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More than one road leads to Rome: A narrative review and meta-analysis of physical activity intervention effects on cognition in youth

Spyridoula Vazou, PhD[1] **[Assistant Professor]**, **Caterina Pesce**[2] **[Associate Professor]**, **Kimberley Lakes**[3] **[Associate Professor]**, and **Ann Smiley-Oyen**[4] **[Associate Professor]**

[1]Department of Kinesiology, Iowa State University, 237 Forker Building, Ames, IA 50011, Phone: 515-294-8677, Fax: 515-294-8740, svazou@iastate.edu

[2]Department of Health Sciences, Italian University Sport and Movement, Piazza Lauro De Bosis, 15, I − 00135 Rome, Telephone number: 0039 06 36733366, Fax number: 0039 06 36733362, caterina.pesce@uniroma4.it

[3]Pediatric Exercise and Genomics Research Center, Department of Pediatrics, School of Medicine, University of California, Irvine 101 Academy, Suite 150, Irvine, CA 92617, Direct Line: (949) 824-3009, klakes@uci.edu.

[4]Department of Kinesiology, Iowa State University, 239 Forker Building, Ames, IA 50011, Phone number: 515 294 8261, asmiley@iastate.edu

Abstract

A growing body of research indicates that physical activity (PA) positively impacts cognitive function in youth. However, not all forms of PA benefit cognition equally. The purpose of this review was to determine the effect of different types of chronic PA interventions on cognition in children and adolescents. A systematic search of electronic databases and examination of the reference lists of relevant studies resulted in the identification of 28 studies. Seven categories of PA were identified, based on all possible combinations of three types of PA (aerobic, motor skill, cognitively engaging), and four comparison groups (no treatment, academic, traditional physical education, aerobic). Effect sizes were calculated based on means and SDs at the post-test using Hedge's g formula, which includes a correction for small sample bias. Each study was only entered once in each intervention-comparator category. Full data were provided from 21 studies (28 effect sizes; n=2042 intervention; n=2002 comparison group). Overall, chronic PA interventions had a significant small-to-moderate effect on cognition (0.46). Moderate significant positive effects were identified when PA interventions were compared to no treatment (0.86) or academic content (0.57). A non-significant effect was noted when PA interventions were compared to traditional physical education (0.09) or aerobic group (0.80). However, high heterogeneity in pooled effect sizes suggests that important differences in the qualitative characteristics of the PA intervention and comparison interventions may exist. Effect sizes based on comparisons between different types of PA interventions and comparison groups are discussed

Corresponding author: Department of Kinesiology, Iowa State University, 237 Forker Building, Ames, IA 50011, Phone: 515-294-8677, Fax: 515-294-8740, svazou@iastate.edu.

in order to identify possible directions for future investigations. We conclude that chronic PA interventions have a positive impact on cognitive function in youth, but more systematic research is needed in this area.

Keywords

exercise; executive function; children; aerobic; cognitive engagement; motor skills

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In recent years, the relationship between exercise and the brain has received increasing attention, and there is a growing body of research indicating that exercise can positively impact cognitive function (Etnier & Chang, 2009; Prakash, Voss, Erickson, & Kramer, 2015). A number of studies have been conducted to examine the impact of physical activity (PA) programs on a wide range of cognitive outcomes, including information processing, executive functioning, fluid intelligence, and attention. Recent studies have brought increasing attention to the interconnection between cognitive and motor functions (e.g., van der Fels et al., 2014). Functional neuroimaging demonstrates a relationship between increased activation of the dorsolateral prefrontal cortex and the contralateral cerebellum, areas previously recognized to be independent processes associated with cognition and physical activity, respectively, illustrating the inter-relatedness of cognitive and motor functioning (see review by Diamond, 2000). Particularly the cerebellum's role in cognitive function beyond its involvement in motor control and adaptation, leading to the conception of a 'cognitive cerebellum', supports a new view on embodied cognition (Ben-Soussan, Glicksohn, & Berkovich-Ohana, 2015; Koziol et al., 2014). This view is closely linked to the emerging line of chronic exercise and cognition research focused on pathways through which qualitative, rather than quantitative physical exercise characteristics may benefit cognitive functioning (Best, 2010; Pesce, 2012).

In a review examining the relationship between exercise and executive function (EF), Best (2010) stated, "*There are at least three general pathways by which aerobic exercise may facilitate EF in children: (1) the cognitive demands inherent in the structure of goal-directed and engaging exercise, (2) the cognitive engagement required to execute complex motor movements, and (3) the physiological changes in the brain induced by aerobic exercise*" (p. 338). Several physiological mechanisms that may explain the effects of exercise on EFs include increases in neurochemicals (e.g., norepinephrine and dopamine), up-regulation of growth factors and neurotrophins (e.g., brain derived neurotrophic factor: BDNF), angiogenesis and increased cerebral blood volume, activation of the prefrontal cortex, and structural changes in the hippocampus and cerebellum (Best, 2010; Gomez-Pinilla & Hillman, 2013). However, evidence also indicates that not all forms of exercise benefit cognition equally (Diamond, 2015; Pesce & Ben-Soussan, 2016; Diamond & Lee, 2011), and that "*the degree to which the exercise requires complex, controlled, and adaptive cognition and movement may determine its impact on EF*" (Best, 2010, p. 336).

Animal studies suggest that exercise may impact cognition by improving functioning in areas of the brain associated with cognitive functioning, and further suggest that not all exercise produces the same results. For example, when compared to simple and repetitive actions, complex and random actions lead to greater neural growth in the hippocampus, cerebellum, and cerebral cortices (Carey, Bhatt, & Nagpal, 2005; Jones, Hawrylak, Klintsova, Greenough, 1998). When exercise is embedded in an engaging context, greater changes occur in the brain's learning and memory centers (Fabel & Kempermann, 2008). In one study, freewheel running promoted angiogenesis in the hippocampus of rats, but an enriched and varying environment (e.g., platforms, ropes, ladders) promoted angiogenesis in both the hippocampus and the prefrontal cortex (Ekstrand, Hellsten, & Tingstrom, 2008). Therefore, the need to consider how specific characteristics of chronic PA interventions may influence cognitive function has been voiced in the literature (Tomporowski, McCullick, Pendleton, Pesce, 2015; Pesce, & Ben-Soussan, 2016).

Importance of the Present Review and Meta-Analysis

There are at least three reasons for examining the evidence on the role of various types of chronic PA interventions in promoting children's cognitive functioning. First, in recent years, an increased interest for the effects of qualitative and not merely quantitative characteristics of PA on cognitive function has emerged (Diamond & Lee, 2011; Diamond, 2015; Diamond & Ling, 2015; Pesce, 2009; Pesce, 2012; Pesce & Ben-Soussan, 2016; Tomporowski, et al., 2015). These authors have argued that not all exercise interventions lead to significant improvements in cognitive functioning in children and have called for more research to identify which exercise interventions are most effective. Pesce and Ben-Soussan (2016) argued that it is time to move beyond a focus on simply the dose of exercise to a rigorous analysis of the qualitative aspects of PA interventions, such as cognitive, emotional, social, and motor coordination demands and their interconnected outcomes. In addition, it is important to better understand why certain PA interventions impact cognitive functioning more than others – what are the common factors across those interventions that have shown strong positive effects? Diamond (2015, p. 963) hypothesized that interventions most likely to improve EFs will be those that, *"a) train and challenge diverse motor and EF skills, b) bring joy, pride, and self-confidence, and c) provide a sense of social belonging (e.g., group or team membership)."* Thus, there has been a shift away from assuming that all PA modes lead to cognitive improvements and towards better understanding the elements of PA interventions that might reap the largest cognitive improvements.

Second, the number of chronic PA interventions investigating the role of PA on children's cognitive function has increased significantly since the last meta-analysis was published (Sibley & Etnier, 2003). There are 11 PA interventions with cognitive outcomes that have been published between 2010 and 2014, and 10 additional studies since 2015, with increased interest in the manipulation/comparison of different qualitative characteristics of PAs. The prior meta-analysis of PA studies with children combined acute and chronic interventions, and did not examine qualitative characteristics of interventions. Therefore, a more recent review and meta-analysis is needed in order to summarize this rapidly developing field of research.

Third, to date, there are no published studies that have quantified the effects of the types of PA interventions on children's cognitive functions using meta-analytic methods. The current study was conducted to fill this gap in the literature and to begin to identify the qualitative aspects or common factors shared by the most effective PA interventions, as well as provide further insight on how to further our understanding from both a basic and an applied research perspective.

Thus, the purpose of the present review was twofold: (a) to review and classify qualitatively different types of chronic PA interventions, whose effects on cognitive function have been studied in samples of children and adolescents; and (b) to meta-analytically compare the effects of different types of chronic PA interventions (i.e., aerobic PA, motor skill development programs, cognitively engaging PA) and their combinations to the effects of different comparator treatments (i.e., no treatment, academic instruction, traditional PE, aerobic exercise) on cognitive function outcomes.

Methods

Selection Criteria

Studies were identified by a combination of (a) previous reviews and meta-analyses of this literature (Barenberg, Berse, & Dutke, 2011; Best, 2010; Diamond & Lee, 2011; Diamond & Ling, 2015; Fedewa & Ahn, 2011; Keeley & Fox, 2009; Pesce, 2009, 2012; Pesce & Ben-Soussan, 2016; Sibley & Etnier, 2003; Tomporowski, et al., 2015; Verburgh, Königs, Schelder, & Oosterlaan, 2012), (b) performing literature searches of the electronic data bases of PubMed, PsycINFO, Web of Knowledge, and Scopus, using keywords including: (children, youth, adolescents) and (cognition, executive function, cognitive performance) and (exercise, PA) (c) conducting an extensive search of reference lists from obtained articles, and (d) monitoring the tables of contents of journals in exercise science, preventive medicine, and exercise psychology.

Studies were included in the review and meta-analysis if they were chronic PA intervention studies with cognitive outcomes, included a comparison group, and targeted typically developing children or adolescents. Based upon the American College of Sports Medicine (2013, p.2), PA is defined as “any bodily movement produced by the contraction of skeletal muscles that results in a substantial increase in caloric requirements over resting energy expenditure”. Cognitive outcomes were included that were direct – not proxy- indicators of information processing, inhibition, working memory, cognitive flexibility, planning, fluid intelligence, and attention (Diamond, 2013; Tomporowski et al., 2015). Chronic PA interventions were identified as PA programs that were manipulated within the study and included multiple sessions per week for an extended period of time.

Therefore, studies were excluded if (a) the intervention did not include PA (e.g., mindful breathing without any movement included), (b) the participants were adults (>18 years) or non-typically developing children, (c) the design was correlational or cross-sectional, (d) the experimental treatment consisted of a single exercise bout, (e) there was no control or comparison group, or (f) the outcome variable was academic achievement and there was no direct measure of cognitive function.

Review Process

A total of 28 studies met the inclusion criteria. Descriptive information about the participants, the type and characteristics of the intervention and control conditions, the cognitive outcomes and the results are presented in Table 1. The demographics for participants included the overall sample size and sample size per group, age and/or school grade (if reported), any specific characteristics of the sample (e.g., weight status), and the country in which the intervention was conducted.

The types of PA intervention were classified based on three conceptually different qualitative characteristics (aerobic, motor skill, cognitively engaging) that have been identified in existing literature (Best, 2010; Diamond & Lee, 2011; Diamond & Ling, 2015; Pesce, 2009, 2012; Pesce & Ben-Soussan, 2016; Tomporowski et al., 2015) and all of their combinations. Therefore, the PA interventions were assigned to one of the following seven categories, according to the main focus of the program as described by the authors: (a) aerobic, (b) motor skill, (c) cognitively engaging, (d) aerobic and motor skill, (e) motor skill and cognitively engaging, (f) aerobic and cognitively engaging, (g) aerobic, motor skill and cognitively engaging. Figure 1 includes a visual representation of the distribution of the interventions as they fit within those categories.

The comparison groups were also classified based on their content into the following categories: (a) no treatment, (b) academic, (c) traditional physical education (PE), and (d) aerobic. Notably, some of these comparison groups also included physical activity. The distinction between the comparison groups and the intervention groups was made based upon the authors' descriptions. Cognitive outcomes are presented here as reported in the studies.

Data Analyses

Of the studies included in the review, those that provided full data for the intervention and comparison group were included in the meta-analysis. Effect sizes were calculated based on means and SDs at the post-test using Hedge's g formula, which includes a correction for small sample bias. Studies were not included when means and SDs were only provided graphically as it was not possible to accurately determine the scores. Studies were not included when only a change score was reported and the posttest mean and SD were not available. Each study was only entered once in each intervention-comparator category. Because most studies employed multiple cognitive outcome measures, the average effect size of all reported outcome measures was calculated (with appropriate recoding of the algebraic sign to maintain consistency in the direction of the effect). All effect sizes were calculated so that positive effect sizes indicate better performance on cognitive outcomes in favor of the intervention group compared to the comparison group.

A pooled effect size was calculated when data from two or more studies were available, using the random effects model, which assumes variability within the sample of effect sizes. Pooled effect sizes were calculated separately for each combination of PA intervention type with each of the aforementioned comparators. Table 2 shows the effect size per study, as well as the pooled effect sizes per type of PA intervention compared to each of the comparators. In addition, pooled effect sizes for all PA categories compared to each comparator are reported.

Results of Narrative Review

Table 1 displays the characteristics of the 28 chronic PA intervention studies that were included in the review. These studies were conducted in 10 countries: USA (10 studies), Italy (4), Australia (3), Germany (3), India (2), the Netherlands (2), UK (1), South Africa (1), Taiwan (1), and Switzerland (1). The studies included typically developing children and adolescents ranging in age from 4 to 16 years, with only five studies (S2, S6, S11, S16, S21) focusing on young children (4–7.5 years). One study (S1) was focused exclusively on overweight and obese children, two studies reported the results separately for lean vs. overweight children (S8, S13), and one study reported results separately for typically vs. atypically developing children (S28). The majority of the studies were conducted within the school environment, 11 during PE (S2, S3, S5, S7, S8, S13-S15, S17, S25, S28), 10 throughout the school day, either as activity breaks or integrated with academics in or outside the classroom (S6, S16, S18–24, S27), and one during lunch recess (S26). Four studies were conducted in an after-school program (S1, S4, S11, S12), and two studies during a summer camp (S9, S10). The duration of the interventions was at least 4 weeks, except for one study (S10) that was across 7 days, but involved 300 minutes per day, as it was conducted during a full day summer camp. None of the PA intervention conditions showed a negative effect on children's cognitive outcomes. In the following sub-sections the program design and the results will be discussed based on the different types of PA interventions.

A. Aerobic.

Seven aerobic intervention programs were identified in the review (S1-S5, S21, S25) with children from ages 4 to 14 years. The aerobic programs included running, along with jump rope and games in PE. Only one study (S1) during an after-school program focused on different doses (20 min/ or 40 min/day) of aerobic exercise. The total minutes spent in the interventions ranged from 120 minutes over 4 weeks to 1,300 minutes over 13 weeks, with the frequency ranging from two to five times per week. The significant cognitive outcomes of executive processing were: (a) planning (S1); (b) creativity (S3, S5); (c) working memory and spatial memory span (S2, S4). Other cognitive outcomes positively affected by PA were: (a) attentional accuracy and spatial inattention (S2), (b) cued recalled memory (S21), and (c) mathematics fluency (S1).

B. Motor Skill.

Four studies (S4, S6–8) with a focus on motor skills were performed with children and youth ranging in age from 6 to 12 years. The intervention programs consisted of balance and coordination tasks and object control skills (S4, S6, S8) and a PE class with an emphasis on fundamental motor skills (S7). The range of the intervention dose was from 1350 minutes over 10 weeks to 5,400 minutes over 24 weeks (6 months). Results from one study (S4) showed that working memory improved, and this improvement in response to the motor skills program was larger than was observed in response to an intervention of aerobic exercise. Spatial processing, reading age, and math age (math fluency) and concentration also improved (S6, S8), and percent errors decreased on attentional tasks (S8). Results from S7 were mixed (including some positive and some negative effects) based on the gender, the age of participants and the sections of the cognitive outcomes; thus, no clear conclusions could be drawn.

C. Cognitively Engaging.

Cognitively engaging PA was examined with youth, ranging in ages from 10 to 16 years at a summer camp in two studies (S9, S10). Children engaged in PA that included mindful behavior, such as yoga, meditation, and breathing exercises, compared to either engagement in aerobic activities and weight lifting, sport skills combined with fine arts, or no treatment. The dose was either 75 minutes per day, 7 days per week for 1 month (total =2,100 minutes) (S9) or 300 minutes per day for 10 days (total = 3,000 minutes) (S10). Planning time, execution time, and number of moves as measured in the Tower of Hanoi planning test (S9), as well as spatial memory, but not verbal memory (S10) improved in the yoga group only.

D. Aerobic and Motor Skill.

Aerobic and motor skill interventions were combined in one study (S11) with young children (6–7.5 years) by comparing soccer practice at high versus low intensity in an after-school program over 8 weeks for a total of 560 minutes (Chang et al., 2013). No differences in inhibition accuracy or reaction time were found. However, as shown in another study (S12), when a PA intervention (FitKids) including PA stations and games centered on a skill theme, lasting over 9 months for a total of 3,600 minutes, was compared to no intervention, inhibition and cognitive flexibility accuracy showed a differential improvement in favor of the intervention group.

E. Motor Skill and Cognitively Engaging.

In the seven studies addressing the effects of cognitively engaging PA integrated with motor skills (S13-S19), children and youth ranged in ages from 5 to 14 years, and the duration of interventions ranged from 900 minutes over 4 months to over 6,000 minutes over 9 months. Motor skills and cognitively engaging interventions programs included: 1) enhanced PE programs with sports, such as tennis (S13), basketball, soccer games and dancing (S18, S19) that require remembering rules and constantly thinking of action plans; 2) mindful Martial Arts (S14, S15); 3) complex motor and cognitively challenging tasks (e.g., constantly changing the rules of a game; S17); or motor tasks in integration with social and emotional skills (S16).

Overweight children engaging in two hours of tennis compared to regular PE improved in inhibition (S13). For children who engaged in a Martial Arts program, cognitive, affective and physical self-regulation improved more pronouncedly than for children assigned to traditional PE. Additional improvements from engagement in Martial Arts were evident in classroom and social behavior, attention related to arithmetic (S14), parent-rated inhibitory behavioral control, as well as reaction time, in 12-year-olds (S15). Engaging in enhanced PE in which the motor tasks were complex and cognitively challenging, children improved in inhibition compared to those in a regular physical education class (S17). Combined motor skill and cognitive interventions, compared to the comparison treatment of an academic classroom, resulted in improvements in attention (S18), inattention and hyperactivity (S16), attentional accuracy (S19) and classroom behavior (S16, S18, S19).

F. Aerobic and Cognitively Engaging.

Investigations of the effect of aerobic and cognitively engaging PA (S20-S27) revealed that combined interventions were more effective than comparable time spent in the academic classroom or other cognitive-only activities. Six of the eight studies (20–25) incorporated integrated PA with classroom content ranging from 120 minutes over 4 weeks to 2,000 minutes over 20 weeks. The students practiced math and/or language arts with aerobic activities such as jumping, hopping, walking, crab walking, or skipping (S20-S24, S27). In the other two studies, the students engaged in aerobic activities with purposeful cognitive engagement such as team games with frequent rule changes (S25) or running games, circuit training, relay games with letters, rope skipping and sit-ups (S26), with the focus of the lesson being on moderate-to-vigorous PA levels. Reported are beneficial influences on several cognitive and cognition-related outcomes: math fluency (S20, S27), math and spelling (measured through cognitive tests; S22), fluid intelligence necessary for problem-solving (S23), cognitive shifting (S25), memory recall (S21), verbal working memory (S26), time-on-task in the classroom (S24), and inhibition (S26).

G. Aerobic, Motor Skill, and Cognitively Engaging.

Pesce et al. (2013, S28) tested 5 to 10 year-olds in a study in which three interventions were incorporated into PE for 1 hour per week for 6 months: 1) aerobic, motor skill, and cognitively engaging PA; 2) traditional PE taught by a specialist, and 3) traditional PE taught by a general teacher. The first intervention type was an enriched environment in which students learned complex motor and cognitively challenging tasks of moderate exercise intensity. The second intervention type emphasized variability of coordinative demands while also staying aerobically active. The results indicated that in typically developing children, receptive attention was positively impacted by the intervention that coupled cognitive enrichment with motor skill learning and moderate aerobic exercise intensity, while in children with or at-risk-for developmental coordination disorder, expressive attention was improved more in the motor skills and aerobic intervention.

Results of Meta-Analysis

Overall Effect

A total of 21 studies provided full data and were included in the meta-analysis. Effect sizes from seven studies could not be calculated because it was not possible to extract the necessary information from the published reports (S3, S5, S6, S7, S11, S18, S19). Table 2 shows the effect sizes representing the differences between the different types of PA interventions and comparison treatments. In total, 28 effect sizes were calculated, representing 2,042 participants in PA interventions and 2,002 participants in comparison groups. Overall, compared to all comparison groups, PA interventions with children and adolescents had a medium effect on measures of cognitive function (overall pooled ES=0.46; 95% CI: 0.28, 0.64), which was significantly different from zero ($p<.001$). However, heterogeneity was high (I^2= 85%), suggesting important differences in the qualitative characteristics of the PA and comparison interventions, the methodology of the studies, or the characteristics of the participants. Thus, the overall effect size should be interpreted with caution. Additionally, two effect sizes, one involving a comparison between cognitively engaging PA and aerobic treatment (S9) and another between the combination of aerobic and cognitively engaging PA with academic instruction (S20) were extraordinarily large (g=5.41 and g=5.39, respectively), well outside the confidence interval of all other estimates in this analysis. For this reason, a sensitivity analysis was deemed necessary. Repeating the analysis after excluding the two potential outliers (S9, S20) reduced the pooled effect size (pooled ES= 0.38, 95% CI: 0.22, 0.53; p<.001) while also slightly reducing heterogeneity (I^2=80%). However, the pooled effect size remained of medium size and significantly different from zero.

Performing a formal moderator analysis was not possible due to the small number of studies within the various categories. Therefore, to facilitate interpretation and identify possible directions for future investigations, we present effect sizes based on comparisons between different types of PA interventions and different types of comparison treatments.

PA Interventions Contrasted with Different Comparison Treatments

Significant positive effects were identified when all PA interventions, regardless of the qualitative characteristics of PA, were compared to no treatment (pooled ES=0.86; 95% CI: 0.18, 1.55; p = .01; n=5) or academic instruction (pooled ES=0.57; 95% CI: 0.32, 0.83; p < .001; n=10), but with high heterogeneity in both of these sub-group analyses (93% and 81%, respectively). Repeating the analysis without S20, the effect size from all PA interventions, compared to academic instruction, was decreased but remained medium and significantly different from zero (pooled ES = 0.42; 95% CI: 0.28, 0.56; p < .001), while also reducing heterogeneity (I^2 = 42%).

A small non-significant effect was noted when all PA interventions were compared to traditional PE classes (pooled ES=0.09; 95% CI: −0.07, 0.24; p = .26; n=9), with low heterogeneity (I^2= 44%). A non-significant effect was also evident when different combinations of PA interventions were compared to aerobic PA, with (pooled ES=0.80; 95% CI: −0.08, 1.67; p = .07; n=4) or without S9 (pooled ES=0.18; 95% CI: −0.08, 0.44; p = .17; n=3). However, heterogeneity was reduced from 88% to 0% with the exclusion of S9.

Qualitatively Different PA Interventions Contrasted with Comparison Conditions

Results regarding aerobic PA interventions (see Table 2, block A) were derived from only five studies (S1, S2, 24, S21, S25). Of these studies, only one aerobic intervention with overweight children in an after-school program, compared to no treatment (S1), could be included, yielding a large effect size (g=1.80). A significant, medium-sized, pooled effect from two studies (S4, S21) was found when aerobic PA was compared to academic instruction (pooled ES=0.57). When aerobic PA was compared to traditional PE, the pooled effect size from two studies (S2, S25) was small and non-significant (pooled ES=−0.08).

Two multiarm studies (additional comparisons being depicted with an *) provided data that allowed motor skill interventions to be compared to academic instruction (S4), aerobic exercise (S4*), no treatment (S8), and traditional PE (S8*). Because only one effect size represented each comparison, pooled effect sizes could not be calculated. According to these effect sizes, the effectiveness of motor-skill interventions were medium to large compared to no treatment or academic instruction and small when compared to aerobic PA (see Table 2, block B). In contrast, the one comparison to traditional PE yielded a small effect in favor of traditional PE.

Cognitively engaging PA (see Table 2, block C), in the form of yoga combined with meditation, was evaluated in two studies (S9, S10), which compared it to no treatment (g= 0.54) and aerobic PA (g=5.41).

One study (S12) examined a combination of motor skill and aerobic PA, which, compared to no treatment, yielded an effect size close to zero (g = 0.05; see Table 2, block D).

Combinations of motor skill training and cognitively engaging PA were examined in five studies, four of which involved comparisons to traditional PE (S13, S14, S15, S17), and one that involved a comparison to academic instruction (S16). Compared to academic instruction, the effect size was small (g = 0.18). Similarly, compared to traditional PE, the pooled effect size was small and non-significant (pooled ES=0.21). In one of the studies (S13), although the effect size was zero, the study included two groups of children (normal-weight and overweight), with effect sizes of similar magnitude, but in opposite directions. The effect size for the overweight children was in favor of the motor skill and cognitively engaging intervention (g=0.24), whereas for normal-weight children the effect was in favor of the traditional PE and motor skill intervention (g=−0.25).

Ten intervention groups received combinations of aerobic and cognitively engaging PA (see Table 2, block F), with the majority being compared to academic instruction. Compared to no treatment, the effect size from a single study (S26) was large (g=1.44). Compared to academic instruction, the pooled effect size from 6 studies (S20-S24, S27) was significant and medium to large (pooled ES=0.69), but with high heterogeneity (I^2 = 88%). Compared to traditional PE (S25) and aerobic PA (S21, S25), the effect sizes were close to zero or small and not significant (g= 0.03 and 0.17, respectively).

Lastly, a combination of all three types of PA (aerobic, motor skill, and cognitively engaging) was examined in only one study (S28), yielding a small positive effect size (g=0.26) compared to traditional PE.

Excluded Comparisons

Certain comparisons between different arms of multiarm trials were excluded after closer examination, for specific reasons, despite providing data for the calculation of effect sizes. A comparison involving one treatment, labeled as “Fine Arts” (S9), was omitted because elements such as crafts, pottery, and drama were predominant compared to the PA content (i.e., sports). Moreover, in two multiarm studies (S21, S28), comparisons involving one arm from each were excluded because the treatments were similar to other (included) comparator treatments and not directly relevant to the focus of the present meta-analysis.

Discussion and Future Directions

The aim of this review and meta-analysis was to describe the characteristics and effects of qualitatively different types of chronic PA interventions on cognitive processing in children and adolescents. The need to consider both the quantitative and qualitative characteristics of PA interventions has been recognized in theory and practice (Garber et al., 2011). As demonstrated in this paper, in recent years, this line of research has shown an increase in the rate of accumulation of data as well as a focus on the qualitatively different types of chronic PA interventions focused on children's cognitive outcomes. Evidence regarding the positive effect of PA on cognitive function in youth is growing (Kahn & Hillman, 2014; Pesce & Ben-Soussan, 2016). Additionally, recommendations in recent review studies and book chapters on exercise and cognition research have suggested moving beyond a focus on the amount of PA by exploring the unique cognitive benefits that may be obtained through qualitatively different types of movement that act as brain stimulation (Best, 2010; Pesce, 2012; Tomporowski, Lambourne & Okumura, 2011; Tomporowski, McCullick, Pendleton, & Pesce, 2015). Such recommendations have also been presented in developmental neurosciences (Diamond, 2015; Diamond & Lee, 2011; Diamond & Ling, 2015; Pesce & Ben-Soussan, 2016) and cognitive training research (Moreau & Conway, 2013, 2014; Moreau, Morrison, & Conway, 2015). Despite that empirical studies have begun to explore the potential distinctions between PA effects relative to qualitative characteristics, until now a meta-analytic approach to the effect of chronic intervention studies based on the different types of PA programs on children's cognitive functioning was lacking.

Overall, the review and meta-analysis results showed that chronic PA interventions have a positive effect on cognitive performance in children and adolescents. This result is consistent with the conclusions drawn by existing meta-analyses on cognition in general and on EF specifically, including both acute and chronic exercise programs as well as those for children and adults (Chang, Labban, Gapin, & Etnier, 2012; Fedewa & Ahn, 2011; McMorris, Sproule, Turner, & Hale, 2011; Sibley & Etnier, 2003; Smith et al., 2010; Verburgh, Königs, Scherder, & Oosterlaan, 2013). Interestingly, Verburgh and colleagues (2013) found a significant positive overall meta-analytic effect of only acute (not chronic) exercise on EFs in children. However, the results of Verburgh et al. were based on only four chronic PA interventions, one of which was conducted with young adults.

Importantly, our results showed that heterogeneity was high for the overall effect size and when all types of PA programs were compared to different comparison groups. This finding confirms that not all types of PA are the same and supports the aforementioned recommendations to account for the unique contributions of the qualitative types of PA on cognitive benefits.

Which Road to Take to Rome: Do We Have Enough Highways to Know Which Ones Work Best?

Although the number of studies contrasting the cognitive outcomes of different types of PA programs has increased in recent years, there is still no clear evidence regarding which programs are more effective for children's cognitive function. If we examine the studies included in Table 2 as if they were on a grid, it is evident that the majority of the cells of the grid are either empty or include no more than two studies with complete data necessary for a meta-analysis. The types of PA that have received the most attention in chronic interventions (regardless of the comparison group) are aerobic combined with cognitively engaging programs (8 studies), which were mainly compared to academic content (6 studies), followed by motor skills combined with cognitively engaging programs, or aerobic programs (7 studies in each category; 5 with complete data for a meta-analysis), which were mainly compared to traditional PE. Based on the results of the meta-analysis, children's cognitive function benefits from all types of PA interventions when compared to no treatment or academic content (i.e., compared to no physically active comparators), but the effects are small or non-existent when they are compared to traditional PE programs that also include PA.

When the focus was to compare different types of PAs with comparators that did not include any type of PA (i.e., no treatment and academic), our results showed that the strongest effects (large or medium effect sizes) emerged from PA programs that focused on aerobic exercise, aerobic exercise that was also cognitively engaging, motor skills, and low-intensity, cognitively engaging exercises (yoga combined with meditation and stretching). This finding is consistent with the outcomes of recent reviews and conceptualized models that describe how cognitively engaging PAs and mentally enriched interventions may promote fundamental changes in the brain that benefit cognition in children (Diamond, 2015; Diamond & Lee, 2011; Diamond & Ling, 2015; Pesce, 2012; Pesce & Ben-Soussan, 2016; Tomporowski et al., 2015). However, it is important to emphasize that interpretation of the results from comparisons between different types of PA programs should be conducted with caution due to the very small number of studies in many types of PAs. For example, only two studies conducted by Manjunath and Telles (2001, 2004) focused on cognitively engaging activities through yoga and meditation, two studies combined motor skills with aerobic PA (Chang et al., 2013; Hillman et al., 2014), and only one study combined aerobic, motor skills and cognitively engaging PA (Pesce et al., 2013).

In addition to the small number of studies within each type of PA or comparison group, high heterogeneity could also reflect differences in the characteristics of each PA intervention or the characteristics of the participants. The amount of time spent practicing, the overall dose, the targeted environment, the content of the activities even if they were within the same type of PA, and the age and characteristics of the participants varied substantially, making it challenging to determine what types of PA programs were most effective.

Therefore, we opted not to derive conclusions about the effectiveness of each type of PA; instead, we aimed to identify directions for future growth based on what we observed as key gaps in the literature. As Diamond and Ling (2015) have also highlighted, there are several unanswered questions pertaining to what types and characteristics of PA programs lead to stronger benefits in EFs and this requires additional exploration. Therefore, we hope that the following discussion may reduce the ambiguities in our research outcomes and redirect efforts toward clear and consistent results from future chronic PA interventions relative to cognitive outcomes in children.

Does One Type of Comparison Work for All?

Although this review primarily focused on the type and characteristics of PA interventions, proper interpretations of the reported effects requires that the nature of the comparison or control interventions is also taken into account. In our review, we were able to identify and categorize four types of comparisons. PA programs were compared to no treatment, academic instruction, traditional PE, and aerobic exercise. It can be assumed that when comparing a PA program with a specific dose and characteristics of exercise to another condition as a comparator, the selection of the comparison group will impact the degree of effectiveness of the intervention. For example, one should expect larger differences when an exercise intervention is compared to no exercise than when it is contrasted with another exercise intervention with different qualitative and/or dose characteristics.

As our results have demonstrated, when PA interventions were compared to traditional PE or aerobic exercise, the size of the pooled effect was small and nonsignificant. In contrast, when PA interventions were compared to no treatment or academic instruction, the pooled effect was significant and large or medium, respectively. The generally small-to-medium differences between treatments that involve different types of PA should be taken into account in planning future investigations. To reach adequate levels of statistical power with realistic sample sizes, trial designs should specifically target factors that strengthen the effects (e.g., longer treatment periods) and improve the reliability of measurement (e.g., by emphasizing consistency and reducing random measurement error).

As shown in Table 2, there are relatively few intervention studies that have compared different types of PA programs to no treatment. Specifically, only five studies were identified, one for each of the categories of aerobic exercise (Davis et al., 2011), motor skill development (Gallotta et al., 2015), cognitively engaging PA (Manjunath & Telles, 2004), motor skills combined with cognitively engaging PA (Hillman et al., 2014), and aerobic exercise combined with cognitively engaging PA (Van der Niet et al., 2016). No studies exist on motor skills combined with cognitively engaging PA or programs that combine all three types, compared to no treatment. Similarly, no studies have compared cognitively engaging PA, motor skills combined with aerobic exercise, or programs that combine all three types of PA to academic content. Therefore, additional research is needed in this area.

Does Everyone Benefit the Same? Characteristics of the Participants

Our results showed that the majority of the studies identified in the review were conducted using elementary school children; only five studies targeted children under the age of 8 years (5–7.5 years) with all of the studies conducted within the last five years. Research studies on aerobic exercise as well as cognitively engaging PA in young children were absent in the literature until recently. The first two studies that examined the effect of cognitively engaging PA combined with motor skill training or with aerobic exercise in young children were those by Piek et al. (2015) and Mavilidi et al (2015). Both studies found significant benefits of PA programs on children’s cognition. This finding is encouraging, especially because the considerable growth in EF skills that is evident between the ages of 3 and 6 years plays a substantial role in future school success (Best & Miller, 2010).

Few studies have evaluated the effect of PA interventions in overweight and obese children. In our review, only three studies either focused exclusively on this population or compared the effects between normal-weight and overweight children (Crova et al., 2014; Davis, et al., 2011; Gallota et al., 2015). Crova et al. (2014) found contradictory results between normal-weight and overweight children; only the overweight children exhibited significant benefits in inhibition from the cognitively engaging motor skill program. Davis et al. (2011) found that among overweight children, a high dose of aerobic exercise, compared to low-dose and no treatment, significantly improved planning and fluency in math, whereas Gallotta et al. (2015) found that all of the children benefited from the motor skill program. Additionally, the only studies that examined cognitively engaging PA, through yoga and meditation, were conducted in India (Manjunath & Telles, 2001, 2004). Therefore, it remains an open research question whether the effects reported in these studies (including an extraordinarily large effect in S9) can be assumed to generalize to other cultures, especially western cultures. Therefore, more research is warranted regarding which types of PA and what doses may be optimal for different age groups and children characteristics.

Does Every Cognitive Function Benefit to the Same Extent from Each Intervention Type?

Several commonalities emerged from the narrative portion of the present review regarding the type of cognitive function that benefited from specific qualitative characteristics of PA interventions. We found consistent evidence that children's spatial abilities and working memory, were enhanced by aerobic or motor skill PA (Fisher et al., 2011; Fredericks, Kokot, & Krog, 2006; Koutsandreou et al., in press), and that this enhancement was more pronounced in response to cognitively engaging activities compared to simply aerobic activities (Mavilidi et al., 2015). Indeed, the practice of designed sports that integrate complex motor skill training and cognitive engagement has demonstrated broad effects on spatial abilities and working memory in contrast to simple aerobic exercise (Moreau et al., 2015).

Another intriguing commonality regarding PA and PA-related aerobic fitness is the consistently beneficial effect on inhibition, which is among the foundational EFs during development (Barenberg et al., 2011; Kahn & Hillman, 2014). In the present review, we found that inhibition was enhanced when the PA intervention focused on motor skills coupled with enriched cognitive task demands (Crova et al., 2014; Lakes et al., 2013; Lakes and Hoyt, 2004; Pesce et al., 2016; Piek et al, 2015).

Finally, metacognitive functions (e.g., planning and creativity) improved by either aerobic PA (Hinkle, Tuckman, & Sampson, 1993; Tuckman and Hinkle, 1986) or cognitively engaging PA (Manjunath & Telles, 2001). The impact of mindfulness sensorimotor practices on both planning and creativity has been reported in the literature (Venditti et al., 2015).

Different Types of PA and Different Programs Within Each Type: How Much Do They Differ?

Our meta-analytic results showed that even within the same categories of PA programs (according to the authors' own description of the main type of PA inherent in the program), high heterogeneity among the effects was still evident. This high heterogeneity could be interpreted in different ways, including the following: (a) there may be many different programs that can be defined as fitting within one type of PA, but their content and characteristics may differ substantially; (b) within one PA program, multiple unexplored characteristics of the PA could be responsible for the stimulation of cognitive development; and (c) the fidelity by which a PA program is implemented in practice can impact its efficacy and effectiveness; for example, implementing the same intervention protocol may lead to different levels of motor skill performance and development in children, depending, among several factors, on the school resources available, the skills and engagement of the instructor, and the complex student-instructor and peer-to-peer interactions within each class.

Specifically, regarding the first point, although the majority of the PA programs that were identified in the review were conducted within a similar context (i.e., during PE or in the classroom), the programs may vary substantially in their content. For example, they may include individual or team sport games, simple or multi-limb coordinative tasks, or different levels of cognitive engagement for mastering new skills or mentally processing information regarding game strategies. Often, a combination of many different sports and tasks that vary both quantitatively and qualitatively may be included in one PA intervention, making it impossible to fully explore the characteristics that are most beneficial to cognitive function. Additionally, a detailed description of the activities implemented in a PA intervention is usually not provided, nor is treatment fidelity evaluated throughout the intervention. Diamond and colleagues predicted that many activities, such as dance, circus arts, and team sports, might improve EFs because of the combination of different characteristics inherent in those activities; however, those activities have not yet been studied (Diamond & Lee, 2011; Diamond & Ling, 2015). Muscle-strengthening activities have also been understudied; thus, their effect on children's cognition needs to be assessed in the future. It is likely that existing PA programs include several of these activities in their curriculum, but it is not possible to examine their efficacy and effectiveness without a detailed description of the programs and treatment fidelity.

Designing programs that focus exclusively on one of those activities is another approach to elucidating whether and how those programs benefit children's cognitive function. However, this approach might be more challenging because the majority of PA interventions are conducted within the school environment. Policy changes, which may be necessary for different programs to be adopted by a school, are difficult to implement. Another likely avenue is through after-school programs, including sports clubs and summer camps, given that a typical nine-month academic school year is followed by an extended summer break. A limited number of after-school and summer camp PA programs were identified in our review. Thus, more investment in summer programs may be informative. Mureau and Conway (2013) reviewed the role of sports programs on cognitive enhancement and argued that principles inherent in sports training, such as novelty, diversity, and complexity in sensorimotor learning combined with aerobic workouts, can be considered the core of an embodied approach to cognition.

In addition to the variety of PA programs, the characteristics within each program may influence cognitive function, as noted in the literature. For example, when we think of aerobic exercise, we might think of running, biking, or swimming as cyclic and somewhat repetitive activities that are often conducted individually on a treadmill or a stationary bike.

This situation may be true for exercise programs that adults adopt, usually as gym members. However, the PA programs that are designed for children typically include a number of different activities, games, or sports that target multiple skills, include extensive social interactions, and are conducted as part of a structured program. Basketball or soccer games, for example, can be defined as aerobic exercise that is also cognitively engaging because the children must comprehend information, make decisions, and process information on how to master new skills. Additionally, these types of sports can be defined as exercises that target a variety of motor, social, and emotional skills, support the psychological need for competence, relatedness and autonomy, and lead to great joy, confidence and high self-esteem (Daniels & Leaper, 2006; Kipp & Weiss, 2013; Smith, 2003). Thus, although the PA programs were categorized based on the main characteristics identified by the study authors (aerobic, motor skills, and cognitively engaging PA; as the primary focus of our review), it is important to remember that multiple other characteristics could and should be operationalized. As researchers have noted (Best, 2010; Diamond & Ling, 2015; Pesce, 2012; Pesce & Ben-Soussan, 2015; Tomporowski et al., 2015), numerous qualitative characteristics inherent in a PA program (e.g., eye-hand coordination, balance, rhythm, cognitive complexity of the motor tasks, and mental strategies used in different conditions and contexts, emotional activation) may influence cognitive function and need to be further explored. Importantly, the quality of the program, the level of knowledge, skill and effort that are presented by the PA specialists, and the time, attention and effort exerted by the children—all of these factors may play a substantial role with respect to the degree that the pieces of information are processed and the skills are learned (Tomporowski, McCullick, & Pesce, 2015) Understanding the mechanisms related to the different characteristics of PA and the methods employed in different contexts may provide insight into how the neural networks function and how they can be applied to an extensive variety of situations and contexts (Pesce et al., in this issue).

Limitations

A limitation of the meta-analysis is that all of the cognitive outcomes were combined to have one effect size per study and to restrict the bias of conducting multiple comparisons with the same sample size. However, cognitive processing is not defined as one global cognitive system but as a set of multiple functions. Thus, although cognitive function was measured uniformly in the meta-analysis because of the small number of studies and specific research focus, the effect of different types of PA interventions on specific cognitive domains should be examined when more research studies are available. For the same reason, an examination of moderators was not conducted in the meta-analysis, and, despite grouping the studies based on the type of PA and the type of comparison treatment, no conclusions could be drawn regarding the effectiveness of different types of chronic PA interventions on children's cognitive outcomes because heterogeneity was still high. Grouping the studies based on the three different types of PA, and all their combinations, has limitations because of the difficulty in teasing apart the different types of PA in intervention programs that include elements of all types. Grouping was made based on the authors' descriptions provided in each study, however, it is possible that different qualitative characteristics of PA were implemented in the intervention but were not fully described in the manuscript.

Conclusions

Overall, the results of this narrative review and meta-analysis showed a positive effect of chronic PA interventions on children's cognitive functioning. To improve our understanding of the individual and interactive role of the different qualities of PA programs on children's and adolescent's cognition, additional well-designed interventions with multiple, specifically tailored types of PAs for children are needed. To conclude, it is important to explore and understand the mechanisms that define the association between PA and cognitive function in children (Pesce et al., 2016). It is also essential to effectively translate the evidence into practice in real-life settings to better reflect a holistic approach to healthy child development (Pesce, Leone, Motta, Marchetti, & Tomporowski, in press).

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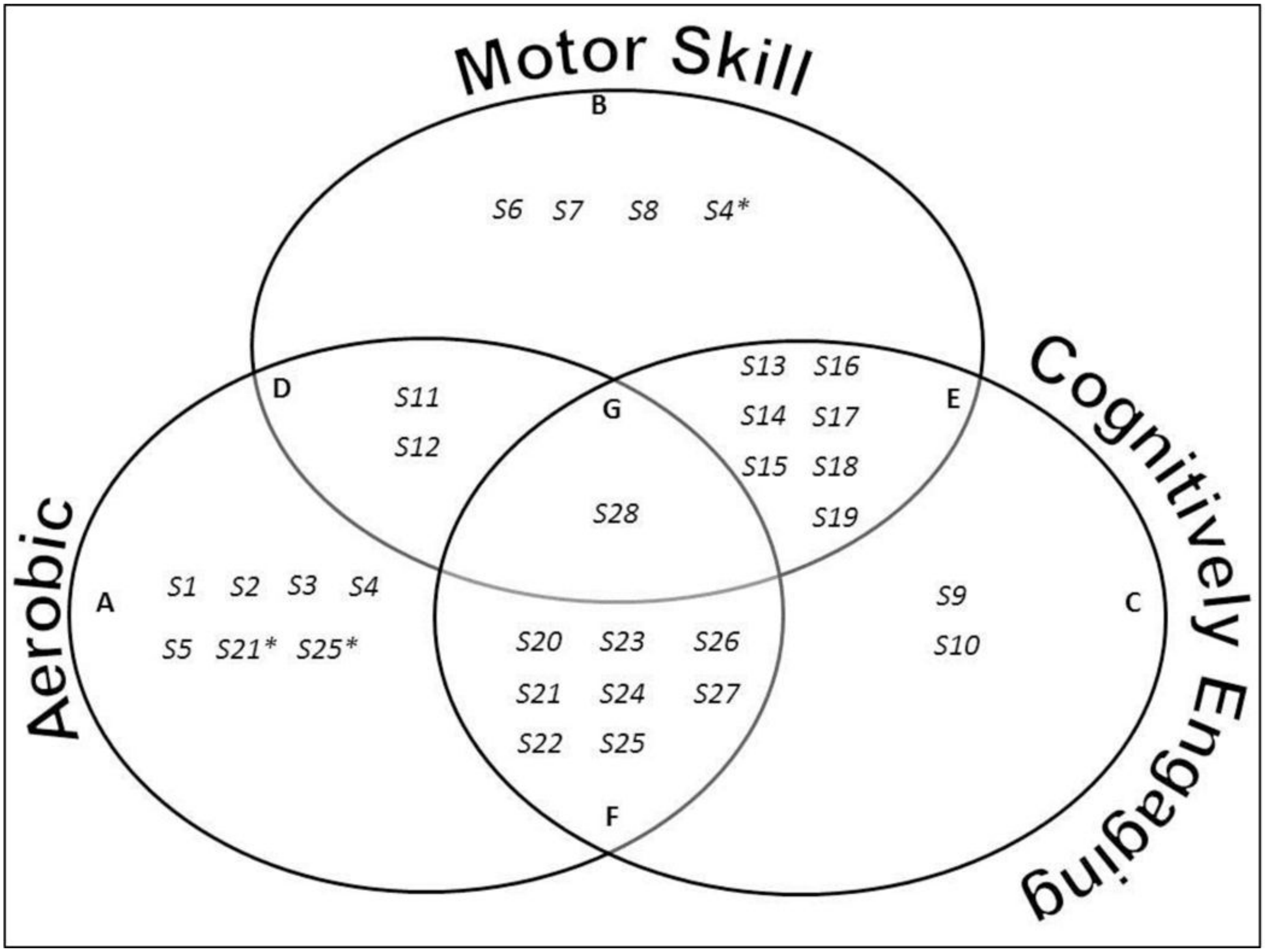

Figure 1.

Visual distribution of chronic PA intervention studies based on types of PA Note. In intervention programs that included more than one set of comparators, the additional comparisons are depicted with an *

Table 1.

Chronic PA intervention studies on cognition in children and youth

Study	Sample	Type of PA intervention and comparison group	Dose of PA	Cognitive Outcomes	Results
Davis et al. (2011) *A - S1*	N = 171 OW M_{age} = 9.3±1y n = 55 I low n = 56 I high n = 60 C USA	**Aerobic** (running, jump rope, games focused on intensity, HR > 150 BPM; I) vs **No Treatment** (no after school program; C)	I: 20 or 40 min/day, for 13±1.6 weeks; at after school program C: no PA	*Cognitive Assessment System:* Planning*, Attention, Simultaneous, Successive Reading Fluency Mathematics Fluency	+* 0 +
Fisher et al. (2011) *A - S2*	N = 60 M_{age} = 6.2±0.3y n = 33 I n = 27 C UK	**Aerobic** (PE focused on aerobic activities; I) vs **Traditional PE** (skill development; object control skills, no emphasis on aerobic; C)	I: 2 hours/week, for 10 weeks (20% of time on MVPA [total 12 min] versus 9% for C); at school C: 1 hour/week for 10 weeks	Cognitive Assessment System Total *(planning, attention, simultaneous, successive)* Attention *RT & Accuracy** Spatial Span, Spatial WM Errors Inattention Hyperactivity	0 0, +* + + 0
Hinkle et al. (1993) *A - S3*	N = 85 8th G USA	**Aerobic** (running; I) vs **Traditional PE** (badminton, volleyball, table tennis; C)	5 × 30 min/week, for 8 weeks; at school (I & C)	Creative Fluency Creative Flexibility Creative Originality	+ + +
Koutsandreou et al. (in press) *A - S4*	N = 71 n = 27 I_1 n = 23 I_2 n = 21 C M_{age} = 9.4±.6 y Germany	**Aerobic** (60–70 % HR_{max}; I_1) vs **Motor Skill** (coordinative, balance, object control; 55–65% HR_{max}; I_2) vs **Academic** (assisted homework; C)	I: 45 min 3 times/ week, for 10 weeks; at after-school program C: no PA	Working Memory *(* for both I_1 and I_2 but the improvement was larger for I_2)*	+*
Tuckman & Hinkle (1986) *A - S5*	N = 154 4th-6th G USA	**Aerobic** (running; I) vs **Traditional PE** (basketball, volleyball; C)	3 × 30 min/week, for 12 weeks; at school (I & C)	Creativity Perceptual-motor ability Planning & Visual-motor Coordination Teacher-rated Disruptive Behavior	+ 0 0 0
Fredericks et al. (2006) *B - S6*	N = 53, 1st G n =13 I n = 13 C n = 14 F n = 13 E South Africa	**Motor Skill** (balance, laterality, coordination, & object control skills; I) vs **Academic** (regular class; C), vs **Free-play** (F), vs **Educational Toys** (E)	20 min/day for 8 weeks; at school (I & C)	Aptitude Test for School Beginners *perception, spatial**, *reasoning, numerical, Gestalt, coordination, memory, verbal comprehension* Reading age Math age	+* 0 + +
Reed et al. (2013) *B - S7*	N = 470 n = 165 I M_{age} = 10.2±2.3 y n = 305 C M_{age} = 11.2±1.9 y USA	**Motor Skill+** (fundamental motor skills in extra PE hours; I) vs **Traditional PE** (C)	I: 45 min/day for 6 months C: 45 min/week; at school	Fluid Intelligence *Five sections* Perceptual Speed *Three sections* ** results varied by gender, age and sub-sections of cognitive outcomes*	+0-* +0-*

Study	Sample	Type of PA intervention and comparison group	Dose of PA	Cognitive Outcomes	Results
Gallotta et al. (2015) *B - S8*	*N* = 156 *n* = 59 I (19 OW) *n* = 56 C_1 (23 OW) *n* = 41 C_2 (11 OW) 3^{rd} – 5^{th} G Italy	**Motor Skill+** (coordinative; I) vs **Traditional PE** (C_1) vs **No Treat** (no PA; C_2)	2 hours/week for 5 months (I, C_1); at school I: Sport games, rhythmic, gymnastics, fitness; 5 weeks each C_2: no info	Attention *Item Processed (* I vs C_1; ** I vs C_2)* *Concentration* *% Errors*	-* 0** + +
Manjunath & Telles (2001) *C - S9*	*N* = 20, 10–13 y *n* = 10 I *n* = 10 C India	**Cognitively Engaging** (yoga: physical postures, regulated breathing, meditation, relaxation; I) vs **Aerobic** (jogging, stretching, weight lifting; C)	75 min, 7days/week for 1 month (I & C); at a summer camp	Planning Time *(*2-moves, *4-moves, 5-moves tasks)* Execution Time *(2-moves, *4-moves, *5-moves tasks)* Number of Moves to complete *(2-moves, *4-moves, 5-moves tasks)*	+* +* +*
Manjunath & Telles (2004) *C - S10*	*N* = 90, 11–16 y *n* = 30 I *n* = 30 C_1 *n* = 30 C_2 India	**Cognitively Engaging** (yoga: physical postures, regulated breathing, meditation, relaxation, games, stories; I_1) vs **Arts** (drama, cricket or volleyball, dance, crafts, pottery; C_1) vs **No Treatment** (no intervention; regular summer activities; C_2)	8 hours/day for 10 days (I & C); at a summer camp I_1: Yoga (300 min), games (120 min), stories (60 min).)	Verbal Memory Spatial Memory (* for I_1)	0 +*
Chang et al. (2013) *D - S11*	*N* = 26, 6–7.5 y *n* = 13 I *n* = 13 C Taiwan	**Aerobic** & **Motor Skill** (moderate intensity [60–70% HR_{max}] of soccer; I_1) vs **Motor Skill** (low intensity [50–60% HR_{max}] of soccer; C)	35 min, 2 times/week for 8 weeks; at after-school program (I_1 & C)	Inhibition Accuracy Inhibition RT	0 0
Hillman et al. (2014) *D - S12*	*N* = 221, 7–9 y *n* = 109 I *n* = 112 C USA	**Aerobic** & **Motor Skill** (PA stations & games centered on a skill theme) vs **No Treatment** (waiting list in after school; C)	I: *FitKids*: 2 hours/day for 9 months (70 min of MVPA; M_{HR} ~ 137 bpm; ~ 35 min PA stations + ~ 50 min games); at after-school program C no PA	Inhibition Accuracy *(* in incongruent trials only)* Inhibition RT Cognitive Flexibility Accuracy *(* in heterogeneous trials only)* Cognitive Flexibility RT	+* 0 +* 0
Crova et al. (2014) *E - S13*	*N* = 70, 9–10 y *n* = 37 I (14 OW) *n* = 33 C (12 OW) Italy	**Motor Skill** & **Cognitively Engaging** (fundamental skills, coordination, tennis skills, tennis games; I) vs **Traditional PE** (C)	I: 1 PE class + 2 hours of tennis training/week for 21 weeks; at school C: 1 PE class/week	Inhibition (*for overweight compared to normal weight children) Working Memory	+* 0
Lakes & Hoyt (2004) *E - S14*	*N* = 193, K-5^{th} G *n* = 104 I *n* = 89 C USA	**Motor Skill** & **Cognitively Engaging** (Martial Arts program; I) vs **Traditional PE** (C)	I: *LEAD*: 2 or 3 of the 4 45-min PE periods/week for 4 months (26 sessions); at school C: same dose with I (4 × 45 min/week of PE)	Cognitive Self-Regulation Affective Self-Regulation Physical Self-Regulation Teacher-rated Strengths & Difficulties *Classroom Conduct*,* *Prosocial Behavior*,* *Hyperactivity/inattention,*	+ + + +* + 0

Study	Sample	Type of PA intervention and comparison group	Dose of PA	Cognitive Outcomes	Results
				Emotional Symptoms, Peer Problems Arithmetic test for attention Digit Span test for attention	
Lakes et al. (2013) *E - S15*	*N* = 81, 7th G *n* = 50 I *n* = 31 C USA	**Motor Skill** & **Cognitively Engaging** (Martial Arts program; I) vs **Traditional PE** (C)	I: 3 of the 5 45 min PE periods/week for 9 months; at school C: same dose (5 × 45 min/week of PE)	Parent-rated inhibitory behavioral control Parent-rated inhibitory attentional control Executive Function Computer Task *Congruent Accuracy*, Congruent RT, Incongruent Accuracy, Incongruent RT, Mixed Accuracy, Mixed RT*	+ 0 +*
Piek et al. (2015) *E - S16*	*N* = 486 M_{age} = 5y and.5 m ± 3.58 m *n* = 265 I *n* = 221 C Australia	**Motor Skill** & **Cognitively Engaging** (balance, locomotor skills, object control skills, fine motor skills, social and emotional skills, relaxation; I) vs **Academic** (regular class; C)	I: *Animal Fun*: 30 min/day for 4 days/ week for 6 months; at school C: no PA	Teacher-rated Strengths & Difficulties Total *Hyperactivity/inattention* *Emotional Symptoms* *Conduct problems* *Prosocial behavior* *& 12 month follow-up results*	+ + 0 0 + +
Pesce et al. (2016) *E - S17*	*N* = 460, 5–10 y *n* = 230 I *n* = 230 C Italy	**Motor Skill** & **Cognitively Engaging** (Enhanced PE with complex motor and cognitively challenging tasks; I) vs **Traditional PE** (C)	1 hour/week for 6 months; at school (I & C)	Inhibition Working Memory Updating Executive Attention	+ 0 0
Spitzer & Hollmann (2013) Study 1 *E - S18*	*N* = 44 *n* = 24 I M_{age} = 12.5 y *n* = 20 C M_{age} = 13 y Germany	**Motor skill** & **Cognitively Engaging** (basketball, soccer, other sport games, dancing; I) vs **Academic** (regular class; C)	I: 30 min 3 times/ week for 4 months (36 lessons) at school C: No PA	Teacher-rated Classroom Behavior: *Accurateness while studying* Attention Accuracy	+ 0
Spitzer & Hollmann (2013) Study 2 *E - S19*	*N* = 88 *n* = 55 I M_{age} = 12.4 y *n* = 33 C M_{age} = 12.3 y Germany	**Motor skill** & **Cognitively Engaging** (basketball, soccer, other sport games, dancing; I) vs **Academic** (regular class; C)	I: 30 min 3 times/ week for 4 months (30 lessons); at school C: No PA	Teacher-rated Classroom Behavior: *Accurateness while studying* Attention Accuracy	+ +
Erwin et al. (2012) *F - S20*	*N* = 29 3rd G *n* = 16 I *n* = 13 C USA	**Aerobic** & **Cognitively Engaging** (integrated physical activity [e.g., jump, walk] with math & reading content; I) vs **Academic** (regular class; C)	I: 20 min/day for 20 weeks C: No PA	Math Fluency Reading Fluency	+ 0
Mavilidi et al. (2015) *F - S21*	*N* = 111 M_{age} = 4.94±.56 y *n* = 31 I_1	**Aerobic** & **Cognitively Engaging** (integrated physical activity with foreign word learning and gesturing; I_1) vs **Aerobic** (running, walking around class; I_2) vs **Academic +**	15 min 2 times/week for 4 weeks; at school (I & C) I_1 Time in MVPA= 3.85± 3.2 min	Free Recall Memory *I_1, **I_2 Cued Recall Memory *I_1, **I_2 ^{b}*I_2 compared to C_2 only*	+*0** +*+**b

Study	Sample	Type of PA intervention and comparison group	Dose of PA	Cognitive Outcomes	Results
	$n = 23$ I_2 $n = 31$ C_1 $n = 26$ C_2 Australia	**Gestures** (pantomimic gestures for words while seated; C_1) vs **Academic** (verbally practice words while seated; C_2)	I_2 Time in MVPA= 3.47± 3.4 min C_1 Time in MVPA= 1.92± 1.68 min C_2 Time in MVPA= 1.75± 1.17 min		
Mullender-Wijnsma et al. (2016) *F - S22*	$N = 499$ 2nd - 3rd G $n = 249$ I $n = 250$ C Netherlands	**Aerobic** & **Cognitively Engaging** (integrated physical activity [jump, hop, march] with math & language arts; I) vs **Academic** (regular class; C)	I: 2 × 10–15 min, 3 times/week for 22 weeks for 2 years; at school 60% MVPA (14 min of an average lesson of 23 min); 63 lessons/year C: No PA	Cognitive Performance end of Year 1 *Arithmetic Speed Test, Reading Ability Spelling Ability, Math Ability** Cognitive Performance end of Year 2 *Arithmetic Speed Test, Reading Ability*, Spelling Ability, Math Ability**	0 +* 0 +*
Reed et al. (2010) *F - S23*	$N = 155$, 3rd G $n = 80$ I $n = 75$ C USA	**Aerobic** & **Cognitively Engaging** (integrated physical activity [e.g., jump, walk] with math & reading content; I) vs **Academic** (regular class; C)	I: 30 min 3 days/ week for 4 months; at school C: No PA	Fluid Intelligence (problem solving)	+
Riley et al. (in press) *F - S24*	$N = 240$, 5th - 6th G $n = 142$ I $n = 98$ C Australia	**Aerobic** & **Cognitively Engaging** (integrated physical activity [e.g., jump, walk] with math; I) vs **Academic** (regular class; C)	I: “EASY Minds”: 60 min 3 days/week for 6 weeks; at school C: No PA	Classroom Behavior (On-task)	+
Schmidt et al. (2015) *F - S25*	$N = 181$ $M_{age} = 11.35 \pm .6$ y $n = 69$ I_1 $n = 57$ I_2 $n = 55$ C Switzerland	**Aerobic** & **Cognitively Engaging** (team games: floorball, basketball with frequent changes of rules; I_1) vs **Aerobic** (running; I_2) vs **Traditional PE** (fitness, gymnastics, dance, low intensity; C)	45 min 2 times/week for 6 weeks (12 lessons; I & C); at school M_{HR}= 147 (I_1); 150 (I_2); 132 (C)	Inhibition Updating Shifting (*only in I_1)	0 0 +*
Van der Niet et al. (2016) *F - S26*	$N = 105$, 8–12 y $n = 53$ I $n = 52$ C Netherlands	**Aerobic** & **Cognitively Engaging** & **Strength** (running games, circuit training, football, relay games with letters, sit-ups, rope skipping; I) vs **No Treatment** (no intervention during lunch recess; C)	I: 30 min 2 times/ week for 22 weeks; at school 57–88% HR_{max} C: No PA	Inhibition Visual-spatial Working Memory Verbal Working Memory Cognitive Flexibility Planning	+ 0 + 0 0
Vazou & Skrade (in press) *F - S27*	$N = 224$, 4th- 5th G $n = 106$ I $n = 118$ C USA	**Aerobic** & **Cognitively Engaging** (integrated physical activity [e.g., jump, walk, skip, crab walk] with math content; I) vs **Academic** (regular class; C)	I: “Move for Thought”: 15 min 3 days/week for 8 weeks; at school C: No PA	Math Fluency	+
Pesce et al. (2013) *G - S28*	$N = 250$, 5–10 y $n = 83$ I_1	**Aerobic, Motor Skill** & **Cognitively Engaging** (enhanced PE with	1 hour/week for 6 months; at school (I & C)	Cognitive Assessment System: Planning Total Attention	0

Study	Sample	Type of PA intervention and comparison group	Dose of PA	Cognitive Outcomes	Results
	n = 71 I_2 *n* = 96 C Italy	complex motor and cognitively challenging tasks; I_1) vs **PE+** (PE taught by a specialist emphasized variability in practice & aerobic exercises; C_1) vs **Traditional PE** (C_2)	54% MVPA (I_1) 66% MVPA (C_1) 44% MVPA (C_2)	*(* for typically developing compared to borderline/DCD children in favor of I_1)* Expressive Attention *(** for borderline/DCD in favor of C_1)* Receptive Attention	+* +** +*

Notes. y = years; m= months; I = intervention; C = comparison; G = grade; OW = overweight; HR = heart rate; HRmax = maximal heart rate; BPM = beats per minute; MVPA = moderate-to-vigorous physical activity; PA = physical activity; PE = physical education; RT = reaction time; DCD = developmental coordination disorder; 0 = no difference; + = difference in favor of the intervention group; - = difference in favor of the comparison group;

* = to clarify when results are not consistent for all groups or tests as presented in the same line; In bold = type of PA intervention and comparison group.

Table 2.

Effect sizes for different types of PA intervention and comparison groups

PA Intervention	Comparison Group: No Treatment ES	No Treatment Study	Academic ES	Academic Study	Traditional PE ES	Traditional PE Study	Aerobic ES	Aerobic Study
A. Aerobic	1.80	*Davis*[S1]	0.53	*Koutsandreou*[S4]*	−0.10	*Fisher*[S2b]	-	-
			0.61	*Mavilidi*[S21]*	−0.07	*Schmidt*[S25]*		
pooled ES **(95% CI)**			**0.57 (0.16, 0.98)** *p* = .006		**-0.08 (−0.38, 0.22)** *p* = .60			
			N_T=50, N_C=47; I^2= 0%		N_T=84, N_C=88; I^2= 0%			
B. Motor Skill	0.54	*Gallotta*[S8]	0.74	*Koutsandreou*[S4]	-0.25	*Gallotta*[S8]*b	0.22	*Koutsandreou*[S4]*
C. Cognitively Engaging	0.53	*Manjunath*[S10]*	-	-	-	-	5.41	*Manjunath*[S9]
D. Motor Skill & Aerobic	0.05	*Hillman*[S12b]	-	-	-	-	-	-
E. Motor Skill & Cognitively Engaging	-	-	0.18	*Piek*[S16b]	0.00#	*Crova*[S13]	-	-
					0.18	*Lakes*[S14b]		
					0.77	*Lakes*[S15b]		
					0.03	*Pesce*[S17]		
pooled ES **(95% CI)**					**0.21 (−0.07, 0.48)** *p* = .14			
					N_T=421, N_C=385; I^2= 66%			
F. Aerobic & Cognitively Engaging	1.44	*VanderNiet*[S26]	5.39	*Erwin*[S20]	0.03	*Schmidt*[S25]	0.22	*Mavilidi*[S21]*
			0.79	*Mavilidi*[S21]			0.15	*Schmidt*[S25]*
			0.36	*Mullender*[S22]				
			0.31	*Reed*[S23]				
			0.34	*Riley*[S24]				
			0.68	*Vazou*[S27]				
Pooled ES **(95% CI)**			**0.69 (0.31, 1.08)** *p* > .001			**0.17 (−0.12, 0.47)** *p* =.25		
			N_T=625, N_C=580; I^2= 88%			N_T=100, N_C=80; I^2 = 0%		
Pooled ES **(95% CI) *w/o S20***			**0.45 (0.29, 0.61)** *p* > .001 N_T=609, N_C=567; I^2 = 38%					
G. Aerobic & Motor Skill & Cognitively Engaging	-	-	-	-	0.26	*Pesce*[S28]	-	-

PA Intervention	**Comparison Group**							
	No Treatment		**Academic**		**Traditional PE**		**Aerobic**	
	ES	***Study***	**ES**	***Study***	**ES**	***Study***	**ES**	***Study***
All PA Interventions ***Pooled ES*** **(95% CI)**	**0.86 (0.18, 1.55)** $p = .01$		**0.57 (0.32, 0.83)** $p > .001$		**0.09 (−0.07, 0.24)** $p = .26$		**0.80 (−0.08, 1.67)** $p = .07$	
	N_I=301, N_C=295; I^2=93%		N_I=892, N_C=910; I^2= 81%		N_I=716, N_C=680; I^2= 47%		N_I=133, N_C=117; I^2= 88%	
Pooled ES (95% CI) ***w/o S9 or S20***			**0.42 (0.28, 0.56)** $p < .001$ N_I=876, N_C=897; I^2= 42%				**0.18 (−0.08, 0.44)** $p = .17$ N_I=123, N_C=107; I^2 = 0%	
Overall ES **(95% CI)** 28 comparisons	**0.46 (0.28, 0.64**) $p<.001$; I^2 = 85%; N_I = 2042, N_C = 2002							
Overall ES **(95% CI)** 26 comparisons **(w/o *S9 and S20*)**	**0.38 (0.22, 0.53**) $p<.001$; I^2 = 80%; N_I = 2016, N_C = 1997							

Notes. ES = effect size; CI = confidence interval; PA = physical activity; PE = physical education; N_I = sample of intervention conditions; N_C = sample of control conditions; w/o = without;

[*] when multiple comparison groups were included from a single study; [b] baseline differences between groups;

[#] ES= −0.25 for normal weight children and ES=0.24 for overweight children. All comparisons were based upon post-tests between two groups (type of PA and comparison group).