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EFFECTS OF PHYSICAL ACTIVITY AND MOTOR SKILLS ACQUISITION ON EXECUTIVE FUNCTIONS AND SCHOLASTIC PERFORMANCE: A REVIEW

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ABSTRACT

The aim of this review was to present some of the current knowledge regarding effects of physical activity and motor skills practice on cognitive function and scholastic performance in children and youth.

Current recommendations for physical activity in children focus on the quantitative aspects of physical activity and selected health-related components of physical fitness. The importance of motor skill acquisition early in life is often overlooked, which may limit qualitative aspects of interventions, such as motor skill development, socialization and enjoyment of exercise (Myer, Faigenbaum, Edwards, Clark, Best, & Sallis, 2015). Searching for reviews and meta-analyses was done in ERIC via Ebsco, Google Scholar, MEDLINE, PUBMED, PsycINFO, SPORTDiscus, Summons, and Research Gate. The main findings show that cognition is grounded in perceptual-motor experiences within social

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and cultural contexts. Executive functions (inhibitory control, working memory, and cognitive flexibility) are sometimes more predictive of academic achievements than even IQ or socioeconomic status (Diamond & Ling, 2016). Perceptual-motor behaviors can, according to Lobo, Harbourne, and Dusing (2013) facilitate future development and readiness to learn in school. Larger gains in aerobic fitness can however be predictive of lesser improvements in cognitive performance (Etnier, Nowell, Landers, & Sibley, 2006).

Conclusions and potential recommendations for children and youth are discussed regarding motor skills and learning/cognitive function, including: Motor skill screening provides a valuable tool for identifying children in need of adapted support in motor skill development. Motor skill observations are recommended at school start to increase the predictability of later achievement. Specific 'adapted' interventions should be offered to children with motor skill deficits in order to benefit motor development and motivation for participation in physical activities. The MUGI model could be used for motor skills screening as well as motor skills training.

Keywords: cognition, developmental coordination disorder, executive functions, health economic analysis, learning, motor skills observation, MUGI motor skills training, physical activity, school intervention

INTRODUCTION

Current recommendations for physical activity (PA) often focus on the quantitative aspects of PA and selected health-related components of physical fitness (e.g., aerobic fitness, muscular strength and endurance, flexibility and body composition). The importance of motor skill acquisition early in life is often overlooked, which may limit qualitative aspects of interventions, such as (1) motor skill development, (2) socialisation and (3) enjoyment of exercise (Myer, Faigenbaum, Edwards et al., 2015). Intellectual skills and perceptual-motor skills are psychologically more alike than different and they are acquired in fundamentally similar ways (Rosenbaum, Carlsson, & Gilmore, 2001). Thus the aim of this review is to present some of the current knowledge regarding effects of PA and motor skills practice on cognitive function and scholastic performance in children and youth. Another aim is to propose potential recommendations for children and youth based on the relationship between motor skills and learning/cognitive function.

Cognition is grounded in perceptual-motor experiences within social and cultural contexts. Perceptual-motor behaviours can, according to Lobo, Harbourne, and Dusing (2013) facilitate future development and advance readiness to learn in school. Object interaction, sitting, and locomotor behaviours can be improved in infants and children by focusing on exploration, active trial and error hypothesis testing, variability of practice, high frequency of practice, and caregiver education and involvement. Self-exploration, problem solving, and active involvement in their own learning process are critical factors in children´s motor skill development. Significant differences in motor abilities between children, who were born early or late in the same year, have been found in a study by Gadzic, Milojević, Veroljub, and Vučković (2016), which may have substantial implications for Physical Education (PE) teaching and assessment. Individual feedback and support from a teacher are important in motor skills development (Westendorp, Houwen, Hartman et al., 2014).

Theoretical Background

According to motor skill learning theory preadolescence is the optional time to develop and maintain long-lasting fundamental movement skills (FMS) as well as visual motor skills, reaction time, and academic attainment in school-age children (Myer et al., 2015). The timing of brain development and associated neuroplasticity for motor skill learning makes the preadolescence period a critical time to develop**,** reinforce and automatize FMS in boys and girls (Myer et al. 2015).

The Motor skills as Ground for Learning (MUGI) model [in Swedish: Motorisk Utveckling som Grund för Inlärning] used e.g., in the Bunkeflo intervention by Ericsson (2003) is built on the assumption that embodied cognition is attained through sensory–motor interactions and experienced automatization of FMS. The MUGI theory was developed with inspiration from the self-efficacy concept in the social cognitive theory (Bandura, 1997).

According to Bandura (1997) cognitive guidance is especially important in early phases of skill development, when a cognitive representation of the skill is formed. It is of importance that any feedback given is structured to build a sense of personal efficacy as well as a specific skill. Corrective feedback that highlights successes and directs attention to relevant aspects of sub skills aids the development of proficiency. Informative feedback improves the performance as well as facilitates observational learning for similar activities. The aim with continued practice is that skills become fully integrated and are executed with ease. Once a skill becomes routinized, it no longer requires higher cognitive control. The execution can then be regulated by lower sensory-motor systems in managing recurrent task demands.

> After people develop adequate ways of managing situations that recur regularly, they act on their perceived efficacy without requiring continuing directive or reflective thought. (Bandura, 1997, p. 34)

This disengagement of thought from action performing has considerable functional value. Having to think about details in every skilled activity would consume most of the brain's attentional and cognitive resources. The automatization of complex skills involves several processes and Bandura (1997) outlines three major steps:

1. Mergerization, i.e., segments of the skill are merged into larger skills until it becomes a fully integrated routine that no longer requires cognitive organization or linkage.
2. Production of contextual linkages. Practiced actions repeatedly in the same situations are linked to recurrent contexts so that performers respond instantly without having to think about what to do.
3. Shift of attention from execution to result of the action.

METHODS

Searching for relevant reviews and meta-analyses was performed in 2016 in the following databases: ERIC via Ebsco, Google Scholar, MEDLINE, PUBMED, PsycINFO, SPORTDiscus, Summons, and Research Gate. Additional studies were identified through back-searching bibliographies. Inclusion criteria were trials conducted 2000-2016, with an intervention of PA in children younger than 19 years that measured cognitive functions or academic outcomes. The following search words were used in different combinations: Control/experimental group, Experiment, Effect size, Matched groups, Physical activity/education, Exercise/physical fitness, Motor coordination, Spatial Ability, Psychomotor Skills, Fundamental Movement Skills (FMS), Academic achievement/attainment, Student promotion/learning, Scholastic grades/marks, Cognition, and Executive Functions (EFs).

RELATIONSHIPS BETWEEN PHYSICAL ACTIVITY AND COGNITION

There are some persuasive evidence that PA can improve children's concentration and arousal, which might indirectly benefit academic performance (Bailey et al., 2009) and these positive relationships between PA and cognitive performance are relatively reliable according to Etnier, Nowell, Landers et al. (2006). Sibley and Etnier (2003) included 44 studies in a meta-analysis and found positive relationships between PA and cognition across all design types, for all participants (4-18 years), and for all types of physical activities (aerobic, perceptual-motor, resistance/circuit and PE programs). Middle school and elementary age students were found to receive the most cognitive benefit from PA.

Across 50 reviewed studies, a total of 251 associations between PA and academic performance were found, representing measures of academic achievement, academic behaviour, and cognitive skills and attitudes (Rasberrya, Leea, Robina et al., 2011). Castelli, Hillman, Buck et al. (2007) examined elementary school children (n=259) and found positive associations between aerobic fitness and academic performance (reading, and mathematic achievements). Negative associations were found between body mass index and academic performance. Also Fedewa and Ahn (2011), who included 59 studies from 1947 to 2009 in a meta-analysis found significant and positive associations. Most of 20 cross-sectional studies showed that children who are more physically fit tend to have higher cognitive functions and academic achievements.

In an extensive literature search of 844 publications Singh, Uijtdewilligen, Twisk et al. (2012) included 14 longitudinal intervention studies in a systematic review and found strong evidence of a significant positive relationship between PA and academic achievement in children. A majority of 137 studies was found to support the view that physical fitness, single bouts of PA, and PA interventions benefit children´s cognitive function (Donnelly, Hillman, Castelli et al., 2016).

Prospective associations between PA at 11, 15, and 18 years of age and cognition in young adulthood were examined in Brazil (n=3235). Adolescents who were active at moderate levels, and specifically if they maintained these levels, showed higher cognitive performance than those who were active at vigorous levels. Esteban-Cornejo et al. (2015) conclude that moderate levels of PA may have the greatest benefit on cognitive performance and high levels of

PA might impair cognitive performance. The earlier to start engaging in moderate levels of PA, the higher improvement can be expected on cognitive performance.

Promoting PA for adults can improve employee health and brain function and increase financial returns for the company (Ratey & Loehr, 2011). However, muscular strength has not been found to be associated with academic performance in children and youth (Castelli, Hillman, Buck et al., 2007; Esteban-Cornejo, Tejero-González, Martinez-Gomez et al. 2014). Resistance training and PA that brings little joy and lacks social components and cognitive challenges appears NOT to improve cognition (Diamond & Ling, 2016).

Relationships between Motor Skills and Cognition

Evidence indicates that motor competence (MC) is positively associated with perceived competence and multiple aspects of health (i.e., PA, cardiorespiratory fitness, muscular strength, muscular endurance, and healthy weight status). Children who do not participate regularly in structured motor skill-enriched activities during physical education (PE) classes or sports programs may never reach their genetic potential for motor skill control which underlies sustainable physical fitness later in life. Youth who are ill-prepared for play and sport have fewer opportunities for positive social interaction and are less likely to experience enjoyment of PA (Ericsson, 2008; Myer et al., 2015).

Children (11 years old) with low MC (n=26) performed poorer on fitness tasks, were less physically active and had lower perception of athletic competence and social acceptance than children with high MC (n=41), (Vedul-Kjelsås, Stensdotter, Sigmundsson et al., 2015). The strength of associations between MC and both cardiorespiratory endurance and muscular strength tends to increase from childhood into adolescence (Robinson, Stodden, Barnett et al., 2015).

Well-developed gross motor skills facilitate children´s cognitive functioning (Westendorp, Hartman, Houwen et al., 2011) and higher levels of MC are associated with higher order cognitive function, working memory and processing speed. Son and Meisels´ (2001) study included 12,583 children in US kindergartens and found that gross motor skills and visual motor skills were unique, significant predictors of first-grade reading and mathematics achievement; suggesting longitudinal relations between early motor skills and the skills in later cognitive achievement (also found by Ericsson & Karlsson, 2012). The results support the hypothesis that motor skills, specifically visual motor skills, are related to later cognitive achievement and are able to successfully identify children at risk for academic underachievement later in school.

Westendorp et al. (2011) compared gross motor skills of 7- to 12-year-old children with learning disabilities (n=104) with those of typically developing children (n=104). Children with learning disabilities scored poorer on both locomotor and object-control than their typically developing peers. A specific relationship was found between reading and locomotor skills and between mathematics and object-control skills: the larger children's learning lag, the poorer their motor skill scores.

Geertsen, Thomas, Larsen et al. (2016) included 423 Danish 9-year-olds in a cross-sectional study and found that both fine and gross motor skills were associated with cognitive domains, such as working memory, episodic memory, sustained attention and processing speed (all $p<0.001$), whereas exercise capacity (i.e., intermittent running) was only associated with sustained attention and spatial working memory.

Effects of Aerobic (Cardiorespiratory) Training on Cognition

Krustrup, Dvorak, and Bangsbo (2016) conclude that small-sided football games (e.g., 5v5 or 8v8) in schools and leisure-time sport clubs improve not only physical fitness and health profile, but also well-being and learning in children.

Lees and Hopkins (2013) reviewed eight randomized control trials (RCT) studying the effects of aerobic PA (APA) on cognitive performance. All studies showed that APA had a generally positive impact on children's cognition and psychosocial function. However, this relationship was found to be minimal in many studies and in some measures, no significant improvement was seen at all. In a meta-analysis Hansen et al. (2014) found that larger gains in aerobic fitness from pretest to posttest were predictive of *lesser improvements* in cognitive performance. A nonlinear relationship was also found between fitness and spelling and mathematics scores among second and third year students (n=687). The greatest effect on academic achievements was found for children below a particular fitness threshold compared to those above. Thus, aerobic fitness does not appear to explain a meaningful percentage of the variance in cognition. A single session of moderate PA can however have positive effects on brain function, cognition, and scholastic performance depending on the characteristics of the PA. But high stress or fatigue from too intense activity may blunt the beneficial effect (Bangsbo, Krustrup, Duda et al., 2016).

Esteban et al. (2014) who included 2038 Spanish youths aged 6-18 years in a cross-sectional study found that cardiorespiratory capacity and motor ability, both independently and combined, may have a beneficial influence on academic performance in youth. Haapala et al. (2014) also investigated associations of cardiovascular and motor performance with academic skills and found, however, that cardiovascular performance in grade 1 (n=174) was *not related* to academic skills in grades 1–3 (n=167). But poorer motor performance was associated with worse academic skills in children, especially among boys. Esteban et al. (2014) observed the same negative effects of low cardiorespiratory capacity and motor ability on academic performance. These findings emphasize early identification of children with poor motor performance and actions to improve children's motor performance and academic skills during the first school years.

EFFECTS OF MOTOR SKILLS TRAINING ON COGNITION

Morgan, Barnett, Cliff et al. (2013) included 22 interventions in a systematic review and meta-analysis. All but one evaluated effects in primary/elementary schools and all reported significant effects for FMS. Meta-analyses revealed large effect sizes for overall gross motor proficiency and locomotor skill competency. A medium effect size for object control skill was observed. The authors´ conclusion is that school- and community-based programs that include developmentally appropriate FMS learning experiences, delivered by PE specialists or highly trained classroom teachers, significantly improve FMS in youth.

The relationship between gross motor skills and cognitive performance appears to be specific rather than general. An intervention of 16 weeks of specific ball skill training (40 minutes per week) was sufficient for improving ball skills (automatization of basic ball skills) in children with learning disabilities but no effects were found on any cognitive parameters (reading and mathematics) or EFs (problem solving or cognitive flexibility) compared to a control group (Westendorp et al., 2014).

Draper, Achmat, Forbes et al. (2012) evaluated the Little Champs program for motor development on gross motor skills and cognitive function of children (n=118). The children were exposed to play with the opportunity to develop motor skills. The results showed that children exposed to eight months of the program had significantly better overall scores for locomotor and object control compared to a control group. There was a statistically significant improvement in the cognitive scores of children who participated regularly in the program. The findings suggest that even a limited low intensity program for motor development can positively impact gross motor skills and cognitive function in disadvantaged preschoolers. The authors conclude that play and opportunity to develop FMS form the foundation for the development of skills needed in sport later in childhood and adolescence. Participation in the program can also serve to enhance the social skills and increase self-efficacy regarding motor skills (Draper et al., 2012).

Koutsandréou, Wegner, Niemann et al. (2016) examined the influence that different types of exercise programs had on primary school children's working memory. Participants (n=71) were randomly assigned to a cardiovascular exercise (CE), a motor exercise (ME) or a control group. The intervention involved 10 weeks of afterschool exercise, 45 minutes three times a week. Students in the control group participated in assisted homework sessions. Working memory performance of the 9-10 year olds benefited from both the CE and ME programs, but not from the control condition. The increase in working memory performance was significantly larger for children in the ME compared to the CE group. Special motor demanding interventions seems to be a beneficial strategy to improve working memory in preadolescent children. In a consensus conference 24 researchers from different areas conclude that mastery of FMS is beneficial to cognition and scholastic performance in children and youth (Bangsbo, Krustrup, Duda et al., 2016).

Effects of Physical Education (PE) Programs

The school is the arena where it is possible to reach the vast majority of children and youth, also those who are not otherwise regularly physically active. Increased focus on and time for PA with qualified activities can be a possible way to promote motor skills, school performance as well as motivation for participation in PA (Bangsbo et al., 2016). Public school curricula have the greatest promise for accessibility to all (Diamond & Lee, 2011; Ericsson, 2003; Ericsson & Karlsson, 2012). Although PE is widely acknowledged to contribute to health and physical development in children and to provide opportunities for FMS acquisition, many schools have reduced or eliminated PE in an effort to increase students' academic performance. However, no empirical evidence exists to suggest that the elimination of PE is related to higher academic achievement and research studies support PE as an important component of children's health and wellbeing (Hillman, Erickson, & Kramer, 2008). In fact, when time is taken away from academic lessons in favor of increased PE, it does not come at cost of scholastic performance (Bangsbo et al., 2016).

Many of the educational benefits claimed for PE and school sport are however dependent on contextual and pedagogic variables. Type of activity and psychological factors (e.g., self-esteem, depression) could mediate the association between PA and academic performance (Bailey et al., 2009).

In 39 intervention studies Fedewa and Ahn (2011) found significant effects on children´s achievement and cognitive outcomes from perceptual motor training, regular PE classes and aerobic training. No significant effects were found from resistance/circuit training on children´s achievement and cognitive outcomes. Significantly higher effect sizes were found when PA was provided three compared to two times per week. Elementary age children were found to benefit the most. Cognitively impaired or physically disabled children appeared to benefit even more than typically developing children.

Costa, Abelairas-Gomez, Arufe-Giraldez et al. (2015) emphasize the importance of PE and qualified PE teachers in child development. In their experiment, motor skills activities were used to enhance children's overall development and body awareness. For 24 weeks, three-year-old children (n=47) underwent a structured PE plan conducted by a PE teacher. The sessions included adequate motor coordination, overall coordination, spatial structure, temporal organization, body structure, body image, body knowledge, and laterality. The control group (n=48) had PA in the school playground, but it was not structured or conducted by a PE teacher. The results showed that ability scores were significantly higher than in the control group, for all measured abilities: coordination and balance, body scheme, temporal organization, and spatial organization abilities.

Eleven of 14 studies found one or more positive associations between school-based PE and indicators of academic performance. Studies in the review examined increased PE time (achieved by increasing the number of days PE was provided each week or lengthening class time) and/or improved quality of PE (e.g., trained instructors and increasing active time during PE class) (Rasberrya et al., 2011).

In the so called Bunkeflo project Ericsson and Karlsson (2014) studied long-term effects on motor skills and school performance of increased PE over nine years. An intervention group (n=129) achieved daily PE (5x45 minutes/week) and if needed one extra lesson (60 minutes/week) of adapted MUGI motor training. The control group (n=91) had PE two lessons (90 minutes/week). Motor skills were evaluated by the MUGI observation checklist and school achievements by grades in Swedish, English, Mathematics, and PE and the proportion of pupils who qualified for upper secondary school. Both boys and girls improved significantly in motor skills and the differences between them decreased with extended PE and extra motor training in school. In school year 9 there were no motor skills deficits in 93% of the pupils in the intervention group compared to 53% in the control group, and 96% of the pupils in the intervention group compared to 89% in the control group qualified for upper secondary school. The conclusion is that daily PE and adapted motor skills training during the compulsory school years is a feasible way to improve not only motor skills but also school performance and the proportion of pupils who qualify for upper secondary school. The study clearly shows that increased PE and adapted motor skills training conferred both higher grades and higher proportion of pupils who reached qualification for upper secondary school. Additionally health-economic analyses of the Bunkeflo intervention (daily PE and adapted MUGI motor skills training) were made, which showed that daily PE in all Malmö schools would increase the potential production value by SEK 59 million (Euro approx. 6.4 million) during the 10-year period after compulsory school. The higher levels of PA would reduce morbidity costs by SEK 56 million (>Euro 6 million). These values exceed the SEK 16 million (Euro 1.2 million) that costs of staff and premises amount to. An investment per pupil of SEK 4,600 (Euro 500) for all nine compulsory school years would give productivity gains and reduced morbidity costs of SEK 38,000 (Euro 4,130) over the 10 years after leaving school (Gerdtham, Ghatnekar, & Svensson, 2012).

Kalaja (2012) conducted a PE intervention study in Finland (n= 446 grade 7 students) during 33 weeks which focused FMS. The intervention group showed more positive development compared to the control group. Girls scored higher in static balance and rope jumping tests, whereas boys scored higher in dynamic balance, leaping, throwing, and dribbling tests as well as in perceived PA competence and ego-involving motivational climate. The results showed that task-involving motivational climate was a strong predictor of perceived PA competence and self-determined motivation toward PE. The study demonstrated that in secondary school PE there is a need to emphasize teaching of students'

FMS. Improved skills might be one factor to prevent the typical decline of PA within adolescence.

The Finnish education system has received worldwide attention due to the top academic performance of Finnish school students (Yli-Piiparia, 2014). PE potentially contributes to the overall success; the subject has a solid foundation in Finnish schools and strong support in Finnish society. Over the past decades, PE has been marginalized across the Western world and PE time in Finland has diminished across four decades. However, the education reform from 2012 allocate more time and funding for elementary and middle school PE by adding an annual weekly lesson for two years during grades 1-9. It is likely that the increased resources will be used for health-enhancing PE. In addition, schools and PE teachers are required to implement a new criterion-referenced assessment and feedback program to evaluate students' fitness levels and to motivate students to participate in health-enhancing PA. This is in contrast to norm-referenced assessment, i.e., judging and grading the learning of students by comparing and *ranking* each student against the performance of other students in the same cohort.

School PE in Finland aims to enhance students' competency in motor skills and movement patterns, promote a physically active lifestyle and physical fitness, promote responsible personal and social behavior, appropriate values, and to promote enjoyment of and self-expression in PA. At the basic education level (grades 1–9) the main emphasis is on learning a wide variety of motor skills. Although the national curriculum has the same PE objectives for girls and boys, the 5th–9th grade curricula states that PE instruction must make allowances for the differing needs of boys and girls at this stage of development, as well as the pupils' differentials in growth and development. Since the 1970s, one of the most central purposes of schooling in Finland has been the holistic development of students; PE is an important piece in an academic education system that helps the nation to achieve the objectives of the 21st century (Yli-Piiparia, 2014).

Soares and Hallal (2015) found a strong negative correlation between students in Brazil who had no PE and the proportion of active adolescents. Despite challenges in terms of infrastructure, lack of materials, low value of discipline in school, and low salaries of teachers as compared to those observed in other countries, the existence of more PE classes is related to higher PA levels among Brazilian youth.

EFFECTS OF CLASS-ROOM BASED PHYSICAL ACTIVITY

Eight of nine studies found positive associations between classroom-based PA and indicators of cognitive skills and attitudes, academic behavior, and academic achievement; none of the studies found negative associations. Most interventions reviewed used short breaks (5–20 minutes) that required little or no teacher preparation, special equipment, or resources (Centers for Disease Control and Prevention, 2010). However, no significant effects were reported on academic achievement after a 16-months intervention of 15 minutes daily classroom-based PA (Singh et al., 2012).

In a randomized controlled trial (RCT), pupils in 12 primary schools were selected to an intervention (n = 249) or control group (n = 250). Physically active academic lessons were given for two years, 22 weeks/year, three times a week, 20-30 min/lesson. Classroom teachers were responsible for PA during the academic lessons, of moderate-to-vigorous intensity. All children started with performing a basic exercise, such as jogging, hopping in place, or marching. For mathematics, children had for example to jump eight times to solve the multiplication '4 x 2'. For language, children had to perform a squat for every spelled letter in the word 'dog'. After performing the specific exercise, children had to continue performing the basic exercise until the next academic task was shown. The control group participated in regular classroom lessons. Academic achievement was measured by two mathematics tests (speed and general math skills) and two language tests (reading and spelling). Mullender-Wijnsma, Hartman, De Greeff et al. (2016) report significantly greater gains in mathematics speed test, general mathematics, and spelling, in comparison with the control group. But no differences were found on the reading test, nor in tests of executive functions (EFs) (inhibition, working memory, or cognitive flexibility) (De Greeff, Hartman, Mullender-Wijnsma et al., 2016).

Howie, Schatz, and Pate (2015) studied effects of classroom exercise breaks (n=96) and found small improvements in girls´, but not in boys´, mathematics performance after 10 and 20 minutes of exercise (e.g., stationary marching, jumping and running in place). No improvements in EFs were found in working memory and/or trial-making test after classroom exercise breaks.

Tarp, Domazet, Froberg et al. (2016) examined effects of PA during academic subjects, recess, school transportation, and leisure-time. Cognitive performance was assessed by mathematics skills (arithmetic's, algebra, problem-solving and geometry) and an EFs test of inhibition (flanker task). No evidence was found for effectiveness of this 20-week school-based intervention (which did not include increased PE).

EFFECTS ON EXECUTIVE FUNCTIONS (INHIBITORY CONTROL, WORKING MEMORY, AND COGNITIVE FLEXIBILITY)

Not all studies on academic achievements, cognition and learning include measures of EFs, i.e., inhibitory control, working memory, and cognitive flexibility. EFs, although sometimes hard to assess, may be considered to be more objective measures of learning and cognition than scholastic performance alone. A review of 84 controlled studies showed that EFs can be more predictive of academic achievements than IQ or socioeconomic status (Diamond & Ling, 2016). EFs are involved when we think before we act, and resist temptations or habitual reactions. They help us stay focused, reason, solve problems, and adjust to changed demands or priorities. Movement planning is related to higher order executive control early in life (Gottwald, Achermann, Marciszko et al., 2016) and EFs can be improved at any age through training and practice. However, wide transfer does not seem to occur, according to Diamond and Lee (2016). PA or resistance training without a cognitive component, i.e., requires no EF skills (e.g., running on a treadmill or riding a stationary bike), does not seem to improve any EF skill. Tomporowski, Davis, Miller et al. (2008) reviewed twelve studies and found that gains in children´s mental functioning due to exercise training were seen most clearly on exercise tasks that involved EFs.

Kamijo, Pontifex, O'Leary et al. (2011) examined the effects of a 9-month RCT on changes in working memory performance in preadolescent children (n=43). The intervention aimed at improving cardiorespiratory fitness and the children intermittently participated in at least 70 minutes of moderate to vigorous PA per day. However, children also engaged in games with a skill theme (e.g., dribbling) and small-area games were offered as part of the motor skill practice. The results indicated that increases in cardiorespiratory fitness were associated with improvements in the cognitive control of working memory in preadolescent children. The beneficial effects of the PA intervention were greater for tasks, which required greater working memory demands. The activities were aerobically demanding, but simultaneously provided opportunities to refine motor skills.

Well-developed gross motor skills facilitate children´s cognitive functioning (Westendorp et al., 2011) and higher levels of motor competence are associated with higher order cognitive function, working memory and processing speed. Structural equation modeling (controlling for verbal comprehension, attention deficit hyperactivity disorder symptoms, and socioeconomic status), used in studies by Rigoli, Piek, Kane, & Oosterlaan, 2012), show that the association between motor coordination and academic achievement could be understood as motor coordination (specifically aiming and catching skills) has an indirect impact on academic outcomes (word reading, spelling, and numerical operations) via working memory.

People who are very overweight tend to have lower EFs than people who are more physically fit. Improvements in aerobic fitness are however uncorrelated with cognitive improvements, but people who are more physically active have better EFs than those who are more sedentary (Diamond & Ling, 2016).

Martial arts and PE programs, that train diverse executive-function abilities, have shown more cognitive benefits than computerized training. Exercise that requires thought, planning, concentration, problem-solving, working memory and/or inhibitory control (e.g., traditional tae-kwon-do, yoga) have resulted in greater EFs gains than other physical activities. Combined cognitive and physical training (balance, eye-hand coordination, motor coordination and flexibility practice in gymnastics, dance, yoga, tennis and table tennis) resulted in significant cognitive benefits, still evident five years later, and the gains were larger for the combined training (physical exercise + cognitive tasks) than for the cognitive training alone (Diamond & Ling, 2016). The more time spent practicing – the larger effect can be expected. But benefits of PA for cognition may also depend on how much joy the PA brings and the way activities are presented and conducted has great importance.

Juvenile delinquents who practiced traditional tae-kwon-do showed less aggression and anxiety and improved in social ability and self-esteem. Another group in modern martial arts (competitive sport) showed more juvenile delinquency and aggressiveness, and decreased self-esteem and social ability. Traditional tae-kwon-do emphasizes respect, humility, responsibility, perseverance, and honor; whereas modern martial arts emphasize competition (Diamond & Lee, 2011).

Exercising bimanual coordination may improve EFs. Better academic performance and class-behavior was found from combined movement plus instruction than for traditional teaching methods. Those with the poorest EFs seem to gain the most (Diamond & Ling, 2016).

Prefrontal cortex is the newest area of the brain and the most vulnerable. Lack of sleep impairs prefrontal cortex and EFs, so does the feeling to be excluded or of not belonging. Since stress, sadness, loneliness, or poor health impair EFs, and the reverse enhances EFs, it seems that interventions that also support emotional, social, and physical needs will be the most successful at improving EFs (Diamond & Ling, 2016).

Evidence show no EF benefits from resistance training (Diamond & Ling, 2016), although significant increases in daily spontaneous PA were found in boys after 19 weeks of resistance training (Myer et al., 2015). Also PA lessons (De Greeff et al., 2016) or classroom exercise breaks (Howie et al., 2015) did not result in any significant change in EFs (inhibition, working memory, or cognitive flexibility). Sports might benefit EFs more than aerobic exercise alone, since sports challenge EFs in requiring sustained attention, working memory, and disciplined action. Sports can also bring joy, pride, and social bonding; all of which decrease sadness, stress and loneliness (Diamond & Lee, 2011).

SUMMARY AND DISCUSSION

Research has shown that both cardiorespiratory fitness and motor skills play an important role in cognitive development during childhood. Children who are more physically fit have higher cognitive functions and academic achievements (Etnier et al., 2006; Fedewa & Ahn, 2011) and people who are more physically active have better executive functions (EFs) than those who are more sedentary. Motor skills and EFs can be improved at all ages, from infants through elders (Diamond & Ling, 2016; Ericsson, 2003; Ericsson & Karlsson, 2012).

PA and cardiorespiratory fitness are beneficial to brain structure, brain function and cognition. Regular PA affects children´s performance on mental tasks and modifies brain structure and function (Donnelly et al., 2016). However, the cardiovascular fitness hypothesis cannot be confirmed by the findings in this review, since there is limited scientific evidence that the clearest effects on cognitive abilities are achieved by improved fitness. Even more uncertain is the relationship between cognition and total PA. A nonlinear relationship between fitness and cognition has been found in several studies. Thus, aerobic fitness does not appear to explain a meaningful percentage of the variance in cognition. Moderate levels of PA may have the greatest benefit and high levels of PA might impair cognitive performance (Hansen et al., 2014).

The earlier to start engaging in moderate levels of PA, the higher improvement can be expected on cognitive performance (Esteban-Cornejo et al., 2015).

Mastery of FMS is beneficial to cognition and scholastic performance in children and youth (Bangsbo et al., 2016). Children with better motor skills show better inhibitory control, attention capacity and academic performance than children with poorer motor skills (Haapala, 2013). They also exhibit higher order cognitive function, working memory and processing speed. The strength of associations between motor competence and both cardiorespiratory endurance and muscular strength tends to increase from childhood into adolescence (Robinson et al., 2015). It is, however unclear as to whether simple aerobic exercise (such as walking) or motor skill training without an aerobic component, assists developing cognitive functions and brain health in growing children. Effects of motor skills training and muscle strength is not enough investigated for any conclusions to be drawn, according to Berg and Ekblom (2015). It may be the case that aerobic training in combination with motor skill training produces the best prerequisites for cognitive development (Haapala, 2013). Motor skills training and regular PA enhance corticomotor development and academic performance in school age youth, according to Myer et al. (2015).

Physiological or psychological mechanisms that are impacted by PA participation, but not on changes in aerobic/cardiovascular fitness may be responsible for the benefits to cognitive performance. Stress, sadness, loneliness, and poor physical health (e.g., infections, overweight, sleeping problems) impair EFs. Resistance training and PA that brings little joy and lacks social components and cognitive challenges appears *not* to improve EFs. Activities that support emotional, social, and physical needs are the most successful at improving EFs (Diamond & Ling, 2016).

Public school curricula have the greatest promise for accessibility to all (Bangsbo et al., 2016; Diamond & Lee, 2011; Ericsson & Karlsson, 2014) and an increase of the school subject PE can be a feasible way to improve not only motor skills, but also scholastic performance in children and youth. The school is the only arena where we can reach the vast majority of children and youth. Compulsory school curricula therefore have the greatest potential in offering PA. For many children and youths, schools curricula are the only way they can receive PA on a daily basis. Before, during and after school, PA can promote scholastic performance in children and youth. Additionally, a single session of moderate PA has an acute benefit to brain function, cognition and scholastic performance and time taken away from lessons in favor of PE does not come at the cost of getting good grades (Bangsbo et al., 2016). The educational benefits from PE and school sport are however dependent on contextual and pedagogic variables (Bailey et al., 2009). Type of activity and psychological factors (e.g., self-esteem, depression) could mediate associations between PA and academic performance. Enhancing physical enjoyable noncompetitive activities in the school curriculum, may yield benefits in academic achievements and psychological health of children, particularly girls (Bunketorp Käll, Malmgren, Olsson, Lindén & Nilsson, 2015). Daily PE in combination with adapted motor skills training during the compulsory school years has shown to be a feasible way to improve not only motor skills but also academic achievements and the proportion of pupils who qualify for upper secondary school (Ericsson & Karlsson, 2012). Research clearly shows that increased PE and adapted motor skills training can positively influence both higher grades and higher proportions of pupils who reach qualification for higher education. The investment can be health-economic profitable for the municipality (Gerdtham, Ghatnekar, & Svensson, 2013; Ratey & Loehr, 2011).

Motor assessment is associated with later school achievement and can be used as one of the indicators of future school achievement of young children. Motor performance, especially visual motor performance, can contribute to predict children's cognitive preparedness for school. Including motor skills in an early school assessment may increase the predictability of later achievement and the probability of identifying children at risk for school failure (Ericsson, 2003, 2008a, 2008b; Ericsson & Karlsson, 2014; Son & Meisels, 2006). Motor skills screening at school start is thus a valuable tool for identification of children in need of adapted support in motor skills development. Specific interventions are needed for children with learning disabilities, programs that facilitate both motor and academic abilities (Bangsbo et al., 2016: Ericsson & Karlsson, 2012; Westendorp et al., 2011).

In summary, based on studies in this review and earlier research (Ericsson, 2003; 2008a; 2008b), a theory regarding the relationships between PA, motor skills and scholastic performance can be formulated as follows: Improvements and automatization of FMS lead to increased physical self-esteem, which give better prerequisites for attention and comfort in school, which lead to increased motivation to learn and to attend classes. An illustration of this positive spiral is shown in Figure 1.

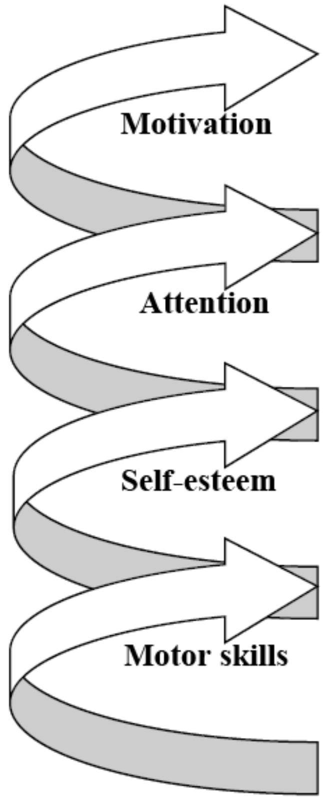

Figure 1. The MUGI model for understanding of the relationship between motor skills and learning: Improvements and automatization of fundamental motor skills lead to increased self-efficacy and physical self-esteem, which give better prerequisites for attention and comfort in school, which lead to increased motivation to learn and to attend classes.

CONCLUSION

This review includes not only RCT interventions, but also school based studies, where perfectly matched control groups as well as randomization of individuals are hard to achieve. The lack of RCT in the area of PA and motor skills research, which is a limitation, makes it relevant to consider also the findings in studies with other designs, e.g., quasi experimental or pre-post trials. However, conclusions derived from the studies reviewed in this article must be drawn and interpreted with cautiousness.

Physical activity (PA) can promote scholastic performance in a broad sense. Whether it does so, depends on active participation and engagement in the physical activities. For children and young people, aged 5-17 years, PA includes play, games, Physical Education (PE), sports, transportation, and recreation. PA immediately prior to a learning session should not be too intense since high stress or fatigue may blunt the beneficial effect. Initiatives and adjusted practice to increase motivation and competence for participation, including automatization of fundamental movement skills (FMS), are essential. Although PA might be beneficial at all stages of life, early interventions are important for the improvement and/or maintenance of cognitive health and function throughout the adult lifespan. The school is the only arena where it is possible to reach all children, also those who are not otherwise regularly physically active. PE can be recommended as a daily subject at least 40 minutes per schoolday. Motor skills screening provides a valuable tool for identifying children in need of adapted support in motor skills development. The MUGI checklist could be used as a pedagogical tool in conducting motor skills screening. Specific 'adapted' interventions should be offered to children with motor skills deficits in order to benefit motor development and motivation for participation in physical activities.

Recommendations Regarding Physical Activity for Children and Adolescents

In order to improve cardiorespiratory and muscular fitness, bone health, cardiovascular and metabolic health biomarkers and reduced symptoms of anxiety and depression, the following are recommended by WHO (2010): Children and young people should accumulate at least 60 minutes of moderate to vigorous-intensity PA daily. All children and adolescents should thus be encouraged to be physically active at least 60 minutes per day in order to achieve health benefits (Berg & Ekblom, 2015). The activities should be as varied as possible to provide aerobic fitness, muscle strength, flexibility, speed, shorter reaction times and coordination (Berg, 2014). Activities should develop children physically and improve movement prerequisites, i.e., enable automatization of FMS. A game-play environment that is mentally engaging and providing joy is recommended (Diamond & Ling, 2016; Myer et al., 2015). In order to improve motor skills and scholastic performance the following recommendations can be formulated:

1. Mastery of FMS is beneficial to cognition and scholastic performance in children and youth, and both PA throughout school and in leisure can benefit motor functions. PA specifically focused to improve motor control in children and adolescents (Myer et al., 2015) are recommended. In secondary school PE there is a need to emphasize teaching of students' FMS. Improved motor skills might be one factor to prevent the typical decline of PA within adolescence (Kalaja, 2012).
2. Motor skills screening provides a valuable tool for identifying children in need of adapted support in motor skills development (Bangsbo et al., 2016). Early identification of children with poor motor performance is recommended in order to improve their motor and academic skills during the first school years (Ericsson, 2003, 2008b; Haapala et al., 2014). Motor skills observations are recommended at school start to increase the predictability of later achievement and the probability of identifying children at risk for school failure (Son & Meisels, 2001). The MUGI checklist could be used as a pedagogical tool in conducting motor skills screening (Ericsson, 2003, 2008a, 2008b; Ericsson & Karlsson, 2012).
3. Pedagogical skills are needed in teaching motor skills. Age-appropriate instructions should be conducted by qualified PE teachers (Costa et al., 2015; Ericsson, 2008b; Myer et al., 2015). Integrative Neuromuscular Training (INT) can be recommended for improvements of FMS, as well as for cortex structural, and cognitive development (Myer et al., 2015); the training should be intermittent rather than continuous. A feasible tool for automatization of FMS can also be the MUGI model. Practice should build self-confidence and create feelings of belonging. See description below.
4. Specific attention to motor skills training in children with learning difficulties is necessary (Ericsson, 2003, 2008a; Westendorp et al., 2014). Pediatric skills are needed in identifying and treating children with development coordination disorder (DCD) (Ericsson, 2003, 2008a, 2008b; Myer et al., 2015). Specific 'adapted' interventions should be offered to children with motor skills deficits in order to benefit motor development and motivation for participation in physical activities (Bangsbo et al., 2016).
5. A single session of moderate intensity PA has transient benefits to brain function, cognition, and scholastic performance with benefits derived for approximately one hour, depending on the characteristics of the PA.

PA immediately prior to a learning session should not be too intense since high stress or fatigue may blunt the beneficial effect. Additional benefits to memory may be derived when moderately-to-vigorous PA is performed after learning (Bangsbo et al., 2016).

6. The school is the arena where it is possible to reach the vast majority of children and youth, also those who are not otherwise regularly physically active. Increased focus on and time for PA with qualified activities can be a possible way to promote motor skills, school performance as well as motivation for participation in PA (Bangsbo et al., 2016). Public school curricula have the greatest promise for accessibility to all (Diamond & Lee, 2011; Ericsson, 2003; Ericsson & Karlsson, 2012) and the National Association for Sport and Physical Education (NASPE) recommends daily PE (Centers for Disease Control and Prevention, 2010). PE can be recommended as a core subject in compulsory school at least 40 min/day (Ericsson & Karlsson, 2014; Myer et al., 2015). Legislation changes require at least three PE classes per week for Brazilian youth (Soares & Hallal, 2015) and are called upon EU member states for all students (European Parliament, 2007).
7. A varied/multisport approach to PE is recommended, coordinated and matched to ability and interest of students for best improvements in aerobic fitness, kinesthetic ability, task orientation and self-efficacy (Ericsson, 2003; Myer et al., 2015). Activities should have EFs (cognitive control functions: flexibility, self-control, working memory) demands (Diamond & Ling, 2016).

CHALLENGES FOR FUTURE RESEARCH

Although research gives us important knowledge all the time, there are still many questions that need to be examined further, in order for any firm conclusions to be drawn. There is a need to synthesize the evidence regarding brain and motor control to provide a framework for a sustainable/life-long interest in PA. Future intervention studies specifically designed to test the dose-response relationship between cardiorespiratory training as well as motor skills training and cognition are needed. Physiological or psychological mechanisms that are impacted by PA participation, but not on changes in aerobic/cardiovascular fitness may be responsible for the benefits to cognitive performance (Etnier et al., 2006). The cognitive components of the PA might thus be the main contributors to any EF benefit. Consensus regarding how to measure EFs (inhibitory control, working memory, and cognitive flexibility) is needed and consensus regarding the concept Fundamental Movement/Motor Skills (FMS) is needed, as well as how to measure different parts of motor skills.

In school-based interventions it is important to clearly separate effects of PE programs, from those of classroom activities or extended recess time. Robust studies and meta-analyses are needed to provide evidence of the effectiveness of different PE programs and motor skills interventions. Here below, some examples of research questions are discussed, that hopefully will give inspiration to design and conduct further studies in the area of PA and cognition.

How Much Can Learning and EFs Be Improved?

We know that motor skills (Ericsson, 2008; Morgan, Barnett, Cliff et al., 2013) and EFs can be improved at all ages, from infants through elders (Diamond & Ling, 2016), but we do not know how much they can be improved.

Are Cognitive Benefits Different in Different Groups, e.g., Age, Gender, SES Level, Ethnic Group, or Numbers of Participants?

Cognitively impaired or physically disabled children appear to benefit more from perceptual motor training, regular PE classes and aerobic training than typically developing children. In the study by Fedewa and Ahn (2011) a small group (n <10) intervention showed the largest effect, followed by a medium group (n= 10-30).

How Long Do Benefits Last?

We do not know if benefits from PA last one lesson, six months, one year, five years, or more. However, combined cognitive and physical training resulted in significant cognitive benefits, evident five years later, and the gains were larger for the combined training than for cognitive training alone (Diamond & Ling, 2016).

When Is the Optimal Time to Be Physically Active?

At the same time or just before a math or language class? PA as regular routine? Or in bouts/periods of refresher sessions?

In an experiment, Learning Readiness PE, at Naperville High School, students taking a PE class right before a literacy class showed twice as much improvement in their literacy skills as students who had several hours between PE and the literacy course (Conyers & Wilson, 2015).

Repeated practice produces benefits in EFs, according to Diamond and Lee (2011). Intermittent, rather than continuous, training is more consistent with how children and youth move and play (Myer et al., 2015). Integrative Neuromuscular Training (INT) is conducted in short bursts of meaningful PA to enhance motor skills development, followed by periods of rest.

In School (PE Classes or Classroom Based), Free Time or in Sport Clubs?

Palma (2008) investigated the motor skills development of preschool children in different play programs. Children in an experimental group participated in two distinct movement programs: one based on Free Play and the other consisting of a combination of exploration, free play, oriented play, and activities conducted by the researcher (Play with Orientation). The results indicated that children´s participation in the Play with Orientation program brought gains in their motor development, whereas no changes were observed in the Free Play group, or in the control group.

In a nine-year intervention study pupils (n=129) achieved daily PE and if needed one extra lesson/week of adapted motor training. The control group (n=91) had PE two lessons/week. Motor skills were evaluated by the MUGI observation checklist and school achievements by grades in Swedish, English, Mathematics, PE and proportion of pupils who qualified for upper secondary school. In school year 9 there were no motor skills deficits in 93% of pupils in the intervention group compared to 53% in the control group and 96% of the pupils in the intervention group compared to 89% in the control group qualified for upper secondary school (Ericsson & Karlsson, 2012).

The FIT Kids program (9-month after-school PA**)** including at least 70 minutes per day of a variety of age-appropriate physical activities, games and refining motor skills at a moderate to vigorous PA (MVPA) level, resulted in improvements (but no significant differences between intervention and wait-list group) in working memory, inhibition and cognitive flexibility. In addition, children in the FIT kids program improved their cardiovascular fitness (Hillman et al., 2014).

Physically active academic lessons did not result in any significant change in EFs (inhibition, working memory, or cognitive flexibility) after two years of intervention (De Greeff et al., 2016). No significant differences in cognition were found between control and intervention group after a 16 months intervention of classroom PA (Singh et.al, 2012). No acute effects of classroom exercise breaks were found on boys´ math performance or on EFs in boys and girls (Howie et al., 2015).

Durations? Frequencies?

16 x 40 minutes of specific ball skill training was sufficient for improving ball skills (automatization of basic ball skills) in children with learning disabilities, but no effects were found on any cognitive parameters (reading and mathematics) or EFs (problem solving or cognitive flexibility) compared to a control group (Westendorp et al. 2014).

Overweight children (n=94) were randomly selected to three groups: one control group, and two who participated in physical training games after each school day during 10-15 weeks; one for 20 minutes exercise and one for 40 minutes. The 40 minutes exercise group, but not the 20 minutes group, improved their planning/EFs (i.e., cognitive control, intentionality, and self-regulation) more than did children in the control group (Tomporowski et al., 2008). Significantly higher effect sizes on cognitive functions and academic achievements were found when PA was provided three compared to two times per week (Fedewa & Ahn, 2011).

PE 45 min/day + adapted MUGI motor skills training had positive effects on students´ scholastic performances in the Bunkeflo project (Ericsson, 2008; Ericsson & Karlsson, 2012).

Cycling or running for 30 minutes can improve reaction time and information processing speed, as well as planning, scheduling, inhibition, and working memory. Adults who exercised 5-7 days/week had better attention, reaction time, and cognitive flexibility after 10 weeks than adults who exercised 3-4 times/week (Ratey & Loehr, 2011).

What Are the Best Methods?

Solitary or Group Activities? Cognitive Challenges (Complexity, Novelty, Variety)? Motor Skills (e.g., Balance, Eye-Hand or Bimanual Coordination) Automatization? Pleasure and Joy in Movement?

Two examples of motor skills programs aiming at improving FMS are described below.

Integrative Neuromuscular Training (INT)

Integrative Neuromuscular Training (INT) for youth focus on integration of physical and cognitive training, i.e., to combine physical practice (FMS, core strength and control, agility and coordination, recovery, postural control, and muscular fitness) with cognitive training (social interaction, cognitive distraction, visual motor, neurocognitive, muscular relaxation, and stress management). INT early in life and maintained throughout adolescence will likely maximize one´s potential to optimize motor skills abilities (FMS), cortex structural, and cognitive development and to engage regularly in PA (Myer et al., 2015).

The Motor Skills as Ground for Learning (MUGI) Model

The Motor skills as Ground for Learning (MUGI) model [in Swedish: Motorisk Utveckling som Grund för Inlärning] (Ericsson, 2003), is influenced by social cognitive theory (Bandura, 1997). MUGI is an education program which includes motor skills screening of pupils at school start, information to teachers and parents, and offers of adapted motor skills training. The aim is to identify children with any problems or difficulties in motor skills in order to give early support and stimulate their motor skills development, before motor deficits become a problem to the children. The training is a part of the school's remedial teaching program for pupils with difficulties in motor skills, perception, and self-esteem. MUGI is based on the principle of success, i.e., the children are never asked to perform tasks they are not good at, but instead offered exercises with the aim of automatization of skills coming earlier in motor skills development. One of the most important goals is that children feel motivated and enjoy taking part in physical activities. It is important that the focus is on what the child wants to learn, that goals are achievable, and that the child takes pleasure in practising. Since children often are very good at finding skills they need to practice, the introduction to the training often includes questions like: "What do you think would be a good skill for you to know? "What would you like to learn?" The principles in MUGI motor training can be summarized as:

- Success instead of failure
- No training of skills the child cannot perform
- Automatization of skills in earlier development

With better, i.e., automatized fundamental motor skills the child will hopefully improve in self-efficacy (Bandura, 1997), social abilities, and eventually also in self-esteem. An early evaluation of the MUGI model showed that the motor training in pre-school had positive effects at school start on children's motor control, perception and ability of remembering details. Positive effects on scholastic performance were also found after two and tree school years (Ericsson, 2003). After nine years of intervention students had higher grades and reached the goals of compulsory school to a larger extent than did students in the control group (Ericsson & Karlsson, 2014).

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