declined less than those of children in the control condition, however. Children in the study were drawn from relatively high socio-economic backgrounds and the observed decline in academic performance was explained by Sallis in terms of a regression-to-the-mean effect. The results were interpreted as evidence that children's time spent in physical activity classes did not have a negative influence on their academic achievement.

*Experimental studies* Two randomized experiments have assessed the impact of physical activity on children's academic achievement. The experiment conducted by Ismail (1967), which was described previously, reported that physical activity did not influence children's performance on a standardized test of intelligence. The exercise program did, however, have a positive effect on children's performance on the Stanford Achievement Test (ES=0.43). An important procedural element of this study was selection and assignment of children to one of three levels of achievement. The children's subgroup classification was based on a combination of pre-intervention IQ and academic achievement scores and teachers' opinion of each child's intellectual ability. Improved performance was observed following exercise regardless of children's pre-treatment level of academic achievement. These results suggest that the benefits of exercise training are similar regardless of children's initial level of academic achievement. Recently, Coe *et al.* (2006) randomly assigned 214 sixth-grade students to physical education classes or to arts or computer classes for a school semester. Participation in physical education classes did not differentially affect children's academic grades or performance on the Terra Nova Standardized Test of Academic Achievement. However, children who reported habitual levels of physical activity that exceeded Healthy People 2010 guidelines achieved higher academic grades than did less active children. These findings led the authors to propose that a threshold level of vigorous physical activity is required to produce improved academic achievement.

In summary, while there is evidence for a relation between chronic exercise and children's academic achievement, the results from these studies must be interpreted cautiously. Only two studies involved random assignment of children to experimental and control conditions. Ismail (1967) found exercise to have robust positive effects on children's academic achievement as measured by a standardized test instrument. Coe *et al.* (2006) observed that vigorous physical activity did not lead to improved performance on a standardized test of academic achievement even though associated with achieving higher class grades. Results obtained from studies that lack subject randomization are difficult to interpret. Dwyer *et al.* (1983) assigned schools to experimental and control conditions, but failed to find any effect of physical activity on standardized tests of academic performance. The SPARK project (Sallis *et al.* 1999) employed standardized tests of academic achievement, but suffered from subject selection bias (high socio-economic status) and high drop-out rates. Researchers who conducted the Three Rivers Project (Shephard *et al.* 1984) employed a cohort subject assignment methodology but interpretation of the findings are limited as teacher-assigned academic grades were used as the primary outcome measure. Exercise-related improvements in academic performance are reported most frequently when children's grades served as outcome measures. It is possible that changes in children's grades in the studies reviewed are due to teachers' expectancies that increased physical activity would enhance class performance rather than physical activity per se (Taras 2005). It is critical to use unbiased tests rather than teacher-assigned grades to assess academic achievement (Sallis *et al.* 1999). At best, the studies reviewed demonstrate that time spent in physical education classes does not have a deleterious impact on children's academic progress.

## Critique of Research and Recommendations

The results of the studies reviewed vary between those that suggest that exercise has little or no effect on children's mental function to those that report robust effects of exercise on specific types of cognitive functioning. Four plausible explanations exist for the lack of agreement among these studies. First, researchers may not have selected tests that are sensitive to the effects of exercise and mental functioning. Second, specific types of exercise training may facilitate cognitive functioning more than others. Third, there are substantial differences among samples of children participating in the studies reviewed, and population difference factors may have contributed to differential outcomes. Fourth, the effect of an exercise intervention may depend on the age, and thus the developmental level, of the children.

### Type of outcome measure

Several researchers who employed global measures of intellectual functioning and academic achievement failed to detect any effect of exercise training. Conversely, researchers who employ process-specific tests designed to measure specific components of mental functioning often report positive effects of exercise training. Success in detecting the effects of an exercise intervention on mental processing will depend both on the outcome measures selected and the measures' sensitivity to change (Lipsey 1990).

The evaluation of children's executive function with appropriate age-based mental tests provides great promise in understanding how physical activity may influence brain development and the emergence of cognitive processes that underlie the ability to monitor and control thought and action. The general consensus among researchers is that children's executive functioning reflects a number of more elemental underlying processes (Hughes 2002). The use of tests that systematically vary mental processing demands provide researchers an opportunity not only to tease apart the components of executive function but also to determine whether physical activity influences the emergence of specific mental processes. As stated previously, many measures are not sensitive to specific components of cognition. It will be important for researchers to assess systematically the moderating effects of physical activity on children's brain development and subsequent behaviors that reflect executive function.

### Dose and type of exercise intervention

Exercise interventions are complex. Exercise training is defined as a procedure designed to enhance a specific dimension of physical fitness; thus, some interventions may be aimed at promoting individual changes in cardiorespiratory fitness, muscular strength, muscular endurance, or muscular flexibility while other interventions may focus on combinations of physiological outcomes. The adaptation to exercise training has been evaluated extensively and the body's response to physiological stress is known to lead to very specific adaptations (Brooks *et al.* 1996).

The physical activity interventions employed in exercise studies conducted with children differ markedly. Some interventions were based on variations of traditional physical education programs that focused on balance and coordination training (Ismail 1967), perceptual-motor training (Corder 1966), or strength-training activities (Brown 1967). The results of these studies are inconsistent and difficult to interpret. A number of procedural differences may explain why movement training interventions resulted in gains in children's intelligence and academic achievement in some but not all studies. Other interventions were designed specifically to promote increases in cardiorespiratory physical fitness, which is seen by some researchers as a "gold standard" to gauge the impact of exercise interventions on cognitive functioning (See Dustman *et al.* 1994; Etnier *et al.* 2006 for reviews). In general, studies that employed vigorous aerobic-based exercise interventions reported gains in specific cognitive functioning (Davis *et al*. 2007; Hinkle *et al.* 1993; Tuckman and Hinkle 1986). It is of interest to note that the exercise programs conducted in each of these studies was relatively intense, designed for relatively small groups of children, and included manipulation checks to determine the impact of exercise training on children's physical fitness. The results obtained in these studies can be contrasted to those obtained from longitudinal, large-scale studies in which children were assigned to physical education training programs that targeted moderate levels of physical activity. These studies consistently failed to observe significant performance gains from exercise (Coe *et al.* 2006; Dwyer *et al.* 1983; Sallis *et al.* 1999; Shephard *et al.* 1984).

It is also plausible that the learning context experienced during exercise interventions impacts children's mental function. The type of exercise task and/or the challenges placed on the child may mediate the relation between exercise training and cognitive function. The impact of enriched and challenging environments on animals' neurological development and cognitive functioning has been reported in numerous studies conducted during the past three decades (See Black *et al.* 1998; Greenough and Black 1992; Will *et al.* 2004; Wolf *et al.* 2006). These studies provide clear evidence for differential effects of task complexity on brain function. Rats involved in exercise training that involved motoric climbing skills developed new neural connections within the cerebellum, whereas rats whose exercise was running improved in cerebral brain blood flow (Black *et al.* 1990). Advances in developmental neuropsychology provide evidence for a relation between children's early experiences and brain development and function (Brody 1992; Garlick 2002; Jensen 1998; Mackintosh 1998; Nelson 1999).

It may be the case that children who are involved in play and structured games that involve learning and group cooperation may adapt differently than children who are involved in individual physical activities that are performed in relative isolation (e.g., treadmill running or cycling on a stationary ergometer) (Pellis and Pellis 2007). Proponents of embodiment theories of action and cognition stress the importance of children's movement in normal cognitive development (Stockman 2004; Thelen 2004). Physical movement that occurs in a problem-solving context is hypothesized to result in implicit cause–effect knowledge that is not derived from tasks that involve only routine mental operations. Unfortunately, the few studies that have been conducted do not provide sufficient information to allow us to tease apart interactions that may exist between physical activity and level of cognitive processing.

In the studies reviewed above, authors seldom provided or vaguely reported descriptions of the types of skills learned during exercise training. Future research should systematically examine whether the type of physical activity in which children engage and the task challenges that occur during physical activity differentially influence cognitive development.

### Population characteristics

The mental and physical characteristics of children who participated in the studies reviewed vary considerably. Several studies evaluated children with developmental disabilities. Two early randomized control experiments conducted with children with mental retardation provide evidence that physical activity programs contribute to improved performance on tests of intelligence. Brown (1967) evaluated children whose average IQ score was 35 and ranged between 30 and 50, and Corder (1966) assessed children with an average IQ score of 66 and a range between 54 and 80. Individuals performing at lower IQ levels might be predicted to achieve the greatest mental gains from exercise interventions as they would have more room to improve (Ellis 1969). Researchers who have evaluated the effects of exercise training on adults with mental retardation at the severe and profound levels of functioning have failed to find evidence of improved performance, however (Tomporowski and Ellis 1984, 1985). It remains to be determined whether children with mental retardation will respond more favorably to exercise training than do adults with mental retardation (See Gabler-Halle *et al.* 1993 for a review).

Overweight children showed clear improvements in executive function following exercise training in one experiment (Davis *et al.* 2007). Being overweight during childhood is negatively associated with academic success (See Taras and Potts-Datema 2005 for a review) and intellectual function (Campos *et al.* 1996; Li 1995). Body weight, however, is not viewed as a causal factor; rather, it is a marker of children's physical inactivity (Datar *et al.* 2004). Several researchers provide evidence that being overweight is associated with a variety of psychosocial (Falkner *et al.* 2001) and cognitive (Alonso-Alonso and Pascual-Leone 2007) factors that are, in turn, linked to academic performance and school success. Additional research is needed to determine whether children who are overweight gain more from participating in systematic exercise programs than their leaner peers.

Children of different gender, races, and socioeconomic classes tend to engage in different sorts of exercise, sport, and leisure activities. For example, there is evidence that middle class boys tend to engage in formal, structured activities that emphasize public performance and skill development, whereas working-class boys tend to engage in informal play, visiting relatives, and "hanging out" (e.g., Lareau 2000). These differences have unknown effects on the success of exercise training on mental function. Exercise activities that include culturally relevant games, for example, would be expected to promote greater levels of interest, cognitive involvement, and motivation to perform than games with less cultural relevance. Thus, future studies that isolate the impact of potential psycho-social mediators on outcome measures are desirable.

## Age

Age could be important is several ways; specifically, in the mediating role of neural, motor, cognitive, or social developmental levels accompanying age. With respect to neural maturation, particular exercise interventions may affect different aspects of executive functioning at different ages because of age differences in the maturation of the pre-frontal cortex; that is, the various aspects of executive functioning may have different developmental trajectories (Welsh *et al.* 1991) and thus the profile of change in executive function as a result of exercise may vary from age to age (Kail 2007). For example, some aspects, such as the ability to inhibit a prepotent response may develop mainly during the preschool years whereas other aspects, such as planning and working memory, may continue to develop through the middle-school years. In this case an exercise intervention may improve inhibition in preschoolers but not in school-age children. With respect to the importance of motor level, a particular exercise intervention may primarily challenge the motor coordination of a young child but challenge the planning skills of an older child who is more advanced motorically. Cognitive level matters when, for example, there is a mismatch between what a child is ready to learn and what learning experiences are provided. Coordination training, for instance, may need to fit with the child's level of cognitive "readiness" (i.e., within or slightly above his or her present cognitive level) in order to teach planning skills.

Children do not develop in a social vacuum. As mentioned earlier, it may matter, with respect to cognition, whether children exercise alone or within a group. Age differences in the types of group physical activities in which children engage thus may affect the impact of group physical activities on cognition. The coordination required for a group activity such as basketball, more likely to be engaged in by older children than younger ones, may encourage a more strategic approach (e.g., planning) than a simpler games, such as tag, which is enjoyed by younger children. In addition, the inter-person coordination required for both types of games may impact cognition differently than does the intra-person coordination required for a solo activity such as jogging. Moreover, the effect of an exercise intervention on cognition may be mediated by other social developmental factors. Feelings of increased self efficacy at physical activities or an improved body image might encourage older children, more than younger ones, to engage in physical activities at school or with their parents, thus increasing the likelihood that exercise will be maintained.

Researchers have not systematically manipulated social, psychological, or biological factors to determine the roles that specific factors play in explaining how physical activity alters children's mental processes. Research on these topics would lead to a model of the effects of exercise on cognition. Such a model might clarify the bases for the inconsistencies in the literature, as well as identify possible mechanisms underlying the role of exercise on cognition.

## Conclusions

Evidence accrued from research conducted over the past few years suggests that gains in children's mental functioning due to exercise training are seen most clearly on tasks that involve executive functions. Executive functions are involved in performing goal-directed actions in complex stimulus environments, especially novel ones, in which elements are constantly changing. Behaviors such as these have long been seen as important for children's adaptive functioning. Exercise training programs may prove to be simple, yet important, methods of enhancing aspects of children's mental functioning that are central to cognitive and social development. Many questions concerning the relation between exercise and children's cognitive functioning remain unanswered, however. It is unknown whether improvements in cognition caused by exercise are maintained following the termination of physical activity or if they decline. Further, it remains to be determined, for instance, if the benefits obtained are related to the type, duration, or intensity of exercise training programs. Answers to these questions will be attained through systematic research designed around contemporary exercise science and cognitive theory. At this time, no theory has been proposed that satisfactorily addresses the relation between exercise and cognition. Several biological hypotheses have been presented that describe how exercise affects brain structure and function (Colcombe *et al.* 2004a, b; Vaynman and Gomez-Pinilla 2006). While intriguing, these hypotheses are limited to the study of physiological adaptations to exercise training. The merits of attempting to relate brain structure and function to children's cognitive development and educational psychology have been the focus of considerable discussion (Byrnes and Fox 1998; Mayer 1998; O'Boyle and Gill 1998). Comprehensive theories have yet to be formulated that address numerous contextual and psycho-social factors that may moderate or mediate the relation between exercise and children's cognitive function.

Research that addresses the impact of physical activity on children's physical health, mental function, and psychological well being is of critical importance. Authorities note that school administrators, who are faced with the demands of preparing children for standardized tests, have reduced children's time spent in systematic physical activity programs. The time spent engaged in physical activity and recess by grade-school children in schools in the United States has declined significantly over the past decade (Allegrante 2004). Pleas to maintain physical activity in school curricula have been made by several researchers who provide evidence that participation in physical activity programs does not negatively impact children's academic performance (Sallis *et al.* 1999; Shephard 1997; Sibley and Etnier 2003). The present review of research findings suggests that systematic exercise programs may actually enhance the development of specific types of mental processing known to be important for meeting challenges encountered both in academics and throughout the lifespan.

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