Physical Activity, Fitness, Cognitive Function, and Academic Achievement in Children: A Systematic Review

AMERICAN COLLEGE of SPORTS MEDICINE®
POSITION STAND

This pronouncement was written for the American College of Sports Medicine by Joseph E. Donnelly, Ed.D, FACSM (Co-Chair); Charles H. Hillman, Ph.D. Co-Chair; Darla Castelli, Ph.D.; Jennifer L. Etnier, Ph.D., FACSM; Sarah Lee, Ph.D.; Phillip Tomporowski, Ph.D., FACSM; Kate Lambourne, Ph.D.; and Amanda N. Szabo-Reed, Ph.D.

SUMMARY

Background: The relationship among physical activity (PA), fitness, cognitive function, and academic achievement in children is receiving considerable attention. The utility of PA to improve cognition and academic achievement is promising but uncertain; thus, this position stand will provide clarity from the available science. **Objective**: The purpose of this study was to answer the following questions: 1) among children age 5–13 yr, do PA and physical fitness influence cognition, learning, brain structure, and brain function? 2) Among children age 5–13 yr, do PA, physical education (PE), and sports programs influence standardized achievement test performance and concentration/attention? **Study Eligibility Criteria**: This study used primary source articles published in English in peer-reviewed journals. Articles that presented data on, PA, fitness, or PE/sport participation and cognition, learning, brain function/structure, academic achievement, or concentration/attention were included. **Data Sources**: Two separate searches were performed to identify studies that focused on 1) cognition, learning, brain structure, and brain function and 2) standardized achievement test performance and concentration/attention. PubMed, ERIC, PsychInfo, SportDiscus, Scopus, Web of Science, Academic Search Premier, and Embase were searched (January 1990–September 2014) for studies that met inclusion criteria. Sixty-four studies met inclusion criteria for the first search (cognition/learning/brain), and 73 studies met inclusion criteria for the second search (academic achievement/concentration). **Study Appraisal and Synthesis Methods**: Articles were grouped by study design as cross-sectional, longitudinal, acute, or intervention trials. Considerable heterogeneity existed for several important study parameters; therefore, results were synthesized and presented by study design. **Results**: A majority of the research supports the view that physical fitness, single bouts of PA, and PA interventions benefit children's cognitive functioning. Limited evidence was available concerning the effects of PA on learning, with only one cross-sectional study meeting the inclusion criteria. Evidence indicates that PA has a relationship to areas of the brain that support complex cognitive processes during laboratory tasks. Although favorable results have been obtained from cross-sectional and longitudinal studies related to academic achievement, the results obtained from controlled experiments evaluating the benefits of PA on academic performance are mixed, and additional, well-designed studies are needed. **Limitations**: Limitations in evidence meeting inclusion criteria for this review include lack of randomized controlled trials, limited studies that are adequately powered, lack of information on participant characteristics, failure to blind for outcome measures, proximity of PA to measurement outcomes, and lack of accountability for known confounders. Therefore, many studies were ranked as high risk for bias because of multiple design limitations. **Conclusions**: The present systematic review found evidence to suggest that there are positive associations among PA, fitness, cognition, and academic achievement. However, the findings are inconsistent, and the effects of numerous elements of PA on cognition remain to be explored, such as type, amount, frequency, and timing. Many questions remain regarding how to best incorporate PA within schools, such as activity breaks versus active lessons in relation to improved academic achievement. Regardless, the literature suggests no indication that increases in PA negatively affect cognition or academic achievement and PA is important for growth and development and general health. On the basis of the evidence available, the authors concluded that PA has a positive influence on cognition as well as brain structure and function; however, more research is necessary to determine mechanisms and long-term effect as well as strategies to translate laboratory findings to the school environment. Therefore, the evidence category rating is B. The literature suggests that PA and PE have a neutral effect on academic achievement. Thus, because of the limitations in the literature and the current information available, the evidence category rating for academic achievement is C. **Key Words:** PHYSICAL ACTIVITY, FITNESS, COGNITIVE FUNCTION, ACADEMIC ACHIEVEMENT, CHILDREN

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Contemporary educational organizations propose that children's experiences in sport and physical education (PE) contribute to the mental acuity, skills, and strategies that are important for navigating challenges faced across the life span (5). The perceived importance of PE and its contribution to children's academic success has varied considerably over the history of the modern educational system (152). For the past decade, mandates of the federal No Child Left Behind Act have placed major emphasis on children's standardized test performance, and, as a consequence, have led to reductions of children's opportunities to engage in physical activities during the school day (89). Physical activity (PA) proponents have long argued for the necessity of school-affiliated PA, suggesting that the time spent in PA would benefit health and might contribute to academic performance (155). Several lines of research address the PA–cognition relation; results obtained from these studies fuel discussions concerning the role of PA in children's cognition and academic success. For the purposes of this review, the terms that will be used throughout are defined as follows:

- *PA:* any bodily movement produced by skeletal muscles that requires energy expenditure.
- *Exercise:* a subset of PA that is planned, structured, and repetitive and has the improvement or maintenance of physical fitness as a final or an intermediate objective.
- *Fitness:* a physiological state of well-being that reduces the risk of hypokinetic disease, a basis for participation in sports, and good health, which enables one to complete the tasks of daily living. Components include cardiorespiratory endurance, muscle strength endurance, flexibility, and body composition.
- *Cognition:* the set of mental processes that contribute to perception, memory, intellect, and action.
- *Academic achievement:* the extent to which a student, teacher, or institution has achieved their educational goals, commonly measured by examinations or continuous assessment (i.e., grades, excluded from this review).
- *Executive function (EF):* A set of cognitive operations underlying the selection, scheduling, coordination, and monitoring of complex, goal-directed processes involved in perception, memory, and action.
- *Learning:* The act of acquiring new, or modifying and reinforcing, existing knowledge, behaviors, skills, values, or preferences and may involve synthesizing different types of information. This is often assessed through recall tasks.

Advances in neuroscience have resulted in substantial progress in linking PA to cognitive performance as well as to brain structure and function. The initial evidence for the direct effects of exercise on brain was obtained from research conducted with animals. Bouts of exercise elicit a cascade of neurological changes in the hippocampus that have been linked to memory consolidation and skilled actions in rodents (75). Considerable animal research led to the neurogenic-reserve hypothesis (94), which proposes that PA in early life optimizes brain networks involved in memory and also creates a reserve of precursor cells that influence individuals' learning capabilities throughout the life span. The relationship between fitness and cognitive vitality was likely first established in children (35); however, the evidence for the benefits of exercise on human cognition has been most fully developed in research with older adults. Several of these experiments clearly demonstrated that routine exercise alters specific brain structures and functions, and the changes were associated with older adults' cognitive performance (40,41,100), particularly on tests requiring greater amounts of EF, which describes a subset of goal-directed cognitive operations underlying perception, memory, and action and are organized along three interrelated component processes: working memory, response inhibition, and mental flexibility (55,112). The EF hypothesis proposes that exercise has the potential to induce vascularization and neural growth and to alter synaptic transmission in ways that alter thinking, decision making, and behavior in those regions of the brain tied to EF, in particular the prefrontal cortices (96).

More recently, the EF hypothesis has been extended to children (55). Laboratory-based tests have revealed a stage-like emergence of the components of EF (10,55) and neuroscientists have linked behavioral test performance to brain development (18). The consensus is that EF is crucial for children's adaptive behavior (1,12) and serves as the capstone for social behaviors expressed across the life span (55).

These "late maturing" EF is thought to broadly underpin learning and cognition and is associated with academic achievement. Measurements of EF in preschool predict achievement on mathematics and literacy in kindergarten (13). Similarly, working memory ability correlates with math and reading scores among children age 5 to 6 yr (4) and 11 to 12 yr (145), and predicts achievement in mathematics and science in adolescents (74). In addition, subtests of standardized tests of academic achievement benefit from processing speed and decision-making ability, which are related to physical fitness and PA. Classroom-based PA programs have been shown to be effective in improving on-task behavior during instruction time (110). This increase in on-task behavior subsequently correlates with EF, which subserves self-regulation and behavioral inhibition, and the ability to inhibit off-task behavior in service of attending to a classroom material that is a prerequisite for successful learning (86). Therefore, cognitive skills seem to affect learning and academic achievement in school, as well as classroom behavior.

The objective of this systematic review was to address the following questions: 1) among children age 5–13 yr, do PA and physical fitness influence cognition, learning, brain structure, and brain function? 2) Among children age 5–13 yr, do PA, PE, and sports programs influence standardized achievement test performance and concentration/attention? This review updates and expands previous position stands (41,43,125) by the inclusion of recent cognitive neuroscience studies. Further, it informs researchers and stakeholders of the salubrious benefits of routine PA and its role in contemporary models of public health (6,105).

METHODS

This systematic review was performed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (104,113) (see Table, Supplemental Digital Content 1, PRISMA 2009 checklist, http://links.lww.com/MSS/A657).

Eligibility criteria. Primary source articles published in English in peer-reviewed journals were eligible for inclusion in this systematic review if data were presented on the relationship among PA levels, fitness, PE or sport participation, and cognitive function or academic achievement. Specific eligibility criteria included the following:

Types of studies: cross-sectional, acute, longitudinal, and intervention studies (both nonrandomized and randomized)

Types of participants: elementary-age children (age 5–13 yr). Studies that include data on older students were not disqualified if data could be interpreted for the eligible age range. This age range was selected to narrow the focus on children as the onset of puberty results in both physical and cognitive changes that differentiate adolescents from children.

Types of outcome measures: for the search relative to question 1, studies were included if cognitive function, learning, brain structure (i.e., magnetic resonance imaging [MRI]), or brain function (i.e., electroencephalography and functional MRI [fMRI]) was assessed. For the search relative to question 2, studies were included if the outcomes included a standardized test or a measure of concentration/attention. Grades were not included as an outcome measure because of their subjective nature and because they are not standardized across teachers.

Exclusion criteria: articles were excluded if they did not meet inclusion criteria or did not include findings related to the inclusion criteria (i.e., measured PA, but failed to compare with academic achievement or cognitive function).

Information sources. Studies were identified by searching electronic databases and related article reference lists and by consulting with experts in the field. The search was applied to PubMed and adapted for Embase, Education Resources Information Center (ERIC), PsychInfo, SportDiscus, Scopus, Web of Science, and Academic Search Premier (1990–September 2014). The last search was conducted on May 1, 2015. The search was developed as a collaborative effort of the research team in consultation with a University of Connecticut reference librarian and conducted by coauthors (KL and AS). No attempts were made to contact study investigators or sponsors to acquire any information missing from the published article.

Search strategy. Search terms were defined through group discussion among the research team and were used in each database (Embase, ERIC, PsychInfo, SportDiscus, Scopus, Web of Science, and Academic Search Premier) to identify potential articles with abstracts for review. The search terms are found in Supplemental Digital Content 2 (see Document, Supplemental Digital Content 2, Cognitive function search, http://links.lww.com/MSS/A658). Additional search filters were applied to eliminate case reports and studies involving participants with physical or developmental disabilities. Separate searches were run for the publication dates 2012–present, removing the filters. The purpose of these searches was to locate preindexed citations, which would not come up when filters were activated.

Study selection. Retrieved abstracts were independently assessed for eligibility for inclusion in the review by two coauthors and coded as "yes," "no," or "maybe." The coauthors who participated in eligibility assessments were trained regarding study inclusion/exclusion criteria and completed practice eligibility assessments on 50 test abstracts before actual coding. Eligibility assessments on the practice abstracts were reviewed by the primary author (JED), and any coding problems were discussed. Disagreements regarding eligibility for inclusion were resolved via the development of consensus among all coauthors. Full text articles for abstracts coded as "yes" or "maybe" were retrieved and reviewed by the same two coauthors before inclusion in the review. A Microsoft Excel spreadsheet was developed to track eligibility status.

Data collection. Extracted data were entered into the University of Kansas secure REDCap database (Research Electronic Data Capture, Version 4.14.5) (80). A REDCap data extraction form was developed, pilot tested, and revised accordingly. Relevant data were extracted from each manuscript by one coauthor, and the coding was verified by a second coauthor. Disagreements were resolved by discussion among these coauthors. Data extracted from each article included basic study information (design, sample size, groups compared, and PA groups/intervention(s)), participant characteristics (age, gender, body mass index [BMI], and minority status), PA/fitness assessment method, cognition or academic achievement assessment method, and results.

Study quality and risk of bias. Study quality was assessed using checklist criteria developed by Downs and Black (59). The checklist is used for assessing the quality of both nonrandomized and randomized intervention trials. The checklist includes items concerning the quality of reporting (nine items), internal validity (bias, seven items, and confounding, six items), external validity (three items), and power (one item). Power was assessed using the following criteria: "Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5% (i.e., if the treatment effect, was noticeable in daily life)." Answers were scored 0 or 1, except for one item in the reporting subscale, which scored 0 to 2 and the single item on power, which was scored 0 to 5. A coauthor (JED) resolved any discrepancies in quality coding. Studies were not excluded based on quality. Detailed comments on study quality according to the checklist criteria have been included throughout the manuscript.

Synthesis of results. Articles were grouped by dependent variable (e.g., cognitive function/brain structure/brain function or academic achievement) and then by study design: cross-sectional, acute, longitudinal, and intervention trials (nonrandomized and randomized). Considerable heterogeneity existed within study groups for several important study parameters. These parameters included the following: 1) participant characteristics (e.g., age, gender, and BMI), 2) PA or fitness assessment methods (e.g., questionnaires, time spent in PE, and FITNESSGRAM™), 3) cognitive assessment measures (e.g., reaction time, flanker task, and Cognitive Assessment System [CAS]), and 4) academic achievement assessment methods (e.g., state administered tests and individualized achievement tests). For each question, the results are presented in a consistent manner. Each question begins with a general overview of the findings, followed by a description of all studies organized by design (cross-sectional studies, longitudinal studies, acute studies, and intervention-based studies such as cohort and randomized controlled trials [RCT]). Each section concludes with a quality assessment of the body of literature as a whole and a summary of the findings. The details for each study, including design, participant characteristics and sample size, measures, methods, and results, are presented in the corresponding tables.

The strength of the overall body of evidence presented in the position stand is summarized via evidence statements and evidence category ratings adapted from the National Institutes of Health and National Heart, Lung and Blood Institute (see Table 1) (123). As an example, a recommendation with an evidence category of A, indicates that the recommendation is supported by the strongest evidence and that the treatment is useful and effective, whereas an evidence category of C indicates that evidence primarily comes from outcomes of uncontrolled or nonrandomized trials or from observational studies. An evidence summary statement and evidence category rating have been presented for each of the two questions addressed by this review.

RESULTS

Question 1: PA, Fitness, Cognition, Learning, and Brain Structure/Function

The potential benefits of PA on cognitive performance, learning, brain structure, and brain function for children are important to understand because these effects may be the foundation upon which more global improvements in academic achievement are attained. Although the extant literature in this area is relatively modest, the early work was meta-analytically reviewed on two occasions. In 1997, Etnier et al. (69) reported that in studies testing the effects of acute PA on cognitive performance with children (6–13 yr), a small positive effect was observed (Hedge's $g = 0.36$). In a 2003 meta-analysis focused exclusively on children ages 6–13 yr, Sibley and Etnier (142) reported a similar overall effect size (Hedge's $g = 0.32$) for 44 studies using a variety of designs (including both chronic and acute PA paradigms).

Since 2003, there has been a gradual increase in annual publications that report on the relationship between PA and cognitive performance by children (e.g., 1 in 2005 and 2007, 6 in 2010, and 12 in 2012). This time period has also seen considerable growth in the field of kinesiological neuroscience, as researchers have recognized the importance of including both mechanistic and behavioral measures in studies on PA and cognitive performance in children. Despite still lagging behind the research on PA and cognition and brain in adult populations, this burgeoning literature has shed light on the influence of PA on cognition, brain structure, and brain function among school-age children, with approximately 25% of the literature using randomized trials.

Although considerable effort will be necessary to fully elucidate our understanding of the relationship of PA and aerobic fitness to cognition and brain, emerging evidence suggests a favorable relationship among these constructs. This section will describe the benefits observed in the literature by detailing the relationship of PA and aerobic fitness to cognition, learning, brain structure, and brain function. The initial database search plus hand searching identified 3192 unique records, of which 3090 were excluded based on

TABLE 1. Evidence categories for the American College of Sports Medicine Position Stands.

Evidence Category	Sources of Evidence	Definition
A	RCT designs (rich body of data)	Evidence is from end points of well-designed RCT designs (or trials that depart only minimally from randomization) that provide a consistent pattern of findings in the population for which the recommendation is made. Category A therefore requires substantial numbers of studies involving substantial numbers of participants
B	RCT designs (limited body of data)	Evidence is from end points of intervention studies that include only a limited number of RCT designs, *post hoc* or subgroup analysis of RCT designs, or meta-analysis of RCT designs. In general, Category B pertains when few randomized trials exist, they are small in size, and the trials results are somewhat inconsistent, or the trials were undertaken in a population that differs from the target population of the recommendation.
C	Nonrandomized trials or observational studies	Evidence is from outcomes of uncontrolled or nonrandomized trials or from observational studies
D	Panel consensus judgment	Expert judgment is based on the panel's synthesis of evidence from experimental research described in the literature and/or derived from the consensus of panel members based on clinical experience or knowledge that does not meet the above-listed criteria. This category is used only in cases where the provision of some guidance was deemed valuable but an adequately compelling clinical literature addressing the subject of the recommendation was deemed insufficient to justify placement in one of the other categories (A through C).

Source: National Institutes of Health and National Heart, Lung, and Blood Institute. (1998). Clinical guidelines on the identification, evaluation, and treatment of overweight and obesity in adults: the Evidence Report. *Obes Res*, 6 (Suppl 2), 5, 51–209S.

review of title and abstract. Full-text articles for the remaining 102 citations were reviewed, of which 38 articles did not satisfy the inclusion criteria and were excluded. Thus, 64 studies published since 1990 were included in the review (Fig. 1). Of these, only a relatively small number of studies have included measures of brain structure and function (n = 22). This smaller number is perhaps not surprising given that the first neuroimaging investigation into the association of childhood fitness with brain function and cognition occurred only one decade ago (83). This section will describe the benefits observed in the literature that has examined the following question: Among children age 5–13 yr, does PA and physical fitness influence cognition, learning, and brain structure/function?

Research examining the relationship among PA or aerobic fitness and cognitive performance, learning, brain structure, and brain function includes studies testing the relationship among PA participation and/or fitness using cross-sectional (n = 25), longitudinal (n = 4), and cohort (n = 3) designs, studies testing the effects of a single session of PA (i.e., acute, n = 16), or RCT (n = 16) testing the effects of a chronic PA program.

PA, Fitness, Cognition, and Learning

A detailed description of studies examining the relationship among PA or aerobic fitness and cognitive performance/learning is included in Table 2 (see Online Content, Table 2: Studies examining the relationship between PA or aerobic fitness and cognitive performance, http://links.lww.com/MSS/A659).

Cross-sectional studies. Results from the 11 cross-sectional studies generally support beneficial relationships among PA or aerobic fitness and cognitive performance with significant positive relationships being reported in all of the studies except two (26,114) in which nonsignificant trends for a positive relationship were described. The sample size in these studies has ranged from 24 to 224 children among the ages of 6 and 13 yr (with a mean age of 9 or 10 yr in 75% of the studies). Fitness has most often been measured using a shuttle-run task (often the PACER) (7,16,82,83,90,139,140) or a graded exercise test (24–27,29,50,60,95,128–130,160,166). In addition to the large number of studies assessing fitness, there is one study that assessed PA objectively using accelerometry (147) and one study that assessed sport participation in addition to their measure of fitness (7). With regard to the statistical analyses, fitness or activity has been either maintained as a continuous variable (7,16,50,60,90, 95,117,139,140,147) or used to categorize participants as low or high fit, with this judgment typically based on normative PACER data (82,83) or normative $\dot{V}O_{2max}$ data (24–27, 29,128–130,160,166), or participants have been identified as athletes or nonathletes (7). When researchers have categorized participants as low or high fit, the average difference in $\dot{V}O_{2max}$ among the groups is 14.75 $mL \cdot kg^{-1} min^{-1}$ (SD = 4.76,

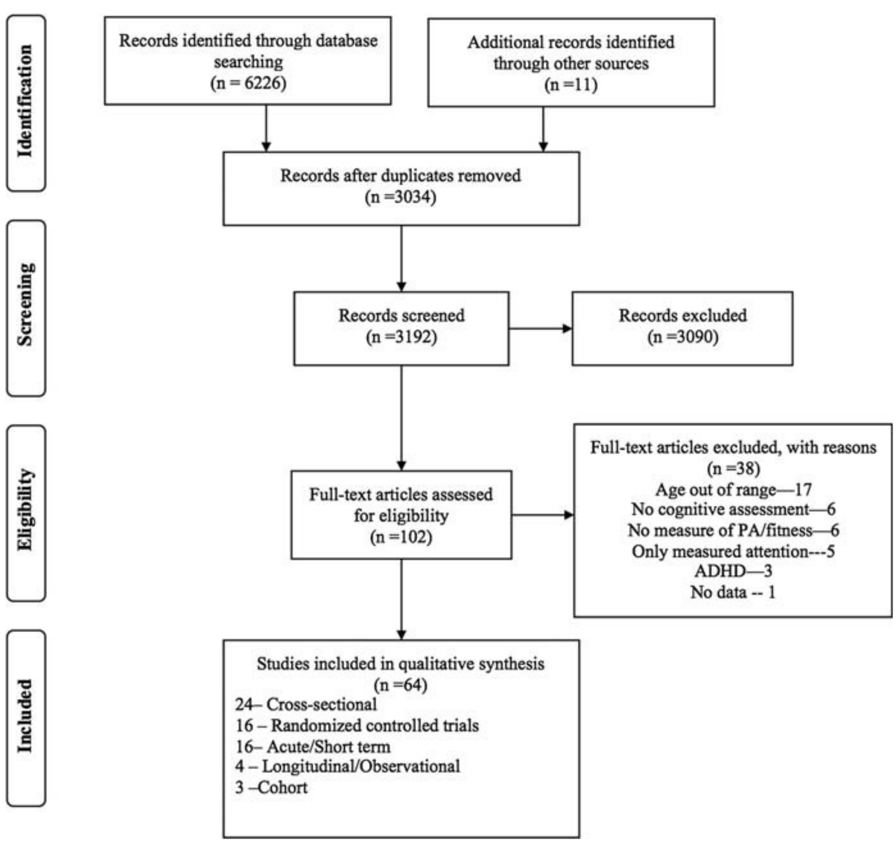

FIGURE 1—Cognition search flow diagram using PRISMA guidelines.

n = 13), and the average difference in the number of laps in a shuttle run task is 18.40 laps (SD = 0.28, n = 2), indicating that there are substantial fitness differences among the groups.

These studies have included behavioral measures of cognitive performance in isolation (7,16,27,29,50,60,90,95,114,129,130,139,140,147,166) or in combination with measures of brain function (82,83,117,128,160,167) or brain structure (24–26). In studies that include only behavioral measures of cognitive performance, a wide variety of cognitive outcomes have been assessed, including processing speed (7,114,166), EF (16,50,129,139,140,147,166), memory (27,60,114,130), learning (130), attention (16,50,95,114,147), crystallized and fluid intelligence, and a novel street crossing/virtual reality task (29). In studies that also incorporated measures of brain function, their use has been almost exclusively during tasks that measure EF with a particular focus on inhibition (25,26,82,117,128,160), which is particularly well suited for the inclusion of assessments of event-related brain potentials (ERP; electroencephalographic measures that reflect neural activity in response to, or in preparation for a stimulus or response).

Most of the studies in this area present their findings after consideration of potential confounding variables that may have offered competing explanations for the results because of their relationship to fitness and cognitive performance. These potential confounders included sex, pubertal stage, socioeconomic status (SES), percent body fat, BMI, age, grade, and IQ. In particular, in studies comparing high-fit and low-fit groups, potential confounding variables were assessed, and either 1) data were reported to confirm that the two fitness groups were statistically equivalent on these variables or that the potential confounders were not predictive of cognitive performance (24–26,83,128–130,160,166) or 2) potential confounders were included as covariates in the analyses (27,82,117). In studies testing fitness as a continuous variable (16,50,60,90,117,139,140,147), potential confounders were consistently considered and statistically controlled, and positive relationships were observed between fitness and cognitive performance in seven of the eight studies. Specific findings were as follows: Buck et al. (16) statistically controlled for age, BMI, and IQ and reported that fitness was predictive of cognitive performance as assessed with the Stroop color, word, and color–word tasks; Jacob et al. (90) controlled for sex and BMI and found that fitness was predictive of comprehension and block design performance; Davis and Cooper (50) controlled for race, gender, and education level of the primary caregiver and reported that fitness was predictive of planning scores on the CAS; and Scudder et al. reported that fitness predicted reaction time on the flanker task (139,140) and performance on the spatial n-back (a measure of working memory) (140) after controlling for grade, sex, household income, and BMI. Drollette et al. (60) consistently found that girls preformed poorer on measures of working memory as compared with boys when controlling for SES and fitness in three distinct data sets. Syväoja et al. (147) controlled for gender, parental education, and remedial education and demonstrated that moderate-to-vigorous PA has a positive association with attention. These studies suggest that fitness and PA are correlated with cognitive outcomes independent of most confounders.

Although this body of literature is only able to provide correlational evidence, researchers using this design have generally taken precautions to control for potential confounders, hence lending additional credibility to their findings indicating that children with higher levels of fitness display significantly better cognitive performance compared with children with lower levels of fitness. The same association is true for those individuals that participate in higher levels of PA. Even with the inclusion of confounding variables, the directionality of these associations (i.e., that fitness influences cognition, but not *vice versa*) cannot be determined. Weaknesses in these studies according to Downs and Black criteria include lack of information about the following: estimates of random variability in the outcome data (22 of 26 studies, 84%), actual probability values (4 of 26 studies, 15%), participants who were lost/excluded from the analysis (2 of 26 studies, 8%), or power (26 of 26 studies, 100%). Adjustments for confounding were not adequate (especially SES) or could not be determined in 6 (23%) of 26 of the studies. The primary outcome measures were not clearly described (e.g., researchers only reported significant values) in 4 (16%) of the 26 studies. Information about the time of day at which the cognitive measures were assessed was not provided in 22 (85%) of the 26 studies.

Longitudinal studies. Two longitudinal studies met the inclusion criteria and had sample sizes 32 and 245 with a mean participant age of 10 and 5 yr, respectively (28,121). The time during which participants were followed was 9 months (121) and 1 yr (28). The two studies evaluated baseline measures of fitness (measured by graded exercise test (28) or a shuttle test (121) and changes in flanker task performance (28) or spatial working memory and attention (121).

Researchers exploring the benefits of PA for older adults have frequently used longitudinal studies to enhance our understanding of the potential protective effects against age-related cognitive decline, mild cognitive impairment, and dementia (see [49,77,143] for reviews). However, in the literature with children, only two prospective studies have been published that report on the changes in cognitive performance observed over time relative to baseline measures of aerobic fitness. Chaddock et al. (28) categorized children as high (>70th percentile) or low (<30th percentile) fit based on their $\dot{V}O_{2max}$ and normative data at baseline and examined flanker task performance at baseline and 1 yr later. At both time points, high-fit children were able to perform accurately on both compatible and incompatible task components as compared with the low-fit children who performed worse on the incompatible task component relative to the compatible task component. In addition, reaction time data showed an interaction of fitness and time, indicating that low-fit children performed the task more slowly at the 1-yr follow-up as compared with baseline, whereas the high-fit children became faster over this same time period. The two fitness groups were not statistically different on relevant demographic variables that might potentially confound the results. Niederer et al. (121) presented data from 245 preschool children (M = 5.2 yr) who were in the control condition in a larger RCT and showed that higher levels of baseline fitness were predictive of improvements in performance on an attention task 9 months later after controlling for potential confounding variables; however, baseline fitness was not predictive of spatial working memory performance. Overall, these longitudinal studies indicate that higher fitness is associated with better cognitive performance across time.

Weaknesses in these studies according to Downs and Black criteria include lack of information about the following: whether results were obtained by data dredging (one of two studies, 50%), the length of follow-up being similar for all participants (two of two studies, 50%), blinding of those measuring primary outcomes (two of two studies, 100%), or power (two of two studies, 100%). Adjustment for confounding was not adequate in one (50%) of two of the studies. Information about the time of day at which the cognitive measures were assessed was not provided in either of the studies.

Acute PA studies. Studies exploring the effects of acute PA on cognitive task performance have been conducted in both laboratory (n = 8) and school (n = 8) settings. Sample sizes have ranged from 20 to 1274, with students ranging in age from 6 to 13 yr. Findings from studies conducted in laboratory settings (n = 9) are mixed, with three failing to definitively support (45,62,151) and six supporting (11,31,61,66,85,159) beneficial effects on tasks that measure both speed and accuracy. All of the studies supporting beneficial effects used a version of the flankers test or a measure of choice reaction time for their cognitive measure. However, the nature of the observed benefits was mixed, with two studies showing benefits for speed (66,159), three for accuracy (33,61,85), and one with no benefits to speed or accuracy but an increase in the efficiency (i.e., decreased interference) of responses (11). It is difficult to explain why the observed benefits are different given that these studies have tended to use relatively similar designs (participants typically completing 15–30 min of aerobic PA at moderate intensity of ~60%–70% heart rate max) and measures (simple and choice reaction time, flanker tasks). It is possible that these mixed findings reflect differences in the participants' cognitive strategies; however, future research will be necessary to confirm this possible explanation. Regardless of the inconsistencies across study results, the overall findings support a beneficial relationship between acute PA and cognitive performance.

The results from studies conducted in school settings are more consistent, with eight studies yielding significant positive results. Researchers have remained focused on moderate-intensity PA but used a broader range of PA durations (~4–42 min) and more varied approaches in PA mode (e.g., standard PE classes [126], team games [124], EF specific games and activities [91], aerobic circuit training [81,124], running tasks [33,44,68], and short activity breaks [109]). These researchers have also focused on a more diverse array of cognitive domains, including measures of EF (e.g., working memory and inhibition), attention, memory, and learning. The findings in some of these studies were similar to the laboratory studies in that they demonstrated task specificity. For example, Cooper et al. (44) found that acute PA benefited speed of performance on a working memory task but had no effect on the Stroop test, which measures EF, attention, and processing speed. Together with the evidence from laboratory studies, these findings suggest that the benefits of acute PA may be task specific, and some evidence indicates that benefits are more consistently observed on measures that reflect higher order EF functions.

Weaknesses in these acute studies as determined by the Downs and Black checklist criteria include lack of reporting of the following items: participant characteristics (7 of 16 studies, 43%), random variability in the main outcome data (7 of 16 studies, 43%), blinding of those measuring the main outcomes (15 of 16 studies, 93%), adequate adjustment for confounding in the analyses from which the main findings were drawn (8 of 16 studies, 50%), and power (14 of 16 studies, 87%). Authors did not report the time of day that measures were conducted or the precise acute intervention performed in 5 (31%) of the 16 studies.

In sum, research exploring the effects of acute PA on cognitive performance by children is limited, and the variability in methods makes it challenging to synthesize the results. Further, given the small overall effect size reported for children ages 6–13 yr in a recent meta-analytic review of the literature on acute PA and cognitive performance [Hedge's g = 0.36], it is not surprising that findings of individual empirical studies are heterogeneous (142). That being said, there was no evidence of deleterious effects, and in fact, evidence does show that beneficial effects can be observed for particular cognitive tasks under specific conditions and hence warrants future efforts to better understand how to maximize benefits from single sessions of PA.

PA intervention studies. Fourteen intervention studies met the inclusion criteria for the review, three of which used cohort designs to examine the effect of PA on intact groups (e.g., schools, preexisting study arm, and nonrandomized) and 11 of which were RCT designs.

Cohort studies. Of the three studies conducted using cohort designs, all showed some support for cognitive benefits associated with greater or enhanced activity levels, where better performance was associated with greater participation in PA. Sample sizes ranged from 60 to 470, and the mean age of the participants ranged from 6 to 10 yr. The length of the intervention ranged from 10 wk to one school year. Interventions included enhanced (47,71) or additional PE (134). Cognitive measures included the random number generation task (47), a perceptual speed task (134), the CAS (71), the Cambridge Neuropsychological Test Battery (CANTAB) (71), and the Attention Network Test (ANT) (71).

The two studies that examined enhanced PE provided evidence for specific benefits that may be dependent on body weight and the specific cognitive domain being assessed. Crova et al. (47) compared changes in performance on two scores from the random number generation task between classes that were randomly assigned to a traditional PE program that met one time per week or to an enhanced PE program that received an additional 2 h of skill training per week. Results showed that improvements in inhibition were moderated by weight status, such that overweight children in the enhanced PE program improved significantly whereas overweight children in the traditional PE program and lean children in both programs did not experience significant gains in performance. Fisher et al. (71) randomly assigned six schools to receive two 1-h sessions of traditional PE per week (control) or two 1-h sessions of more aerobically active PE per week (treatment) for 10 wk and examined the effect on the CAS, the CANTAB, and the Attention Network Test. Results of this study are difficult to interpret because there were only minimal differences in minutes spent in moderate-to-vigorous PA among the groups. However, the results showed a significant interaction of group and time after adjustment for confounding variables, such that participants in the treatment condition had a significant decrease in working memory errors on the CANTAB whereas those in the control group had no change in performance. On all other measures, the interaction was not significant after controlling for confounding variables.

Reed et al. (134) examined additional PE by comparing performance on cognitive measures from the beginning (pretest) to the end (posttest) of a school year; students at an experimental school received 45 min of daily PE for the entire year, whereas students in control schools received either 45 min of daily PE for one semester (middle school) or 45 min of PE 1 $d \cdot wk^{-1}$ for the entire year (elementary school). Results were reported separately for boys and girls, for elementary and middle school ages, and for fluid intelligence and perceptual speed (elementary school only). Boys in the experimental elementary and middle schools improved significantly on fluid intelligence measures, whereas boys in the control schools did not significantly improve on these measures. Girls in the experimental middle school also demonstrated significant improvements in fluid intelligence, and these gains were larger than the gains for girls in the control school. However, no gains in fluid intelligence were observed for girls in the experimental elementary school. Conversely, on a perceptual speed task, girls in the experimental elementary school improved significantly on all sections whereas control participants showed no change, and boys in both the control and the experimental elementary school improved with no differences among the groups.

Clearly, the focus of these cohort studies has been on understanding how increases in the volume or nature of PE classes affect changes in cognitive performance. This small body of literature provides limited evidence supporting that greater volume or enhanced forms of PA result in greater cognitive improvements. Although beneficial effects were limited to particular cognitive domains and were sometimes only seen in particular subgroups, it is important to point out that none of the studies demonstrated deleterious effects of PE on cognition. That being said, enthusiasm for these results is limited by the threats to validity inherent in their quasi-experimental design.

RCT. The strongest evidence with regard to the effects of PA on cognitive outcomes comes from the 11 studies using RCT designs, which allow for conclusions to be drawn regarding cause and effect relationships. Relative to the question of whether chronic PA is causally linked to cognitive outcomes for children, only 10 studies have clearly satisfied the first necessary requirement of an RCT by randomly assigning individual participants to conditions (30,31,51,52,84,92,97–99,115). Multiple measures of cognition were measured in all 10 studies, and seven studies showed an improvement in at least one measure of cognition because of a PA intervention. The cognitive tests used in these 10 studies included the CAS (51,52,97–99), the Sternberg task (92), a novel relational memory task (115), and the flanker task (30,31,84). Sample sizes ranged from 18 to 221, and the length of the intervention ranged from 8 wk to 9 months. Researchers administered PA via an after-school program in nine of the studies using RCT designs (30,51,52,84,92,97–99,115), and one study reported data from a program administered during the school day (31). Two of these studies report on data from the same RCT (51,52), in which overweight children (8–11 yr) were randomly assigned to a low dose (20 min) or a high dose (40 min) of moderate-intensity PA or to an attention control condition for 8 months (hereafter referred to as the Georgia trial). Four studies report on data from the FITKids trial (30,84,92,115), in which 221 children (age 7–9 yr) were randomly assigned to an after-school PA condition (2 $h \cdot d^{-1}$, 5 $d \cdot wk^{-1}$) or a waitlist control during the 9-month school year. Three studies provide evidence relative to the SMART trial (97–99), an 8-month trial in which overweight children (8–11 yr) were randomly assigned to an aerobic PA program or to an attention control condition for 8 months. Overall, the results of studies using RCT designs have consistently demonstrated significant improvements in the treatment groups, particularly for EF tasks.

In the studies reporting on data from the Georgia trial, performance on cognitive tasks was presented in one study for the first three cohorts (51) and in another for the entire sample of five cohorts (52). Results from the entire sample (n = 170) showed that there was a significant benefit of PA to performance on the planning (i.e., EF) task, but effects were not observed for measures of attention, simultaneous processing, or successive processing. Further, there was significant support for a dose–response relationship between the amount of PA and the performance on the measure of planning.

Several studies report on cognitive outcomes assessed relative to the FITKids trial, including three studies using various subsets of the larger sample. Relative to these manuscripts using subsets from the FITKids trials, Kamijo et al. (92) observed significant improvements in response accuracy for the PA group (n = 20) but not the waitlist control group (n = 16) on a measure of working memory (a modified Sternberg task). They (92) observed significant improvements in response accuracy for the PA group (n = 20) but not the waitlist control group (n = 16) on a measure of working memory (a modified Sternberg task). Similarly, Chaddock-Heyman et al. (30) reported significant gains in response speed and accuracy in the PA group for neutral trials and significant improvements in accuracy for incongruent trials on the flanker task, whereas the waitlist control group experienced no significant changes in performance from pretest to posttest. By contrast, Monti et al. (115) reported no significant differences in performance changes from pretest to posttest among groups on a relational memory task. In the study reporting on the full FITKids sample (84), children (n = 221) who received the daily PA intervention demonstrated selective improvements for EF tasks that tapped inhibition and cognitive flexibility along with significant changes in brain function (described in the following paragraph). In particular, with regard to the behavioral measures, the intervention group improved significantly more from pretest to posttest than did the waitlist control group on response accuracy for the inhibition task and for heterogeneous trials of the cognitive flexibility task. In addition, a significant dose–response relationship was observed such that greater attendance in the after-school program was associated with greater improvements in executive control from pretest to posttest function from pretest to posttest (84).

With regard to the SMART trial, cognitive performance data were also reported in studies based on subsets of the larger sample that agreed to participate in neuroimaging measures (i.e., MRI and fMRI, a neuroimaging tool that measures brain structure [MRI] or indirectly measures brain function by detecting associated changes in blood flow [fMRI]). Krafft et al. (97) reported on data from 43 participants, and Krafft et al. (98) reported on data from 18 participants. Results in both studies indicated that there were no significant interactions of group with time, suggesting that PA participation did not influence changes in cognitive performance as assessed using the CAS from pretest to posttest.

Literature Summary and Study Quality: PA, Fitness, Cognition, and Learning

There were only two studies that reported having sufficient statistical power relative to their analysis of the effects of chronic PA for cognitive performance (52,84). Importantly, results from these trials provide support for a significant effect of PA participation on select measures of cognitive performance with additional evidence of a dose–response relationship. Additional evidence supporting a causal link among PA and brain function or structure is reported in the Chang et al. (31) study and in publications related to the Georgia trial (52), the FITKids trial (30,84,92,115), and the SMART trial (97–99,137). Given that changes in brain function or structure may underlie changes in cognitive performance, this causal evidence is consistent with an expectation that PA and cognitive performance are themselves causally linked. These studies on PA and brain function and structure are described later in this manuscript. Clearly, this body of evidence is in its infancy and in need of substantial growth if firm conclusions are to be drawn regarding causal links between PA and cognitive outcomes.

Weaknesses in the intervention studies as determined by the Downs and Black checklist criteria include lack of description of the following: participant characteristics (12 of 23 studies, 52%), interventions of interest (13 of 23 studies, 59%), distributions of principal confounders in each group of subjects to be compared (16 of 23 studies, 72%), adverse events (17 of 23 studies, 74%), characteristics of patients lost to follow-up (12 of 23 studies, 52%), blinding of those measuring primary outcomes (11 of 23 studies, 48%), compliance with the interventions (16 of 23 studies, 72%), whether participants lost to follow-up were taken into account (18 of 23 studies, 78%), or power (12 of 23 studies, 52%). Adjustment for confounding was inadequate or could not be determined in 14 (60%) of 23 studies. Information about the time of day at which the cognitive measures were assessed was not provided in 12 (52%) of 23 studies.

PA, Fitness, and Brain Structure

Of studies assessing the effect of PA on the brain, investigations into the relationship of PA and aerobic fitness to brain structure has received the least amount of attention in this field to date, with only five studies found in the extant literature (see Online Content, Table 3: Studies examining the relationship between PA or aerobic fitness and brain structure, http://links.lww.com/MSS/A660). Sample sizes have ranged from 18 to 55 children between the ages of 8 and 11 yr. Of these studies, three used cross-sectional designs (24–26) and two were randomized controlled pilot investigations using subsets of children from the larger intervention (99,137). Accordingly, the evidence base is in desperate need of growth to improve our understanding of the relationship of PA to neural architecture during child development. However, the five studies conducted thus far provide a sound basis on which the field can expand, based on study designs that have demonstrated selective benefits to neural structures that support specific aspects of cognition.

Cross-sectional studies. Cross-sectional studies have investigated neural architecture by calculating the volume of specific structures within the brain. To date, two unique cross-sectional studies have investigated the relationship of aerobic fitness to subcortical structures that are critical for learning and memory. In particular, Chaddock et al. (25,26) used structural MRI (i.e., a neuroimaging approach to discriminate between gray matter, white matter, and cerebral spinal fluid in the brain) and observed that specific regions of the basal ganglia (i.e., regions of the dorsal striatum: caudate nucleus, putamen, globus pallidus), which support EF, are larger in higher-fit relative to lower-fit children age 9 to 10 yr. However, other regions of the basal ganglia (i.e., nucleus accumbens), which support affect and reward, do not demonstrate similar fitness-related differences, suggesting that the relationship of fitness is selective to specific structures within the basal ganglia, rather than generalized throughout these subcortical structures. Interestingly, higher-fit children exhibited better behavioral performance during a task requiring the modulation of EF, and these fitness performance findings were mediated by basal ganglia volume. Accordingly, the findings provided initial support that fitness is related to the volume of specific subcortical structures within the striatum, which support behavioral interactions during tasks that require the modulation of EF (26).

Additional research by the same group (24) demonstrated the relationship of aerobic fitness to the hippocampus (i.e., a subcortical structure that is part of the limbic system and supports learning and memory) and relational memory in children age 9–10 yr. Relational memory refers to the ability to bind arbitrary items into cohesive entities and form lasting memories of these new associations (39). Chaddock et al. (24) observed that hippocampal volume was greater in higher-fit children, and further that hippocampal volume mediated the relationship between fitness and relational memory performance. Such findings suggest that greater aerobic fitness may have a selective and disproportionate influence on cognitive functions supported by specific subcortical structures, rather than a more global influence on brain structure and cognition.

PA intervention studies. Further evidence of the effects of PA on brain structure stems from two randomized controlled pilot studies (98,137). These studies were conducted using subsamples from the SMART study that used diffusion tensor imaging, which is an MRI technique that affords in vivo characterization of white matter microstructure based on the properties of diffusion. In particular, in addition to the cognitive outcomes noted previously, Krafft et al. (98,137) used diffusion tensor imaging to investigate structural integrity (i.e., axonal membrane structure, myelination) of the uncinate fasciculus, which is a white matter tract connecting the frontal and temporal cortices with projections between the hippocampus and the amygdala and with the prefrontral cortex and the superior longitudinal fasciculus, which is a white matter tract connecting the frontal and parietal cortices to form part of the EF network. It was found that children randomized to the PA intervention demonstrated greater white matter integrity in the uncinate fasciculus from baseline to posttest compared with children assigned to the attentional control group (137). With respect to the superior longitudinal fasciculus, the initial analysis failed to demonstrate a differential effect of PA participation on white matter integrity from baseline to posttest; however, an effect emerged when attendance in the after-school program was considered. In particular, children randomized to the PA intervention demonstrated increased white matter integrity (i.e., fractional anisotropy or the degree of directionally dependent diffusion along the axon, and decreased radial diffusivity or diffusion perpendicular to axons) from baseline to posttest with greater attendance in the after-school program. No such effect was realized for the attentional control after-school program. Together, these findings suggest that PA is related to brain structure via integrity of white matter tracts that are part of the neural network supporting EF (98,137), and that such a relationship may be dependent on the amount of PA participation (i.e., attendance) during an 8-month period (98).

Literature Summary and Study Quality: PA, Fitness, and Brain Structure

Collectively, the data collected thus far point to a relationship among PA and aerobic fitness with specific brain structures that support EF and memory. Such findings, while encouraging, are preliminary but should serve to motivate future research using RCT and larger sample sizes. Weaknesses in these studies as assessed by the Downs and Black criteria include lack of reporting of the following: blinding of those measuring primary outcomes (five of five studies, 100%), whether participants lost to follow-up were taken into account (one of five studies, 20%), or power (five of five studies, 100%). Adjustment for confounding was inadequate or could not be determined in both cross-sectional studies (two of five studies, 40%). Information about the time of day at which the cognitive measures were assessed was not provided in two of five studies, or 40%.

PA, Fitness, and Brain Function

Samples in the 18 studies relating fitness and PA to brain function ranged from 22 to 221 participants and consisted of children ages 6 to 11 yr (with the mean age being 9 or 10 yr in 76% of these studies). The cognitive tasks used included a modified flanker task (26,31,61,84,85,117,128,160), an oddball task (83), an anti-saccade task (50), CAS (97,99), an attentional blink task (167), an online sentence processing task (138), an arithmetic verification task, and a modified Sternberg task. Brain function was measured with electroencephalography in 12 studies (31,61,82–85,92,116,117,128,138,167) and with fMRI in the other six studies (26,30,52,97,99,160). A cross-sectional design was used in nine studies, two used an acute design, and seven were RCT designs. In the cross-sectional studies (n = 9), fitness was assessed using either $\dot{V}O_{2max}$ tests (26,116,117,128,138,160,167) or FITNESSGRAM (82,83) (see Online Content, Table 4: Studies examining the relationship between PA or aerobic fitness and brain function, http://links.lww.com/MSS/A661).

Cross-sectional studies. Early cross-sectional work in this area first emerged 10 yr ago (83) in a study using ERP to examine differences in the deployment of attentional resources between higher- and lower-fit preadolescent children. ERP is identified from time-locked electroencephalographic activity, which assesses consistent neuroelectric responses to environmental stimuli and allows for inferences regarding cognitive processes that occur between stimulus engagement and response execution. Results from that seminal study indicated that high-fit children exhibited greater allocation of attentional resources and faster cognitive processing speed (as measured via the P3 component of the stimulus-locked ERP) along with better task performance relative to low-fit children (83). Since that time, several investigations have used cross-sectional designs to demonstrate a robust relationship between aerobic fitness and PA on aspects of the neuroelectric system during tasks involving attention (167), inhibition/interference control (82,117,128), cognitive flexibility (128), conflict monitoring/error detection (128), and language (138) and mathematical (116) processing. In addition, robust observations of the transient effects of single bouts of PA on the neuroelectric system have also been noted in preadolescent children, with findings demonstrating short-term benefits to cognitive processes reflected in the P3 component (61,82,127), which is often associated with the allocation of attentional resources during the updating of working memory (127).

PA intervention studies. More recently, three publications (31,84,92) have described randomized trials that used ERP to understand the effects of PA interventions on preadolescent brain function and cognition. The findings from two of these studies indicated significantly improved brain function (i.e., the P3–ERP component) and behavioral performance after the FITKids intervention (84,92). Importantly, these effects were selective to aspects of cognition that required extensive amounts of EF, with no changes observed for task components requiring lesser amounts of EF. In addition, the benefits of the PA intervention followed a dose–response relationship, as higher attendance rate was associated with larger changes in neural indices of attention allocation (i.e., P3 amplitude), faster cognitive processing speed (i.e., P3 latency), and improved behavioral performance during the EF tasks. Because significant differences were not observed for children randomized to the waitlist control, the findings indicated that a daily PA program enhances brain function underlying EF.

Additional support for the effects of PA and aerobic fitness on neuroelectric indices of EF comes from two other studies with preadolescent children, which have reported beneficial effects of PA interventions on brain function and have extended the field to include neuroelectric indices of working memory and attentional inhibition using a coordinative PA intervention (31). However, it should be noted that the Chang et al. study failed to include a control group. Despite this limitation, the study provides corroborative evidence in this developing area of research.

fMRI investigations also support the beneficial effects of PA and aerobic fitness on brain function. To date, two correlational studies (26,160) and four RCT designs (30,52,97,99) using this measure have been published. Despite a small literature base, the findings provide compelling evidence for the effects of PA and aerobic fitness on childhood brain function during EF tasks. In particular, the correlational studies used blood oxygen level-dependent fMRI to demonstrate that higher-fit children had increased recruitment and activation in frontal and parietal regions during tasks that modulated EF (26,160). That is, differences in fitness were related to differential activation of brain regions that underlie monitoring (anterior cingulate cortex) of adjustments in attentional control (middle and inferior frontal gyrus and precentral gyrus) in the presence of distracting information and response conflict (superior parietal cortex), as well as the preparation and execution of a motor response (supplementary motor area [8]). Importantly, fitness-related differences in fMRI activation were increased during task conditions requiring greater amounts of EF.

RCT designs have extended these initial correlational data and provided the necessary rigor to make suggestions about causal attributions. In particular, Chaddock-Heyman et al. (30) conducted a randomized controlled pilot study using a subset (n = 23) of 8- to 9-yr-old children from the FITKids intervention and showed decreases in fMRI activation in a region of the right anterior prefrontal cortex, along with within-group improvements in cognitive performance during task conditions requiring greater amounts of EF. Alternatively, children assigned to a waitlist control group did not demonstrate changes in brain activation from baseline to posttest. Further, at posttest, children in the FITKids intervention group exhibited no differences in anterior frontal brain activation and behavioral performance from a group of young adults (mean = 22.5 yr) who served as a reference point, given that adult cognitive capacity together with the related brain activation is often characterized as the "mature" or "optimal" model of brain function (107). At posttest, children in the waitlist control group continued to exhibit greater amounts of activation in anterior prefrontal regions and poorer performance relative to the young adults. Such findings raise the possibility that childhood participation in PA may lead to more "optimal" recruitment of prefrontal brain areas that support EF.

A second RCT included a subset of 20 children in the Georgia trial, who were assigned to either the PA intervention or the control condition (52). The results indicated that only the PA group exhibited increases in prefrontal cortex activity and decreases in parietal cortex activity from baseline to posttest during a task that modulated EF. Although performance was not reported for the subsample taking part in the fMRI portion of the study, increases in EF from baseline to posttest were observed for mathematical achievement for the full sample on a task conducted outside the MRI environment (52). Replication of these findings was published by the same group in the SMART study, demonstrating the robustness of the effect, with children receiving PA exhibiting adjustments in frontal and parietal brain activation after intervention, an effect not observed in the non-PA control group.

Literature Summary and Study Quality: PA, Fitness, and Brain Function

Overall, the findings support the benefits of daily PA on the neural network supporting EF (52,99). Also, emerging functional imaging findings have indicated that PA interventions may alter the resting state of specific neural networks (i.e., default mode, EF, motor), but not others (i.e., salience) in the absence of performing a task (97). Such findings indicate that PA interventions may improve brain function not only in response to environmental demands, but also while at rest.

Weaknesses in these studies as assessed by the Downs and Black criteria include lack of reporting about the following: adverse events (5 of 18 studies, 29%), characteristics of participants lost to follow-up (3 of 7 of RCT designs, 43%), blinding of those measuring primary outcomes (16 of 18 studies, 88%), accounting of participants lost to follow-up (4 of 18 studies, 24%), or power (17 of 18 studies, 93%). Adjustment for confounding was inadequate or could not be determined in 5 (29%) of 18 studies. Information about the time of day at which the cognitive measures were assessed was not provided in 9 (50%) of 18 studies.

Overall Summary: PA, Fitness, Cognition, Learning, and Brain Structure and Function

The purpose of this section was to answer the following question: Among children age 5–13 yr, do PA and physical fitness influence cognition, learning, brain structure, and brain function? Overall, the studies in which the relations among PA, cognition, brain structure, and brain function were examined have generally found promising results with no evidence of deleterious effects. Cross-sectional and cohort-based studies involving PA have provided positive support for the relationship between PA and cognitive function, with greater amounts or enhanced forms of PA being associated with greater improvements in cognitive function. There was only one study (130) examining the effects on learning with findings suggesting that fitness is associated with better retention. Acute PA studies also show a positive relationship between PA and cognition. Currently, there are only two published prospective studies that report on the changes in cognitive performance observed over time relative to baseline measures of aerobic fitness (28,121). Even so, these studies support a positive relationship between PA and cognitive function in elementary schoolchildren. Although only a relatively small number of studies using RCT designs exist in the literature to date, the findings are promising in that they provide a causal link among PA, cognition, and brain structure and function.

Evidence summary statement: The literature suggests that PA has a positive influence on cognitive function as well as brain structure and function; however, more research is necessary to establish causality, to determine mechanisms, and to investigate long-term effects. Therefore, based on the current information available the evidence category rating is B.

Question 2: PA, PE, Sports Programs, Academic Achievement, and Concentration/Attention

The potential benefits of PA on cognitive performance, learning, brain structure, and brain function may be the foundation upon which improvements in academic achievement are attained. The study of the associations between PA and academic success has grown exponentially in recent years, with more than 230 published articles addressing related topics among school-age children (19). The summary of extensive scientific evidence has resulted in multiple national organizations (e.g., Centers for Disease Control and Prevention, Institute of Medicine) endorsing and supporting PE and PA throughout the school day as a way to reduce health risk and possibly enhance academic achievement.

Few dispute that healthier children learn better (9), as educators and scientists alike understand the importance of physical, cognitive, and brain health among school-age children (19). Participation in PA has been associated with academic success among elementary-age children (23).

The purpose of this section is to summarize the findings of research on PA participation (including PE and sports programs), fitness, and academic success/concentration and classroom attention among elementary-age schoolchildren. The initial database search plus hand searching identified 1346 unique records, of which 1235 were excluded based on review of title and abstract. Full-text articles for the remaining 111 citations were reviewed, of which 38 articles did not satisfy the inclusion criteria and were excluded. Thus, 73 research articles published since 1990 met the inclusion criteria and were examined in this portion of the review (Fig. 2). Studies that met the inclusion criteria focused on three different areas and will be presented according to these categories: 1) the relationship between academic achievement and physical fitness (n = 27); 2) studies of PA, including the relationship between PA levels and academic achievement and the effects of participation in acute PA and PA interventions on academic achievement (n = 35); and 3) the relationship between academic achievement and PE (n = 12). Within these three topics, most of the articles that met inclusion criteria involved standardized tests of academic achievement, but seven studies were also included that used tests of attention and concentration (2,51,71,108–110,150), as the ability to attend to material presented in the classroom is a prerequisite for learning and achievement. Although studies of the effects of sports programs were a part of the search strategy and were reviewed, none met the inclusion criteria, and as such, this review does not include a section on this topic.

Other than an abundance of cross-sectional studies (n = 37), the research designs were longitudinal studies (n = 4), acute (n = 12, which measured time on task [TOT] or attention during or immediately after a single bout of PA), or

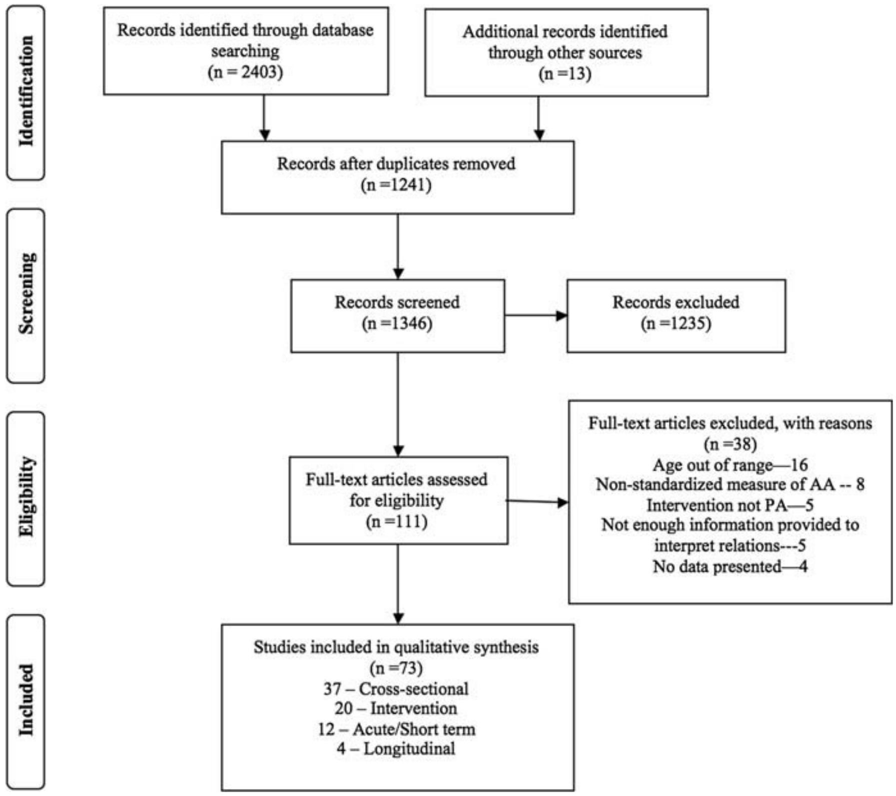

FIGURE 2—Academic Achievement search flow diagram using PRISMA guidelines.

interventional (including nonrandomized trials and RCT designs, *n* = 20).

Physical Fitness and Academic Achievement

Twenty-seven studies focused on the relationship among physical fitness and academic achievement (see Online Content, Table 5: Studies examining the relationship between physical fitness and academic achievement, http://links.lww.com/MSS/A662). The majority of the studies (*n* = 24) were cross-sectional and three were longitudinal studies.

Cross-sectional studies. The majority of the cross-sectional studies (*n* = 20) supported the positive association of physical fitness to academic success. The sample sizes among these studies ranged from 46 participants to a review of 254,743 student records, and the majority of the studies focused on children in grades 3–8. The majority of the studies (62%, *n* = 15) used the FITNESSGRAM® to assess fitness (14,20,34,36,38,42,63,65,78,131,135,158,161,163,164), and the remaining eight studies used the 1-mile run test (70), a 20-m shuttle run (54), the EUROFIT (53,162), the Presidential Youth Fitness Test (162), an 800-m run (70), or a graded exercise test (50,116,138). State or national tests were used to measure academic achievement in 57% (*n* = 12) of the studies (14,20,34,36,42,53,54,131,135,158,161–164), whereas the remaining studies used the Terra Nova (38,70), the Wide Range Achievement Test (138), the Woodcock–Johnson Test (50), the Weschler Individual Achievement Test III (78), the National Curriculum Statement (63), or tests described as standardized but that were not specifically identified (101,157).

Consistent positive associations were shown among the number of physical fitness tests passed on the FITNESSGRAM® and academic achievement scores within these studies (46). Further, several cross-sectional studies examined associations among the Healthy Fitness Zone (HFZ) designation from the FITNESSGRAM® and performance on academic achievement tests, and children in the HFZ also tended to score higher on tests of academic achievement (34,163,164). Research by van Dusen et al. (158) showed significant, positive associations between FITNESSGRAM tests and academic performance after adjustment for sociodemographic variables. Fitness was also positively related to math and reading scores in a study by Davis and Cooper (50). The majority of these studies on relations of PA and fitness with academic achievement have used linear analytic models, thereby precluding the possibility that PA and fitness could have a differing, nonlinear effect on achievement for those more or less active or fit. By contrast, Hansen et al. (78) evaluated both linear and nonlinear associations of PA and aerobic fitness with children's academic achievement among 687 second- and third-grade students and showed that fitness had a significant quadratic association with both spelling and mathematics achievement, indicating that 22–28 laps on the PACER were the point at which the associated increase in achievement per lap plateaued for spelling and mathematics.

Although the findings from the cross-sectional studies were mainly positive, the effects were sometimes unclear and inconsistent. In some studies, these relationships varied by gender (associations only significant for females [70,162]) and the subject matter of the academic achievement (significant for mathematics, but not reading [53,65,70,78] or *vice versa* [138]). One potential explanation for inconsistencies in the research on the relationship among PA, aerobic fitness, and academic achievement may be the lack of appropriate control variables such as SES. Researchers controlled for SES in only 55% of the cross-sectional studies included in this review. In addition, it is not clear if or how researchers controlled for schools in these studies, and nesting effects could have influenced the differences in results.

Weaknesses in this body of literature as determined by the Downs and Black checklist criteria include lack of information about the following: participant characteristics (10 of 24 studies, 42%), distributions of principal confounders (13 of 24 studies, 54%), and estimates of the random variability of the main outcomes (8 for 24 studies, or 33%). The main findings of the study were not clearly described in 7 (29%) of the 24 studies. Actual probability values were not reported in 13 (54%) of 24 of these studies, and none of the studies reported on blinding of those measuring the main outcomes (although preexisting data were used in 9 [38%] of the 24 studies). In 9 (38%) of the 24 studies, there was either inadequate adjustment for confounding variables in the analyses from which the main findings were drawn or there was not enough information provided to make this determination. Finally, 95% of the studies made no mention of statistical power.

Longitudinal studies. Fitness was consistently associated with academic achievement across the three longitudinal studies (106,149,165). Sample sizes across the studies ranged from 757 to 1725, and the participants involved ranged from second through seventh grade. All three studies used the FITNESSGRAM® to assess the fitness level. One study used the WESTEST (165), one used a California standardized test in math and English, and one study used tests of literacy and numeracy designed by the Australian government education authority and the Australian Curriculum, Assessment and Reporting Authority (149). The studies showed that students who increased their fitness or maintained fitness across time had higher academic achievement scores than students who did not achieve the HFZ (the gender- and age-specific fitness goals) on the physical fitness tests that are part of the FITNESSGRAM™ (106,165), and that students and schools with higher fitness levels had achieved better literacy and numeracy scores (149). Interestingly, SES has been shown to moderate the relationship between fitness and achievement; the study of London et al. (106) in fifth to seventh graders showed that more advantaged students have a greater ability to maintain higher levels of academic achievement despite lower levels of fitness, whereas less advantaged students experience an even greater level of academic disadvantage when they are also physically unfit. Telford et al. (149) concluded that associations were stronger between schools than among children in the schools, suggesting that differences in school cultures or support for fitness programming and achievement might play a more meaningful role in the associations than direct effects of fitness on academic achievement.

Overall, the findings across these longitudinal/observational studies were fairly consistent in showing that fitness was positively associated with academic achievement. However, the fitness measures used and the way that fitness test results were categorized differed across the studies. Measures of academic achievement also varied, from different standardized tests to specific scores on reading or writing. Furthermore, the way data were collected across these studies was not consistent. For example, FITNESSGRAM™ data were obtained by trained data collectors in some studies, but in others, the data were collected by teachers. The small number of studies that have used a longitudinal study design makes it difficult to establish a conclusive statement, as few studies have specifically replicated the findings of previous research. Weaknesses in these longitudinal/observational studies as determined by the Downs and Black checklist criteria include lack of information about confounders (two of the three studies, or 66%), blinding (three studies, 100%), and power (three studies, 100%). The studies also lacked adjustment for confounders such as SES (two studies, 66%).

Literature Summary and Study Quality: Physical Fitness and Academic Achievement

The literature that has examined the relationship between physical fitness and academic achievement in children demonstrates largely positive findings. However, there were inconsistencies within the findings, likely because of measurement approach. These studies had further limitations with regard to study quality and reporting. Many of the cross-sectional studies did not provide adequate information about participants and did not include exact statistical values or information about variability in the data. Further, large portions of both the cross-sectional and the longitudinal studies did not adjust for important confounders such as SES, which has been shown to both predict academic achievement and moderate the relationship between fitness and achievement. Hence, the failure to include appropriate moderators is a critical shortcoming of this literature.

PA and Academic Achievement

The relationship between PA and academic achievement was examined in 32 studies using the following approaches: 1) cross-sectional comparisons of academic achievement scores among students with different PA levels (n = 10); 2) investigation of the effects of single, acute bout of PA on tests of academic achievement, attention, or concentration (n = 8); and 3) examination of academic achievement scores after implementation of a PA intervention (n = 14; see Online Content,

Table 6: Studies examining the relationship between PA and academic achievement, http://links.lww.com/MSS/A663).

Cross-sectional studies. The findings from 10 cross-sectional comparisons of PA and academic achievement are varied, with four studies that showed positive relations (15,118,146,168), three studies that showed positive relations in some academic areas but not others (79,102,122), two studies that showed no relationship (48,103), and one study that showed a negative relationship (154). Sample sizes in these studies ranged from 55 to 4755 children ranging from kindergarteners to fifth graders. PA was measured by accelerometry (15,79,102,103) or by questionnaires administered to students (118,122,154,168), parents (146), teachers (48), or school administrators (146). The majority of the studies used government-mandated standardized tests (15,79,103,118,122,154). Other studies used cognitive assessment (48), the Wechsler Individual Achievement Test III, a latent variable created using standardized math and reading scores (146), or examination results from a test administered to elementary students in Hong Kong (168).

The four cross-sectional studies that found only positive associations between all measured PA and academic achievement variables varied widely in design. In a large nationally representative sample of grade-schoolchildren (15) that used an objective measure of PA (accelerometer) and controlled for SES factors, higher PA levels were associated with higher attainment on tests of English, math, and science. Stevens et al. (146) also controlled for SES factors but assessed PA via a questionnaire administered to parents, and they found that higher PA levels were associated with higher math and reading scores in children from grades K–5. The other two studies both administered a PA questionnaire to the students and did not control for SES; one (118) showed positive relations among extracurricular PA, math, and oral skills in 9- to 12-yr-olds, and the other showed positive relations among habitual PA and achievement scores in 8- to-12-yr-olds, although the academic areas tested were not specified in the study.

Of the three studies that found positive relations among PA and some academic areas but not others, two showed positive relations with math but not reading (102,122) and one showed a positive relationship with reading but not math (79). O'Dea et al. (122) examined PA data (7-d accelerometer) and SES predictors of math and reading scores and found PA predicted math scores, but SES was a stronger predictor of literacy and numeracy scores. Lambourne et al. examined indirect and direct relations among PA (7-d accelerometer), fitness, and academic achievement in second and third graders and found that aerobic fitness positively moderated the relationship between PA and math achievement, but that PA was not associated with reading or spelling. By contrast, Harrington et al. (79) assessed PA via accelerometer in low-income third graders and found positive associations between the number of bouts per day of PA and reading, but no associations with math scores. On the basis of the limited findings available, it is challenging to conclude that PA has a positive influence on academic achievement, and further, it is unclear if PA improves all aspects of academic achievement or whether the effect is selective in nature.

One study that found no relationship between PA and academic achievement used correlated 3-d accelerometer data with English/language arts, math, science, and social studies scores in fourth through sixth graders. Similar to O'Dea et al. (122), SES was a stronger predictor of academic achievement than PA. Another study with a null relationship (48) collected information about kindergarteners' time spent in recess from teachers, which did not correlate with students' reading scores. Finally, Trembley et al. (154) showed a weak but negative relationship among PA measured by questionnaire and math and reading scores in sixth graders. Again, SES was a strong predictor of math and reading scores. Overall, it is difficult to draw conclusions from the cross-sectional studies performed to evaluate the relationship between academic achievement and participation in PA, as studies have found inconsistent and even contradictory results. Similar to the cross-sectional studies of fitness and academic achievement, the differences in methodology, measurements used, and control for confounders vary widely, which may account for the inconsistent results.

Weaknesses in these cross-sectional studies as determined by the Downs and Black checklist criteria include lack of information about distributions of principal confounders (4 of 10, or 40% of studies), blinding of those measuring the main outcomes (10 studies, 100%), and validity and reliability information for outcome measures (5 of 10 studies, 50%). Actual probability values were reported in 5 (50%) of the 10 studies, adequate adjustment for confounding was not performed in 3 (30%) of the 10 studies (and in one it could not be determined), and there was no mention of power in 6 (60%) of the 10 studies.

Acute PA studies. Ten studies included in this review specifically examined the effects of acute bouts of PA on academic achievement or concentration/attention. Four studies examined the immediate effects of physically active lessons in the classroom (76,108–110), three studies used a within-subjects design to compare PA to rest conditions (64,85,111), and three studies examined academic achievement performance among groups assigned to different PA conditions (21,22,150). Sample sizes ranged from 20 to 177 participants who were in grades K–7. The outcome measures included TOT (76,108,110), the Wide-Range Achievement task (64,85), the Woodcock–Johnson Test of Concentration (21,22), the d2 Test of Attention (109,150), and a series of timed mathematical tests designed to measure concentration.

Immediate effects of physically active lessons in the classroom. Three of the four studies (76,108–110) that examined the effects of physically active classroom lessons on TOT showed positive results. Mahar et al. measured TOT after sedentary lessons or energizers, which are 10-min classroom-based physical activities. From pre- to postenergizers, the mean percentage of on-task behavior increased by more than 8%. Ma et al. found that off-task behavior decreased in both second and fourth graders after FUNtervals (4-min high-intensity interval exercises) when compared with a no-activity break. In a similar study, Ma et al. (109) examined the effects of FUNtervals on performance on the d2 test of attention and showed that third- to fifth-grade students made fewer errors on the d2 after FUNtervals when compared with rest. Finally, Greico et al. (76) measured TOT after a physically active academic lesson and an inactive control lesson. Although TOT decreased significantly in the inactive control lesson condition from before to after the lesson, it did not increase significantly after the active lesson.

Other school-based PA. Four school-based studies examined the effects of PA on concentration/attention, with one study that used a within-subjects design and three that used a between-subjects design (21,22,150). In the within-subjects study, McNaughten et al. (111) compared the effects of varying durations of physical exertion on concentration/attention at different times of day and showed improvements in attention after the noon hour after PA that lasted 30 and 40 min (but there were no significant differences in mathematical performance after PA of any duration when performed before noon). All three studies that used between-subjects designs examined differences in concentration/attention immediately after different PA conditions, with one finding no effect and two finding positive or mixed effects. Caterino et al. (21) administered the Woodcock–Johnson Test of Concentration to fourth graders immediately after different PA conditions (recess, classroom PA, and rest) and found no differences among conditions. In a later study, Caterino et al. (22) compared concentration scores after a sedentary classroom activity or directed PA performed in the gymnasium and found a significant improvement in concentration scores for fourth graders after PA (but no improvement after PA for second or third graders). Tine et al. (150) administered the d2 Test of Concentration to sixth through seventh graders after PA or passive (movie) condition, and students in the PA condition had higher selective attention scores than students in the movie condition. In summary, these studies provided inconsistent results (e.g., improvements in concentration in fourth graders after acute activity in one study but not another), improvements in concentration for older students (sixth through seventh graders), and differential effects of on concentration after acute PA based on the time of day.

Laboratory studies. Two laboratory-based studies used within-subjects designs to examine the effect of acute PA on academic achievement that showed positive effects on reading. Hillman et al. (85) compared a physically active condition (i.e., brisk walking on a treadmill) to an inactive condition (i.e., sitting) and found significant benefits for performance in reading but not math or spelling. Duncan and Johnson (64) compared a rest condition with cycling at both moderate and vigorous intensities and found that spelling and reading were significantly higher after moderate-intensity PA, whereas math scores were statistically significantly lower. The two laboratory-based studies reported that PA positively affects reading, whereas the results for spelling and reading differed across these studies.

In summary, the studies of acute PA interventions have mixed results, likely owing to the differences in tasks administered, the nature of the task used (i.e., the aspect of academic achievement assessed), and the PA type. Only two of the eight studies focused on achievement scores, and both agreed that acute PA had a positive effect on reading and disagreed with regard to the effect on math and spelling. Acute PA was shown to improve concentration/attention in three of the six studies that measured this construct, and an additional study found a positive effect for fourth graders only. Overall, the evidence suggests that acute PA positively affected reading but not math, and no definite conclusions can be made with regard to the effect on concentration/attention because of mixed results. The generalizability of acute studies is limited because of the small number of studies as well as small sample sizes within the studies.

Furthermore, weaknesses in acute studies as determined by the Downs and Black checklist criteria include lack of reporting of the following: participant characteristics (7 of 10 studies, or 70% of studies), distributions of principal confounders (9 of 10 studies, or 90%), information about participants lost to follow-up (6 of 10 studies, or 60%), accounting for participants who were lost to follow-up in the analysis (8 of 10 studies, or 80%), blinding of those performing outcome measurements (9 of 10 studies, or 90%), compliance to the PA intervention (7 of 10 studies, or 70%), adjustment for confounding in the analysis (10 studies, 100%), actual probability values (4 of 10 studies, or 40%), or statistical power (8 of 10 studies, 80%).

PA intervention studies. This section will describe the 14 studies that examined a PA intervention, with five studies finding clear improvements (2,32,58,72,87), three studies finding improvements in some aspects of academic achievement or some students but not others (73,119,133), and six studies finding no improvements in academic achievement after PA (3,51,52,67,93,141) (see Online Content, Table 7: Studies examining the relationship between PE and academic achievement, http://links.lww.com/MSS/A664). These studies used either a randomized controlled design (32,50,51,72,133), a cluster randomized design (3,58,67,87,93), a crossover with control design (73), or a control group comparison with no randomization (2,119,141). Sample sizes ranged from 29 to 546 participants, with participants' grade ranging from first to sixth. The duration of the interventions ranged from 8 wk to 3 yr. The interventions attempted to increase participant PA with physically active classroom lessons (58,67,87,119,133), classroom PA breaks (3,93), additional school PA (2,73,141), an after-school fitness program (51,52), or specialized programs, including a developmental movement program (72) and a yoga program delivered at school (32). Outcome measures used included government-mandated standardized tests

(3,73,87,93,133,141), the WIAT II (58), standardized reading and math speed tests, the Discovery Education Assessment (67), the Woodcock–Johnson Tests of Achievement III (52), the CAS (51), the Aptitude Test for School Beginners (72), Malin's Intelligence Scale for Indian Children (32), and the Bourdon Attention Test (2).

Physically active classroom lessons. The five studies that measured academic achievement after the implementation of physically active academic lessons reported mixed results. In a 3-yr cluster randomized trial (58), significant improvements in reading, math, spelling, and composite scores were observed from baseline to 3 yr. Erwin et al. (67) found that a 20-wk intervention to provide more than 20 $\text{min}\cdot\text{d}^{-1}$ of physically active lessons resulted in significantly higher reading fluency and mathematics scores on a validated curriculum-based measure, but no differences were seen on standardized test scores. In a 2-yr study of a school-based PA program that included physically active academic lessons (Healthier Options for Public Schoolchildren), Hollar et al. (87) found significantly higher math scores for intervention participants but no significant difference in reading. Furthermore, Reed et al. (133) integrated PA into elementary curriculum for 4 months and found significant improvements in social studies but no differences in math, language arts, or science. Mullender-Wijnsma et al. (119) compared performance on speeded tests of math and reading after 1 yr of physically active academic lessons or a control condition and showed that math and reading scores improved in third graders when compared with controls, but math scores of second graders were significantly lower than the controls. Thus, three of the four studies (58,67,87) on physically active academic lessons showed improvements in mathematics scores. A fourth study showed no effect of active lessons on math scores but did show significant improvements in social studies scores (133), and a fifth study showed improvements in third graders but not in second graders.

Classroom PA breaks. Neither of the two studies that examined the use of PA "breaks" in the classroom showed positive results on academic achievement. There were no differences in mathematics, reading, or language scores among children attending schools that received a 16-month intervention and children attending control schools (3). Similarly, no significant differences among the intervention (Activity Bursts in the Classroom or ABC for Fitness) and control groups were observed in reading or mathematics scores after an 8-month intervention.

After-school fitness program. Two published studies reported results from the same study performed by Davis et al. (51,52) on the effects of a 12-wk fitness program on academic achievement as well as attention, showing positive and no effects, respectively. One of these studies reported on the effect of the program on scores on the Woodcock–Johnson Tests of Achievement and showed the dose–response benefits of PA on mathematics achievement but no effect on reading achievement (52). The other study reported on scores on the CAS, which includes an attention scale that requires focused, selective cognitive activity, and resistance to distraction. The PA program had no effect on the scores on this subscale (51).

Additional school PA. Similar to the studies on physically active academic lessons, studies that examined additional PA throughout the day found favorable effects on mathematics achievement (2,73,141). In the Trois Rivières experiment, Shepard modified the curriculum of elementary students to incorporate one additional hour of PA per day and showed that these students scored higher on standardized math tests. However, the students in the experimental group had lower scores in English achievement. Gao et al. (73) incorporated extra PA in the school day for 1 yr using the Dance Dance Revolution program and found greater improvements in mathematics scores but not reading scores. The final study in this category (2) examined the effect of a 12-wk program that added sport activities three times per week on attention measured by the Bourdon Attention Test. Children who engaged in physical activities had 83% higher attention levels than sedentary children.

Specialized programs. Two studies examined the effect of specialized PA programs on student achievement and both showed positive effects of PA. Fredericks et al. (72) implemented an 8-wk developmental movement program and examined the effect on reading and mathematics scores on the Aptitude Test for School Beginners. The program resulted in significant improvement in both reading and mathematics scores. Chaya et al. (32) compared 12 months of yoga to regular PE classes, as the school would not allow a nonactive comparison group. Both groups experienced improvements in comprehension, mathematics, and vocabulary scores measured using Malin's Intelligence Scale for Indian Children, the Indian adaptation of the Wechsler Intelligence Scale for Children II.

Weaknesses in these intervention studies as determined by the Downs and Black checklist criteria include lack of reporting of the following: participant characteristics (8 of 14 studies, or 57% of studies), distributions of principal confounders in each group (12 of 14 studies, or 86%), estimates of the random variability in the data for the main outcomes (4 of 14, or 29%), information about participants lost to follow-up (13 of the 14 studies, or 93%), accounting for participant who were lost to follow-up in the analysis (12 of 14 studies, or 86%), blinding of those performing outcome measurements (11 of 14 studies, or 78%), and reliability of intervention compliance (10 of 14 studies, or 77%). More than half of the studies did not perform adequate adjustment for confounding in the analyses (7 of 14 studies, 50%), and 43% (6 of 14 studies) either did not randomize participants/schools or did not provide any information about randomization. The majority of the studies made no mention of power (10 of 14 studies, or 71%). Therefore, there is room for improvement in both study design and reporting in future interventions.

Literature Summary and Study Quality: PA and Academic Achievement

Overall, the studies in which interventions designed to increase participants' PA levels were implemented showed positive effects on mathematics scores, with the exception of the studies that examined classroom PA breaks. Interestingly, the positive effect of PA on mathematics scores was evident across studies as short as 8 wk to studies as long as 3 yr. Similarly, these interventions generally had a positive effect on reading, with four of the seven studies that measured reading finding a positive effect. Two of the three studies that showed no effect of PA on reading scores were studies that focused on classroom PA breaks. From this small subset of studies, it would seem that PA in the classroom has more effect when the PA is integrated into the curriculum rather than being implemented as a break from academic content, a finding that may warrant further investigation.

Many researchers have explored the relationship between participation in PA and academic achievement through cross-sectional analyses or implementation of chronic or acute PA. The results of the cross-sectional studies are mixed, with no clear patterns among the type or level of PA and specific subjects such as math, reading, or spelling or the ability to concentrate or attend to a task. Inconsistencies are also likely due to the large variation in the type of PA studied, the age of participants, the sample size, and the type of measure used to assess academic achievement or concentration/attention.

PE and Academic Achievement

Twelve studies that examined the relationship between PE and academic achievement were included in this review and used the following designs: three cross-sectional, two acute, one longitudinal, and six interventions (see Online Content, Table 6: Studies examining the relationship between PA and academic achievement, http://links.lww.com/MSS/A663). Because of the small number of studies of each design type, the Downs and Black checklist criteria were used to evaluate the quality of the PE studies together rather than by each type of design (see Literature Summary and Study Quality: PE and Academic Achievement section).

Cross-sectional studies. One of the three studies that examined cross-sectional associations between PE participation and academic achievement showed a positive relation. All three studies measured PE based on the amount of time that it was provided (e.g., time spent in PE and self-reported minutes of PE), and academic achievement was measured by state standardized tests (57,153) or standardized *t*-scores from cognitive testing for the Early Childhood Longitudinal Survey Kindergarten Class of 1998–1999 (56). One examined PE time using student self-report in two schools with 311 participants (153), one administered a survey to 117 administrators (57), and one administered a survey to teachers of grades K–5 but did not report the sample size (56). The participants ranged from kindergarten to seventh grade. The study that measured PE level by questionnaire given to administrators found no relationship among PE curriculum time and scores on a state Literacy and Numeracy Test (57), nor was any significant relationship found in a study that measured PE level by teacher questionnaire (56). In the third study (153), students who received more hours of quality PE per school year scored higher in English and language arts, but not in mathematics. It is important to note that these studies relied on subjective estimates of time spent in PE measured by survey rather than more objective observation, which might have led to inconsistencies within the results. The only study to find positive results assessed PE participation by administering a survey to students rather than teachers or administrators.

Acute PA studies. The influence of PE on attention was examined in two acute studies using within-subjects designs, neither of which found a positive effect of PE on attention. The sample sizes in these studies ranged from 39 to 96; the participants in one study were in fourth grade, and the second study did not report the age or grade of participants (132). Raviv and Low (132) administered the d2 Test of Attention before and after active or sedentary lessons and found no influence of active lessons on attention. Pirrie et al. (126) administered the CAS to fourth-grade students after a PE class or after sitting in the classroom and found that there was no difference on the attention scale between the two conditions. Overall, these studies did not provide evidence to support the notion that PE has a positive effect on concentration/attention.

Longitudinal studies. The longitudinal, observational cohort study (17) on PE and academic achievement reported positive results for girls but not boys. The study used data from the Early Childhood Longitudinal Survey Kindergarten Class of 1998–1999 and a sample of 5316 children observed for 6 yr. Higher participation in PE led to a small but significant improvement in reading and math in girls.

PA intervention studies. Overall, the intervention studies that have investigated additional or enhanced PE did not show positive results, with only two of six finding any positive effect of a PE program on achievement scores. Three studies used cluster randomized designs (71,136,148), one used a crossover design (37), one used a retrospective analysis (120), and one assigned classes to additional PA lessons or control but made no mention of randomization (144). The sample sizes in these studies ranged from 44 to 754, and the participants ranged from second to sixth grade. Four studies evaluated academic achievement and two evaluated attention as outcome measures. Academic achievement was measured by the Metropolitan Achievement Tests (136), the Terra Nova (37), the Iowa Test of Basic Skills (120), or government-mandated tests of literacy and numeracy (148); attention was measured using the CAS (71) or the d2 test of attention (144). Interventions ranged in length from 10 wk to 6 yr.

The first cluster randomized trial was project SPARK (136), which examined the effects of a 2-yr, health-related fitness PE curriculum and professional development program on reading, math, language, and composite scores starting in fourth grade. Improvements were found in reading, although there were decreases in language scores and no effects on composite or math scores. Another cluster randomized study (71) compared 10 wk of intense PE to a standard PE control group in second graders and found no significant between-group differences in attention measured by the CAS. Similarly, Telford et al. (148) randomly assigned 13 schools to a specialist-taught PE condition and 16 schools to the common-practice PE condition and followed third graders' achievement scores for 2 yr. Math scores during the 2 yr were significantly higher in the specialist-taught PE condition, but no differences were observed in reading or writing scores. Spitzer et al. (144) showed that extra PE lessons in fifth and sixth graders for 4 months did not lead to improvements in attention when compared with control. Finally, Coe et al. (37) randomized sixth graders to receive PE during the first semester or the second semester of the school year and showed that academic achievement scores on the Terra Nova were not affected by the timing of the PE class. Overall, the results of interventions that increased time spent in PE did not show a positive effect on academic achievement and attention, with the exception of a retrospective study (120) that examined secular trends in academic performance after the implementation of Healthy Kids, Smart Kids, a 6-yr school-based PA and dietary program. The standardized test scores showed an upward trend beginning the year of the program implementation, and the length of time that the intervention had been implemented significantly predicted the test scores (which increased each year of the program). However, this cannot be attributed to changes in the PE curriculum alone, as there was also a nutrition component.

Literature Summary and Study Quality: PE and Academic Achievement

Bearing in mind the limited number of PE studies that met inclusion criteria for this review, the studies that have examined relations between PE and academic achievement have generally found no association or null results. Two exceptions are 2-yr intervention studies that compared PE led by specialists to common-practice PE led by classroom teachers (136,148). However, these studies had opposing findings, with one that showed improvements in math but not reading whereas the other found the reverse. Previous reviews of the literature have concluded that interrupting academic instruction time to provide PA through PE has no positive effect on achievement but also does no harm (155). However, the limitations in these studies preclude making any inferences about the relationship between PA and academic achievement. On the whole, these studies suffer from lack of controlled designs, reliance on self-report, no measurement of intervention fidelity, and lack of control for SES.

Weaknesses in the PE studies as determined by the Downs and Black checklist criteria include lack of reporting on the following: participant characteristics (7 of 12 studies, 58%), intervention description (three of the seven intervention studies, or 43%), distributions of principal confounders (9 of 12 studies, or 75%), estimates of the random variability in the data (6 of 12 studies, or 50%), actual probability values (5 of 12 studies, or 42%), information about participants lost to follow-up (66% of relevant trials), accounting for participants who were lost to follow-up in the analysis (66%), blinding of those performing outcome measurements (12 studies, 100%), compliance to the PA intervention (85% of relevant trials), adjustment for confounding in the analysis (12 studies, 100%), actual probability values (10 of 12 studies, or 83%), randomization (38% of relevant trials), or statistical power (10 of 12 studies, 88%). The main findings were not clearly described in 4 (33%) of the 12 studies.

Overall summary: PA, Physical Fitness, PE, Academic Achievement, and Attention/Concentration

Perhaps the most striking feature for the outcomes of the studies reviewed is the mixed findings for most categories of investigation (e.g., cross-sectional and longitudinal). Although findings tend to be positive for a relationship between PA and academic achievement, not all findings were positive, and the outcomes that were positive frequently varied among studies, whether the same study design or setting was present (e.g., cross-sectional, intervention; laboratory or field). That is, some studies found positive associations between PA and math but not reading or spelling, whereas other studies found the opposite. Some studies found positive associations for PA and academic achievement for girls but not boys. In the cases where negative associations were observed, it is not clear if this is actually an adverse effect. Attention, which is thought important for learning, did not show a strong improvement from increased PA and would benefit from further investigation. Attempts to increase PA in the context of PE were generally unsuccessful. Acute laboratory studies of PA and academic achievement and classroom studies that delivered physically active lessons seem to have the most consistent positive associations for increased academic achievement. Many limitations exist in the literature and are discussed in the summary of each section.

Evidence summary statement: Overall, the literature suggests that PA and PE have a neutral effect on academic achievement. Thus, because of the limitations in the literature and the current information available, the evidence category rating is C.

DISCUSSION

Summary of Evidence

In this paper, we systematically reviewed 137 (64 cognitive function and 73 academic achievement) studies that used a variety of study designs, including cross-sectional, acute/short-term, nonrandomized, and randomized trials to address two interrelated questions: 1) Among children age 5–13 yr, are PA and physical fitness related to brain structure, brain function, cognition, and learning? 2) Among children age 5–13 yr, are fitness, PA, and PE related to standardized achievement test performance and attention/concentration? Recently, researchers have proposed that children's cognitive functions (e.g., information processing, EF, and memory) are related positively to the level of physical fitness and/or PA participation; further, these adaptations, in turn, are hypothesized to underlie academic performance (88). If supported, these findings would have important implications for educators, health professionals, and researchers. Our results can be summarized as follows.

Cognitive Function

The bulk of the research findings support the view that physical fitness, single bouts of PA, and participation in PA interventions benefit children's mental functioning. In particular, cross-sectional studies that are properly designed and use adequate controls for potential confounding variables consistently reveal that physically fit children perform better on cognitive tests than less-fit children. Further, studies that have assessed children's brain structure and function consistently show fitness-related differences. Longitudinal and cohort studies, although limited in number and quality, suggest that higher levels of fitness or increased PA are predictive of better cognitive performance. Although not uniform in methods or results, the evidence obtained from laboratory and school-based studies suggests that individual short-term bouts of PA selectively improve children's cognitive test performance, particularly when assessed in terms of speed and accuracy. Further, in several well-designed experiments, children's cognitive test performance was accompanied by *a priori*–predicted changes of brain function (e.g., electroencephalography and fMRI). Few RCT designs have been conducted; however, when reviewed closely, they reveal that regular PA affects children's performance on specific mental tasks and modifies brain structure and function. Further, there is some evidence for a dose–response effect relation, with better cognitive performance as a function of the length of PA sessions and the frequency of attendance.

These conclusions should be cautiously interpreted as they are based on both data from cross-sectional, acute/short-term, nonrandomized trials and from randomized trials with a high risk of one or more forms of bias. With few exceptions (e.g., [52,84]), many of the studies conducted thus far used small samples or correlational methodologies that cannot provide evidence on causation. As for brain structure, the field has only begun to scratch the surface in understanding effects of PA because of the small number of neural structures and networks investigated thus far.

Future research: cognition/brain. Relative to brain function, future research should provide proper control groups, as several studies included no-contact controls (e.g., [52,84]) or failed to include a proper control group (e.g., [31]). In addition, properly powered sample sizes are needed to move many of the findings from randomized pilot studies to fully powered RCT. These strategies are necessary for the field to advance in a manner that can inform public health. Lastly, future research must continue to aid our understanding of PA and aerobic fitness effects on brain structure and function using the most recent innovations in neuroimaging to gain a more complete understanding of the effects of PA on the entire brain rather than on isolated brain regions. Early attempts on this front have been made (97), and future research will need to follow-up on these interesting findings. Although brain structure and function data are intriguing, our understanding of the relationship of PA and aerobic fitness to childhood brain structure and function remains incomplete at this time.

Academic Achievement

PA-related changes in children's brain function and cognition (e.g., attention, information processing, EF, and memory) have been implicated as cornerstones for gains in academic performance. Improvements in these processes, which are observed under laboratory conditions, are hypothesized to transfer to school and classroom conditions. Although favorable results have been obtained from cross-sectional and longitudinal studies, the results obtained from controlled experiments evaluating the benefits of PA on academic performance are mixed. The lack of clear and consistent findings may be due to a variety of reasons. Analyses of cross-sectional data often fail to take into account the role of such moderators as SES, family roles, age, psychosocial variables, nutritional habits, and home environment. Problematic is that the measures of academic performance varied considerably across studies, using several different standardized tests of academic achievement. Given that regular PA may result in specific, as opposed to global, effects on children's cognitive function, it is plausible that the methods of measuring academic performance may explain the lack of agreement among studies. Indeed, the results of studies using standardized tests that focus on specific aspects of performance tend to be more informative than tests that are more global in nature. Many of the test items that comprise standardized tests of academic performance benefit from processing speed and rapid decision making, which are processes shown to be related to physical fitness and regular PA.

The wide variation in PA interventions also may help explain the ambiguity among the results of studies and controlled experiments reviewed here. PA interventions differed considerably, with some researchers focusing on methods intentionally designed to improve cardiorespiratory function and others who used cognitively demanding skill-based games. Besides differences in the types of PA used, such factors as frequency, intensity, and duration also varied considerably across the studies reviewed, which limited the conclusions drawn.

Future research: academics. There is little doubt that PA benefits children's health and well-being, and the studies reviewed here suggest that it has a positive effect on cognitive functioning; however, the supposition that participation in PA will favorably affect the way that children think and learn in school settings has yet to be validated. Theory-based efficacy research, which identifies conditions that best promote improvements in children's cognitive functioning, and effectiveness research, which evaluates the success of specific types of interventions in authentic school environments, are needed. Progress in these areas of research will benefit from the consistent selection of reliable and valid measures of PA and academic achievement. Additional RCT designs will contribute to our understanding of both the relationship and the necessary dose of PA to improve academic achievement.

Limitations in the Available Literature

The literature on PA, fitness, cognitive function, and academic achievement has grown rapidly; however, relative to other fields of scientific inquiry, it may be considered in its infancy. Existing literature is difficult to interpret because of the myriad methodologies used and outcomes measured. Even when studies do have similar methodologies and outcome measures, findings frequently differ. For example, similar studies may differ in their findings for reaction time or other task performance measures. Studies of brain structure and function are limited by time constraints and expense (i.e., fMRI).

In a similar fashion, studies that include measures of academic achievement may find associations for PA or fitness for math and reading, and a similar study may find associations for spelling and science but not math and reading. Although most studies provide design information for intended dose of PA, measures of fidelity for PA delivered are frequently absent or inadequately described. There is also no abundance of RCT designs, as most of the literature is cross-sectional or observational. Few studies are adequately powered, participant characteristics are lacking, blinding for outcome measures is rarely discussed, and proximity of PA to measurement outcomes is infrequently described. Many studies did not account for known confounders such as BMI and SES. Many studies were ranked as being at high risk for bias because of exhibiting multiple design limitations.

Future research suggestions to address specific limitations. The challenges present within the currently available research help provide clear pathways for future research. In particular, future research is needed to clearly establish the links among PA, cognition/brain/learning, and academic achievement. It is critical for future research to expand our understanding of mechanisms responsible for observed effects of PA on cognitive outcomes. The identification of mechanisms will help us to dramatically advance our appreciation for how to prescribe PA to optimally benefit cognition. In particular, we are sorely limited in our ability to provide specific direction with regard to the mode, duration, frequency, and intensity of exercise necessary to provide meaningful benefits for cognition.

An additional limitation is that we do not have a clear understanding of possible synergistic relationships among PA and cognition/brain/learning and academic achievement. For instance, how do changes in PA affect EF, and do improvements in EF then affect PA behavior? In the future, researchers may explore whether the pathways underlying the relationship of PA to improved cognition and academic achievement is unidirectional or the extent to which cognitive skills can influence PA behaviors.

Researchers also need to clearly establish which tests, both cognitive and academic alike, are influenced by PA, PE, and changes in fitness as the literature to date is mixed. Longitudinal research and follow-up assessments for RCT designs should be conducted to provide a better understanding of the longevity of PA effects on cognition and academic achievement. It is also important to consider consistency within measures of cognition and academic achievement as differences in findings have been noted based on assessment type, study type, and testing setting. In studies of cognition/brain/learning and academic achievement, appropriate control groups with levels of contact and social interaction similar to PA intervention groups have not typically been used; therefore, the level to which these variables have influenced study outcomes is not known and should be considered in future research. It should be noted that in many cases, several publications are produced as a result of the same study or from the same set of researchers and could potentially exaggerate or bias some of the findings presented. Therefore, more replication and additional RCT designs need to occur in order to improve the evidence available.

Finally, although the best evidence will come from RCT designs, in cases where cross-sectional data are still collected, it is recommended that researchers study the entire range of fitness and/or PA scores. Literature has indicated that when the full range of scores is analyzed/included, the effects that were previously shown when using extreme group analysis disappear (156). Therefore, it is important that future research evaluate this possibility related to PA, fitness, cognition, and academic achievement.

Limitations of This Review

Limitations exist in the available evidence included in this review, which restrict our ability to draw absolute conclusions. In addition, we did not contact authors to obtain missing data or other information.

Public Health and Policy Implications

The primary responsibility of schools is to educate students, and this is measured by various forms of academic achievement. Education to foster academic achievement traditionally occurs in a sedentary environment where the majority of learning takes place in a classroom where students sit and receive instruction.

PA and fitness may affect learning and academic achievement in a positive fashion; however, the traditional way of achieving PA and fitness in school is PE class, and this has been reduced in favor of classroom instruction and cannot compensate for the predominantly sedentary environment. New and innovative strategies are needed to provide adequate PA. Fortunately, PA can be provided in many before, during, and after school activities that do not compete for time spent on academic instruction. Furthermore, there are plausible biological models linking PA and fitness to improved cognitive control that in turn is linked to learning. Moreover, programs to increase PA at schools do not show interference with learning and academic achievement. Indeed, evidence accumulates showing predominantly positive increases in academic achievement in students that exhibit more rather than less PA. Increasing PA that is congruent with school health mandates and public policy initiatives can contribute to higher levels of PA and fitness in an effort to improve learning and academic achievement. Therefore, public policy initiatives are needed to support programs to increase PA that in turn will foster healthier children and an improved learning environment.

CONCLUSIONS

The present systematic review found evidence to suggest that there are associations among PA, fitness, cognition, and academic achievement. Improvements in EF are frequently associated with acute bouts of activity and fitness. Improvements in academic achievement are also found with acute activity. Delivery of physically active lessons generally results in improvements in academic achievement, whereas attempts to increase activity in PE do not. As previously discussed, the available literature on this topic contains numerous methodological shortcomings and inconsistencies among studies that make synthesis difficult. To advance the literature on PA, cognition, and academic achievement in elementary schoolchildren, further studies are needed that use advanced technology (e.g., fMRI and EEG) to establish the anatomical and biological models to determine the biological basis for the observed effects on cognition and academic achievement, and long-term RCT designs to determine whether increased PA has a causal role in improvement of academic achievement. Numerous elements of PA remain to be explored, such as type, amount, frequency, timing, and activity breaks versus active lessons in relation to improved cognition and academic achievement. Overall, the literature suggests that PA has a positive effect on cognition and academic achievement, whereas attempts to increase PE have a neutral effect on academic achievement. Regardless of the effects of PA and PE on cognition and academic achievement, PA is widely acknowledged to contribute to the health and physical development of children and provides opportunities for fundamental motor skill acquisition. Changes in public policy are likely needed to systematically provide incentive and direction for increasing PA in elementary schools.

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