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Review

Exercise and children's cognition: The role of exercise characteristics and a place for metacognition

Phillip D. Tomporowski [a,*], Bryan McCullick [a], Daniel M. Pendleton [a], Caterina Pesce [b]

[a] Department of Kinesiology, University of Georgia, Athens, GA 30602, USA
[b] Department of Human Motion and Sport Science, Italian University Sport and Movement, Rome, Italy

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Abstract

Definitive conclusions concerning the impact of exercise interventions on children's mental functioning are difficult to ascertain because of procedural differences among studies. A narrative review of studies was conducted to evaluate the role of two types of exercise interventions on children's cognition. Acute and chronic exercise interventions were classified as quantitative or qualitative on the basis of manipulations of task complexity and, by inference, mental engagement. Both types of interventions enhance aspects of children's cognition; however, their effects on metacognitive processes are unknown. The role of metacognitive processes and their regulation of children's behavior and academic performance are highlighted.
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1. Introduction

The importance of children's movement during physical and mental development has been of interest to both parents and academicians for over a century. The notion that physical and mental prowess are linked is part of cultural wisdom and is embedded as an assumption in western civilization. A cursory historical review of parenting practices and recommendations made by developmental specialists reveals the consensus belief that infants and children who are raised in stimulating conditions that provide the opportunity to move and explore come to learn about their environments. Growing evidence has been amassed over the past 2 decades that exercise, which is a subset of physical activity (PA) defined by methods that are planned, structured, repetitive, and purposeful in the sense that the improvement or maintenance of one or more components of physical fitness is the objective,[1] may promote improvements in mental function. Particularly affected are those cognitive processes termed executive functions, which are involved in behavioral control. Recently, much has been made of the importance of the role of executive processes in daily life and how they benefit children's adaptive behaviors, intellectual functioning, and academic success.

Several quantitative and narrative reviews of research conducted to assess the effects of bouts of acute exercise and exercise training on children's cognitive function have been conducted. All have concluded that the weight of the evidence supports a benefit for both acute exercise bouts and chronic exercise programs. However, several important themes consistently emerge from these reviews. Reviewers who employ meta-analytic methods report that the strength of the relation is small and is moderated by multiple factors.[2,3] Similarly, reviewers who have conducted narrative evaluations point out differences among study characteristics that make definitive conclusions concerning the impact of exercise on children's cognitive function difficult to ascertain.[4–6] Virtually all reviewers recommend additional research that focuses on specific factors that may influence the linkage between exercise and children's cognitive function.

* Corresponding author.
E-mail address: ptomporo@uga.edu (P.D. Tomporowski)
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Reviewers frequently point to the wide variation in the types of exercise interventions that have been employed and suggest that the variations in methods used to engage children in exercise may provide one potential explanation for inconsistencies in research outcomes. Pesce[7] proposed a conceptual model that describes multiple ways in which task factors may moderate the outcomes of acute exercise activities embedded within chronic exercise training. Unique to this model is its emphasis on two inter-related phenomena: 1) learning that occurs during and immediately following acute bouts of exercise, and 2) how that knowledge is modified over the course of repeated exercise bouts. The model provides a way to conceptualize why some types of exercise would produce temporary changes in an individual's cognitive test performance and other types of exercise would produce relatively permanent changes in knowledge that would reflect in better mental functioning. The importance of identifying task conditions that separate effects that are temporary from those that are relatively permanent cannot be overstated. For instance, given that acute bouts of exercise or chronic exercise training results in improvements on tests of executive function, what are the consequences of exercise termination? If the effects of exercise are temporary, declines in performance would be predicted. Thus, a continuous regimen of exercise would be required to maintain exercise's mental boost.[8] However, if the changes in mental processing and learning that occur during exercise reflect relatively permanent changes in knowledge, they would have to be available for an individual's use at later times and, perhaps, under different conditions.

The need to consider how specific characteristics of exercise interventions may influence cognitive function has been voiced; however, only recently have specific recommendations been published. Building on American College of Sport Medicine guidelines for exercise prescriptions developed by Garber et al.,[1] Pesce[9] proposed that studies designed to assess the effects of acute and chronic exercise training can be differentiated into two broad categories: a) those that adhere to a quantitative approach and design their exercise intervention based primarily upon considerations of intensity and duration; and b) those that adhere to a qualitative approach and manipulate exercise in terms of exercise type and the mental engagement involved during exercise. The purpose of the present review is to evaluate examples of exercise interventions that are representative of these two research approaches. An in-depth analysis of representative studies may help identify contextual conditions that maximize the cognitive benefits of exercise interventions designed for children.

We consider the present review and commentary to be timely, as recent advances in cognitive psychology, coupled with neurophysiological data, provide contemporary researchers and theorists with increasingly clearer insight into the mechanisms by which mental enrichment interventions, such as exercise, may promote fundamental changes in the neural networks that lead to meaningful gains in cognition that are expressed in a wide variety of situations and contexts. The gains derived via specific types of interventions may be of importance for children, as neuronal networks of the central nervous system are guided by both genetic and environmental factors.

2. Methods

Studies were categorized as either quantitative or qualitative on the basis of the degree to which the intervention was designed with a primary focus on considerations of intensity and/or duration or was designed primarily to promote mental engagement. Quantitative interventions were characterized as those requiring minimal skill, involving repetitive movements controlled with negligible top-down control (e.g., treadmill running, ergometer cycling, or calisthenics), and whose intervention fidelity was based primarily on indices of cardiorespiratory function (e.g., heart rate, oxygen uptake, or accelerometry). Qualitative interventions were characterized as those involving exercise with high cognitive effort and/or skill learning (e.g., exergames, multi-limb coordination games, or strategy/learning games), and whose intervention fidelity was based on indices of mental engagement (e.g., observational methods, self-report). Mental engagement was defined as behavior reflecting thoughtfulness and exertion of effort required to comprehend new information and to master new skills.[10] Studies were restricted to those conducted with healthy, pre-adolescent children and to those that employed recognized outcome measures of cognitive function.[11] The primary goal of this review was to identify and highlight specific quantitative and qualitative exercise characteristics that may elucidate how PA benefits children's mental functions and contributes to classroom behavior and academic success.

3. Results

3.1. Quantitative exercise interventions

3.1.1. Acute quantitative exercise interventions

Most interventions that assess the acute effects of exercise on children's cognition have been designed based on the long-held assumption that change in physiological arousal alters mental functioning.[12] Several researchers have assessed the short-term after effects of exercise bouts on children's mental functioning. Most studies involved children performing moderately intense aerobic exercise for durations of about 20 min. The selection of these exercise parameters were typically based on exercise physiology evidence related to the metabolic changes that occur during and following exercise, or evidence from experiments showing that aerobic exercise performed below the lactate threshold for durations of 20−30 min reliably improved adults' mood states or cognitive performance. Both field-based and laboratory-based studies have been conducted. Research conducted in school settings has evaluated psychological test performance immediately following relays,[13] paced walking,[14] paced running,[15] and shuttle runs.[16] Research conducted in laboratory settings typically involves the measurement of children's information processing speed, executive function, or response accuracy[17−20] following treadmill running or cycling at specified intensities for set durations.

The experiment by Hillman et al.[19] provides an example of a laboratory-based quantitative acute exercise intervention. In their experiment, 20 children (mean 9.5 years) performed a modified Flanker Test and a test of academic achievement following 20 min of exercise or seated rest. Exercise involved solitary treadmill walking at 60% of the child's estimated maximum heart rate, which presumably required minimal mental engagement as the only demand placed on the child was to maintain a specific walking pace. The Flanker Test that was administered provided an index of inhibitory control and involved measuring response times to congruent and incongruent targets. Exercise led to increased response accuracy, suggesting improved inhibitory control, and it also resulted in selective improvement on the children's performance on the Wide Range Achievement Test, such that performance on the reading subscale increased but there were no changes on spelling and mathematics subscales.

3.1.2. Chronic quantitative exercise interventions

Exercise training is known to improve physiological functioning in a wide variety of ways. Considerable evidence has revealed that systematic exercise can profoundly influence multiple body systems. The evidence that chronic exercise can alter cardio-respiratory functions led some researchers to speculate that any effects of chronic exercise training on cognitive function might be explained by improved blood flow and oxygen availability to the brain. In the late 1990s, research conducted with animals demonstrated that aerobic training led to widespread changes in the brain structures and networks. Currently, there exists solid evidence that aerobic exercise training alters the structures and functions of the brain.[21,22] These findings have led to several neurologically-based hypotheses that attempt to explain how chronic exercise alters brain and cognition. Studies designed to examine the chronic exercise—cognition relation have tended to employ aerobic training programs in which the intensity, duration, and frequency of exercise are manipulated.

Several studies have been conducted as part of school-based physical education (PE) interventions or after-school programs. Typically, children were enrolled in traditional PE classes or a class modified to emphasize aerobic training and physical conditioning. Three studies provide a select, historical description of the type and limitation of older studies. Tuckman and Hinkle[23] and Hinkle et al.[24] assigned fourth-, fifth-, and sixth-grade children to a running program that consisted of sprinting, relays, and distance runs that were gradually made more physiological demanding over the course of training. The results of these early studies were inconsistent, with some finding no effect of treatments on measures of cognition[25] and others reporting selective improvements.[23,24] Clearer evidence for the beneficial effects of aerobic exercise on children's cognitive functions has been obtained from recent randomized controlled experiments.[26,27] The experiment conducted by Davis et al.[26] provides an example of contemporary research in this area. In their experiment, 171 overweight and inactive children were assigned to a no-exercise control group, a low-exercise dose group (20 min/day), or a high-exercise dose group (40 min/day). The daily after-school exercise intervention focused on intermittent vigorous movement. The activities were designed primarily to induce increases in heart rate and rewards were provided for maintaining an average above 150 beats per minute. Exercises included running laps, sprinting, jump rope, and modified games that stressed ball kicking and throwing. Importantly for the classification scheme used in the present review, games emphasized intensity but not skill development or instruction methods purposefully designed to promote mental engagement. Standardized tests of cognition and academic achievement administered prior to and following approximately 3 months of training revealed a dose—response improvement in planning on the cognitive assessment system and on the mathematics subscale of the Woodcock—Johnson Test of Achievement.

3.1.3. Critique of the quantitative research approach

The majority of studies that have examined the effects of exercise on children's cognition have been based on neurophysiological mechanisms hypothesized to underlie the relation. In general, studies conducted by researchers who view exercise in terms of dosage, similar to a drug prescription, provide ample evidence for its capacity to exert a direct change on children's cognition. Acute bouts of exercise alter children's attention, processing speed, and executive control in a manner that is predicted by theories of information-processing.[28,29] Chronic exercise training alters children's executive functions as predicted from contemporary neurophysiological research.[30] The exercise studies conducted thus far provide strong support for neurophysiological hypotheses.

3.2. Qualitative exercise interventions

3.2.1. Acute qualitative exercise interventions

Only recently have researchers developed interventions that focus specifically on the role of task complexity and, by inference, mental engagement. Common across these studies is the use of activities that involve complex multi-limb sequencing and rapid decision making. Budde et al.[31] employed a 10-min coordinative intervention based on soccer training that stressed the ability to balance and adjust to changing conditions (e.g., bouncing a volleyball alternating with left and right hands while standing on a moving platform). Following exercise, adolescents who participated in the complex movement program performed better on a test of attention than children who participated in a normal PE class in which students exercised at a moderate intensity for 10 min without specific coordinative demands. Pesce et al.[32] developed a 40-min intervention that included team games and circuit training characterized by rapidly changing conditions that required decisional responses made under time pressure. After exercising, children showed improved memory encoding compared to a control condition in which memory testing was not preceded by any physical or mentally engaging activity. Interestingly, while both team games and circuit training benefited memory recall, participating in team games elicited an additional memory benefit, suggesting that task conditions that promote mental engagement may prime the encoding of information. Best[33] employed Exergames, which are computer-based games that require children's PA to control game conditions. In a within-subject design study conducted across four sessions, each child watched a video, performed a mentally-challenging video game (Super Mario World) while seated, performed an Exergame ("Marathon" on the Nintendo Wii) that required running in place at a rate needed to control a computer figure who was running a marathon, and performed an Exergame (Active Life: Outdoor Challenge) that combined side-to-side movements that directed the actions of a computer figure over and around obstacles. Following each session, a modified Flanker Test tapping the inhibitory component of executive function was administered. PA, regardless of the level of complexity, facilitated children's cognitive test performance.

3.2.2. Chronic qualitative exercise interventions

Recent research and theorizing have led some researchers to design chronic exercise interventions that purposefully include games and PAs that are intended to be physically and cognitively challenging and that capitalize on social interactions among children and teachers. Lakes and Hoyt[34] employed a traditional martial arts program that was administered in place of PE classes to elementary school-age children. The 3-month training program involved instruction on body control during strikes, kicks, and blocks, as well as questions designed to promote self-monitoring (e.g., Where am I? What am I doing? What should I be doing?). All techniques were taught by a high-ranking martial arts instructor in an environment that emphasized respect, discipline, and self-control. Compared to children in traditional PE classes, those in the martial arts program improved on mathematics tests, cognitive and affective-self regulation, and classroom conduct. Castelli et al.[35] provided elementary-school children a 9-month multimodal after-school PA program. The FIT Kids program consisted of 40 min of fitness activities followed by PA time devoted to motor skill development and cooperative games. The intervention led to improvements in cognitive function as well as alterations in brain neurological activity,[36] structure, and function. A limitation of this study was the lack of the inclusion of data obtained from children assigned to a control condition.[37] Crova et al.[38] developed a 6-month enhanced PE class for 9–10-year children classified as normal- or overweight. Thirty-seven children assigned to an enhanced training program received tennis skill instruction during 2-h sessions designed to develop children's fundamental motor skills, object control abilities, and game strategies. The concept of cognitive challenge was central to instructional methods. Thirty-three children were assigned to a standard 1-h PE program that focused on motor skill development, body expression, and play. Tests of executive function indicated that overweight children derived the greatest gains in inhibitory efficiency but only if they participated in the enhanced training program. In a similar study, Chang et al.[39] developed a soccer-based coordinative exercise program for kindergarten children. The intervention consisted of either low- or moderate-intensity exercise sessions that took place for 35 min, twice a week for 8 weeks. Sessions focused on soccer activities (dribbling, passing, and kicking) that required multi-limb coordination. A pre-post evaluation of children's performance on a Flanker Test revealed faster responding and greater accuracy following the intervention, regardless of exercise intensity. The lack of a control group limits the interpretation of the study, however.

Several in-class PA interventions have been developed that intertwine movements with academic instruction. Perhaps the most frequently used intervention is TAKE 10!®, an activity program developed by the International Life Sciences Institute (ILSI).[40] Children's movements are designed to solidify specific academic contexts (e.g., jump-rope actions linked to learning basic mathematics; marching in place to a story about exploration). Modified versions of the TAKE 10!® program have been incorporated into several large-scale studies.[41,42] Kibbe et al.[43] summarized evidence on the effectiveness of the TAKE 10!® program and concluded that the program improved children's academic performance (e.g., grades, standardized test performance) and in-class behavior. Similar in-class interventions have been developed by Mahar and colleagues[44] that improve children's attention and by Erwin et al.,[45] who reported improvements in children's academic performance.

3.2.3. Critique of the qualitative research approach

Proponents of qualitative exercise methods contend that exercise interventions that include components of mental engagement provide children with cognitive benefits that are not obtained from quantitative exercise interventions.[9,46] The rationale for the additive cognitive effects derived from mental engagement was based primarily on the contextual-interference effect hypothesis and its application to motor skill acquisition and rehabilitation research.[47] Considerable evidence has accumulated in these and other research areas that show how the context of the training environments (e.g., stable, repetitive practice *vs*. unpredictable, random practice) influences learning. The exercise studies conducted with children thus far provide only limited support for the mental-engagement hypothesis. Few studies have been designed specifically to isolate the influence of task complexity on the exercise–cognition relation. A recent intervention developed by Pesce et al.[48] highlights the usefulness of operationalizing task complexity of PA games and of exploring whether and how it moderates the relation between quality PA and cognitive efficiency in children. Their 6-month intervention, which was developed for children with and without developmental disabilities, manipulated the delivery and task complexity of three types of classes provided for the same duration and frequency. There were two types of experimental PE interventions directed by PE specialist teachers and one standard PE program directed by classroom generalist teachers. While all teachers taught PE according to curricular age-related PE goals, the specialists applied two intervention programs both made of similar PA games that emphasized variability of practice, but differing from one another in that in one of them, the PA games were altered to challenge executive functions to a higher degree by joining instructional principles of executive tasks used in cognitive developmental research with the principle of contextual interference as applied in children's motor learning.[47] Typically developing children reaped largest benefits for executive attention from the "enriched" specialist-led program. Additional research on the roles of task complexity and mental engagement is warranted to identify how to match children's cognitively optimal challenge point and capitalize on quality PA for aiding cognitive development.

4. The benefits of adding the process of meta-cognition to existing exercise models

Evidence accrued over the past decade indicates that children derive cognitive benefits from exercise, both acute and chronic. While these findings are important for academic researchers interested in hypothesis testing, there remain questions concerning how this evidence can best be translated into practice in real-world conditions.[49]

A model recently proposed by Howie and Pate[6] and presented in Fig. 1, hypothesizes a sequence of outcomes: first, PA will modify children's cognition defined in terms of executive function, attention, memory, and intelligence; second, improvements in cognition will underlie improvements in academic performance defined by class grades, standardized test performance, and class behavior.

Notably absent in the mainstream exercise psychology literature, however, is the construct of metacognition and discussions of the role it may play as a mediator between exercise training and academic performance. Metacognition reflects an individual's understanding of what he or she knows and how to use that knowledge to regulate behavior.[50] Executive functions and metacognition overlap but are clearly distinguishable.[51] While executive function and metacognition appear on the surface to be essentially the same, they differ in several important ways. Perhaps the clearest difference is seen in processing duration. Consider that tests of executive function typically include instructions for the participant to respond as rapidly and accurately as possible. Under these test conditions, the participant's response times to individual test items rarely exceeds 2 s. In a sense, tests of executive function provide an estimate of performers' "on-line" processing and their capacity to adapt rapidly to changes in task conditions. In contrast to tests of executive function, tests that assess metacognition ask the participant to solve multiple-step problems (e.g., the Tower of London Test). Also, tests of creative thinking and motor creativity involving executive function[52,53] require applying problem-solving strategies without time pressure. Metacognition reflects the use of strategies that are thoughtfully brought to mind as one prepares to solve a problem and then a monitoring of progress towards a specific goal. Response times can range from seconds to minutes in these types of tests.

Consider an adaptation of the Howie and Pate model shown in Fig. 2. The model now includes both cognition and metacognition as mediators. Examining how exercise influences both "on-line" rapid executive processing and slower strategic planning may help researchers better understand how different types of PA affect children's performance in real-world conditions.

4.1. Does exercise alter children's metacognitive function?

Our review of the literature reveals that few researchers acknowledge the distinction between executive functions and metacognition. Doing so may help reduce ambiguities in research outcomes found in the field. Historically, research in children's metacognition addresses three topics that are relevant to exercise researchers: first, the degree to which declarative knowledge is acquired and used to maximize task performance; second, how procedural knowledge is acquired and how skill and expertise influence task performance; and third, how strategic knowledge is acquired and applied. Children's metacognitive capabilities and their ability to transfer and generalize strategies are known to be poorer than those of adults, so it would seem that exercise researchers would be particularly keen to address how their interventions differentially impact cognitive and metacognitive processes. It is plausible that qualitative exercise interventions that are mentally challenging, lead to procedural and declarative skill development, and stress the formulation of strategies would alter metacognitive processes that build upon basic executive functions. Studies conducted by Lakes et al.,[34,54] Pesce et al.,[32] and Crova et al.[38] that employ qualitative interventions provide preliminary evidence for the instantiation of skills and utilization of strategies. Furthermore, interesting studies in children's sports training show that enrichment interventions may promote the development of tactical creativity skills that involve executive control and the acquisition, usage, and transfer of declarative, procedural, and strategic knowledge

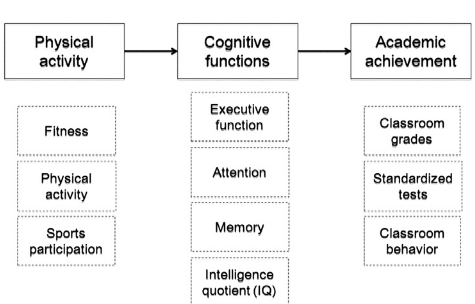

Fig. 1. The relationship of physical activity, cognitive function, and academic achievement.

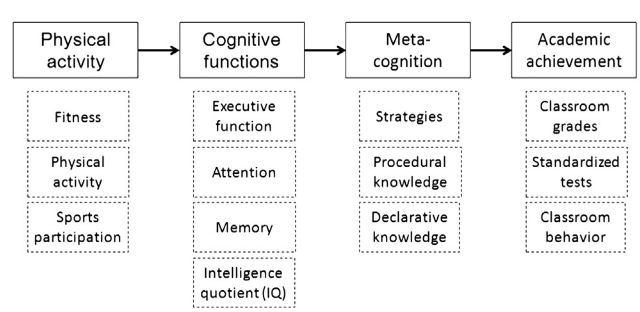

Fig. 2. Relationship among physical activity, cognition, metacognition, and academic achievement.

within the sport environment.[55,56] Given the increasing interest in the linkage between exercise and children's classroom behavior and academic performance, additional research that focuses on both cognition and metacognition is warranted.

4.2. Evaluating the roles of cognition and meta-cognition

Differentiating between cognition and metacognition may be critical to explaining how specific types of exercise interventions might lead to improvements in children's academic performance. Numerous cross-sectional studies provide evidence that PA, exercise, physical fitness, motor proficiency, PE, and sports are positively correlated with academic performance. Historically, educators and researchers alike have considered that children's experiences in sport and games encourage them to adopt strategies that can be used in school settings and other contexts. The assumption is that the lessons children learn from being engaged in sport and games transfer to engagement in the classroom. The empirical support for this assumption is not strong, however.[57,58]

5. Future methodological issues for exercise and cognition in children

Adding the construct metacognition to the model shown in Fig. 2, while potentially useful from a conceptual standpoint, adds a significant level of complexity for exercise researchers. There are several issues that have historically beset the study of metacognition. These include operationalization of mental engagement, determining how mental strategies transfer across conditions and contexts, and assessing the potential for long-term gains.

5.1. Defining mental engagement

The term engagement has been part of the scientific and public lexicons for many decades; however, concerted efforts to define the construct have arisen only relatively recently.[10] While debate continues in the academic community, most educational researchers agree that engagement is multidimensional in nature and is composed of three aspects: behavioral engagement, which is observed as persistence and concentration; cognitive engagement, which is inferred to represent the allocation of attentional resources and effort that is needed to master difficult skills; and emotional engagement, which is observed as children's positive or negative reactions to teachers and inferences of students' pleasure, happiness, withdrawal, sadness, and anxiety.[59]

A challenge for exercise researchers will be to identify or develop reliable methods of operationalizing the construct of engagement that can be used in both laboratory and field conditions. The recent resurgence in the application of psychophysiological methods to assess mental effort and engagement has led to a number of novel approaches.[60] Engagement is intertwined with discussions of both cognition and metacognition. Recall that executive functions reflect children's "on-line" task performance that is measured in the realm of seconds or milliseconds. Metacognition reflects thoughtful decision making and monitoring that occurs over the course of minutes or even hours. Engagement underlies the motivation to plan, prepare, and then maintain effort and persistence over hours, days, weeks, and longer.

5.2. Theory development

There are advantages for researchers to recognize how results obtained both from tasks that assess rapid decision making, such as tests of executive function, and from tasks that provide sufficient time to ponder how to solve complex problems that require the sequencing of multiple responses, may clarify the putative relation between PA and children's academic performance. Differentiating between cognitive and metacognitive processes provides researchers opportunities to apply existing theories that may help explain how and why PA influences mental functions. Theories developed by experimental psychologists[61–63] and neuroscientists[64] have led researchers to develop laboratory methods that focus on factors that affect an individual's attention and effort during tests of "on-line" processing. Theories developed by cognitive-social psychologists[65,66] focus on factors that underlie individuals' sense of self and beliefs concerning the likelihood of achieving short- and long-term goals. These theories may be helpful to explain how exercise impacts children's metacognitive processes. In the field of health behavior, several meta-theories have emerged[67,68] that explain behaviors in terms of macro-level factors that affect how individuals develop behavioral patterns that endure over the course of weeks, months, years, and perhaps a lifetime. These various theories could improve our understanding of the many factors that impact children's engagement in laboratory, home, and school settings.

The few studies that have been conducted specifically to assess the impact of exercise interventions on children's academic performance have focused on children's performance on standardized tests and/or class grades. Some researchers have reported improvements in these outcome measures; however, these studies have been largely atheoretical in nature.[2] Presently, explanations for exercise-related improvements in academic performance remain unclear. Advances in understanding how PA interventions alter children's academic performance will depend greatly on the selection of theories that best address the questions at hand. At this time, the executive function hypothesis dominates exercise psychology research.[69] Given that a comprehensive theory of exercise psychology has not been proposed, it falls to researchers to acquaint themselves with extant theories that provide hypotheses that help answer specific research questions.

5.3. Transfer and generalization

The identification of instructional conditions that promote generalization of knowledge across conditions has been a central focus for educators for over a century[70] and continues to be a topic of debate.[71] Historically, interventions designed to improve or maintain cognitive function in children and adults have been characterized as being successful in the sense that performance improves, sometimes substantially, but these interventions are limited because studies fail to demonstrate that the knowledge derived transfers to other conditions. For example, individuals who participate in memory-training programs that involve a mnemonic strategy may evidence remarkable gains in task-specific memory performance.[72] However, these performance gains drop dramatically when the memory task conditions are altered, even slightly. These observations are typically taken as evidence for the principle of specificity of learning, which predicts that the beneficial effects of an intervention are restricted to sets of underlying elements. The degree to which knowledge transfers from one condition to another, then, is determined by the similarity of the underlying elements.

Over the past decade, however, several well-designed and controlled experiments conducted with young children have demonstrated that cognitive skill training does generalize across conditions.[73] These findings are consistent with the view that the mental strategies that children acquire in a training environment can influence how they deal with tasks that involve executive control in academic conditions. Of particular importance to the present review are the types of interventions employed during training. For instance, the training methods used by Lakes and Hoyt[34] to teach martial arts skills to children targeted both executive functions and metacognitive control. Children were trained not only to make rapid choice responses that required cognitive control, but also to reflect on knowledge obtained during training and deduce strategies that underlie optimal performance. Thus, children were trained to think quickly and respond within milliseconds and to think through the tasks they were learning. The time required for children to recall memories, process, and formulate principles that explain their actions would require effortful cognitive engagement expended over periods of seconds or minutes. Thus, a case could be made that the type of training children receive is an important factor for determining the breath of transfer and the degree to which knowledge generalizes to academic environments. This conclusion is not unique, as researchers in the fields of developmental psychology and educational psychology have had longstanding interests in instructional programs that involve "training for transfer".[50] Of particular interest for exercise researchers is evidence that isolates the degree to which specific types of exercise interventions generalize to real-world contexts. Exercise interventions purposely designed to emphasize both executive functions and cognitive control (described in terms of rapid mental processing) and metacognition (described in terms of slower, thoughtful mental processing) may provide the "training for transfer" that may be necessary to create the linkage between exercise training and children's academic performance.

5.4. Are the effects of exercise on cognition enduring?

Voiced in the introduction of the present review were questions concerning the maintenance of the effects of exercise interventions on children's cognition. The distinctions we have drawn between quantitative and qualitative exercise interventions may be helpful when it comes to making predictions concerning the consequences of acute and chronic exercise on children's cognition. One of the strengths of quantitative interventions and their focus on manipulation of the intensity and duration of exercise is that exercise prescriptions are based on an extensive literature that describes somatic adaptations to physical training. Much has been learned of adults' and children's biological responses to exercise training over many decades.[74] More recently, evidence of exercise-related changes in brain plasticity has amassed. A landmark review of data obtained from research conducted with animals and humans identified several brain adaptations that plausibly explain how exercise might alter mental function;[75] these include changes in neurons (synaptogenesis), increased blood flow (angiogenesis), and the development of new brain cells (neurogenesis). More recently, neuroscientists have expanded the number of potential explanatory candidates.[76] The perspective of some researchers is that, as cognitive functions improve with changes in physical fitness, it is also the case that the gains in cognition brought about by exercise will decline if exercise is reduced or curtailed.[8] As a consequence, the maintenance of the cognitive benefits derived from exercise will require individuals to maintain PA regimens indefinitely.

Alternatively, qualitative exercise interventions that purposefully include problem solving demands that lead to the acquisition of declarative and procedural knowledge as well as response strategies could plausibly result in long-term development of abilities to exert control over thought and actions. Children asked to coordinate their thoughts and movements would be predicted to retain knowledge about the context in which they performed, the actions that were taken, and their consequences. Thus, metacognitive processes that are involved in preparing to act, engaging in actions, and maintaining actions would not necessarily be diminished should exercise training be reduced or terminated. Indeed, levels of health or fitness may decline, but unless they were associated with a disease state it would be difficult to see how reductions in physical functions to pre-exercise levels would compromise mental functioning.

A number of prospective and longitudinal-design studies[77−80] have examined the relation between children's levels of cognitive performance across multiple time points and report the value of PA and level of cognitive function. There are no published experiments that we are aware of at this time that have examined systematically the maintenance of exercise-based gains in children's cognition following the termination of chronic training interventions. Given the re-emergence of interest in the benefits of school-based exercise intervention on children's academic performance, such experiments are clearly warranted. The typical 8- to 9-month academic school year is followed by extended summer breaks. Should well-designed exercise interventions be provided during the academic year, is it conceivable that gains in cognition due to increased PA would degrade during summer periods when PA levels decreased by comparison?

6. Conclusion

The primary goal of the present review was to identify and highlight task factors that may clarify how exercise alters mental functions in ways that contribute to children's academic success. Contemporary researchers suggest that the effects of exercise on children's academic performance are mediated by changes in cognition (executive function, memory, and fluid intelligence). There is substantial evidence that both acute bouts of exercise and exercise training alter children's cognition. Further, our review suggests both quantitative and qualitative types of exercise enhance cognitive processing. While there is a clear causal link between exercise and children's cognition, the linkage between exercise-induced changes in cognition and academic performance is less clear. There is little debate that children's level of cognitive function is positively related to their academic performance; however, the critical question is the degree to which exercise-induced improvements in children's cognition is related to their academic performance. The association between exercise and academic performance is complex and probably influenced by a number of mediators and moderators.[81] We suggest that our understanding of the relation between exercise and children's academic performance may be improved significantly by including the construct of metacognition in the causal pathway.

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