Developmental Review 30 (2010) 331–351

Contents lists available at ScienceDirect

Developmental Review

journal homepage: www.elsevier.com/locate/dr

Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise

John R. Best

Department of Psychology, University of Georgia, Athens, GA 30602, United States

ARTICLE INFO

Article history:
Received 14 October 2009
Revised 26 March 2010
Available online 15 September 2010

Keywords:
Aerobic exercise
Physical activity
Executive function
Cognition
Infancy/childhood

ABSTRACT

Executive function refers to the cognitive processes necessary for goal-directed cognition and behavior, which develop across childhood and adolescence. Recent experimental research indicates that both acute and chronic aerobic exercise promote children's executive function. Furthermore, there is tentative evidence that not all forms of aerobic exercise benefit executive function equally: Cognitively-engaging exercise appears to have a stronger effect than non-engaging exercise on children's executive function. This review discusses this evidence as well as the mechanisms that may underlie the association between exercise and executive function. Research from a variety of disciplines is covered, including developmental psychology, kinesiology, cognitive neuroscience, and biopsychology. Finally, these experimental findings are placed within the larger context of known links between action and cognition in infancy and early childhood, and the clinical and practical implications of this research are discussed.

Introduction

Recent experimental research has converged on an intriguing finding: Aerobic exercise at a moderate to vigorous intensity appears to promote children's effortful and goal-directed cognition and behavior, commonly described as executive function (EF). The effects have been detected immediately following completion of single bouts of exercise (Budde, Voelcker-Rehage, Pietrabyk-Kendziorra, Ribeiro, & Tidow, 2008; Ellemberg & St. Louis-Deschênes, 2010; Hillman et al., 2009; Pesce, Crova, Cereatti, Casella, & Bellucci, 2009) and after chronic training (Davis et al., 2007; Davis et al., in press;

E-mail address: jbest755@uga.edu

0273-2297/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.dr.2010.08.001

Hinkle, Tuckman, & Sampson, 1993). Since EF is considered to be higher-order cognition, this finding indicates that aerobic exercise does not have a limited effect on lower-level perceptual or automatic cognitive processes (McMorris & Graydon, 1996) but instead impacts the complex cognitive abilities that permit humans to behave in an adaptive and goal-directed fashion.

To understand why aerobic exercise promotes children's EF, several questions need to be addressed: First, *what is EF, how is it supported by the brain, and how does it typically develop*? Answers to this set of questions will provide the basis for theorizing why EF would be sensitive to aerobic exercise. Second, *what is the experimental evidence that aerobic exercise impacts children's EF?* The focus of this review will be on experimental studies that have examined the link between aerobic exercise, both acute or chronic, and cognitive tasks requiring EF in non-clinical populations of children and adolescents. Although there are only a few studies that meet these criteria, they provide a sufficient base from which to examine specific mechanisms underlying the connection between aerobic exercise and EF and suggest directions for future research. These studies contrast with those that have employed less rigorous designs and/or have utilized global or non-theory-based measures of cognitive functioning (Tomporowski, 2003). For reviews of such studies and studies involving various clinical populations, see Tomporowski (2003) regarding the impact of acute exercise on children's cognition, and Tomporowski, Davis, Miller, and Naglieri (2008) regarding the impact of chronic exercise on children's cognition. These previous reviews made tentative conclusions that both acute and chronic aerobic exercise promote children's EF but urged that future research use more rigorous experimental designs.

The review of these recent experimental studies leads to a third question: *What mechanisms underlie the link between aerobic exercise and EF*? To answer this question, we must consider multiple research disciplines that investigate the link between movement and cognition in one fashion or another. Notable among these are developmental psychology, kinesiology, and neuroscience. Historically, these different disciplines, particularly developmental psychology and kinesiology, have had little interaction despite asking similar questions. The multidisciplinary approach of this review will bring together research from these disciplines and suggest how they could interact to further this research. Furthermore, we must consider how aerobic exercise may cause changes at several levels—including morphological and functional changes to the brain—and then examine how these changes produce a robust effect on cognition and behavior. Animal models are necessary to discover the specific chemical and neural changes that occur, and cognitive neuroscience techniques (e.g., EEG, fMRI) document functional changes at the systems level. Finally, the bigger developmental picture needs to be considered: *How are aerobic exercise* (*and physical activity, more generally*) *and cognition connected at earlier developmental time points*? Although the primary focus is in children's aerobic exercise and cognition, a comprehensive understanding will be informed by research on early connections between physical activity and cognition in infancy and early childhood. As a side note, whereas *exercise* is the intentional engagement in physical activity to enhance fitness, *physical activity* encompasses all forms of movement produced by skeletal muscles (Caspersen, Powell, & Christenson, 1985). As discussed below, both exercise and physical activity may be important to cognitive development.

This review will attend to each of these questions in order to achieve a richer understanding of why and how aerobic exercise has a positive impact on EF in children. Unlike previous reviews, the current review will discuss developmental issues pertinent to the effects of exercise on cognition. Moreover, these findings will be placed within the larger developmental context of an action–cognition connection that begins in early infancy. A final section discusses the implications for children's development and suggests themes that should guide future research.

What is EF, how is it supported by the brain, and how does it typically develop?

EF is an umbrella term that encompasses the cognitive processes responsible for organizing and controlling goal-directed behavior (Banich, 2009). Although still a matter of debate, one prominent theoretical framework suggests that EF consists of three foundational components: Inhibition, updating of working memory, and shifting (Diamond, 2006; Miyake et al., 2000). These three components are believed to be bound by some common underlying process(es) but are employed differentially based on the task at hand to guide behavior. Factor analysis studies support this framework in young adults (Friedman et al., 2008; Miyake et al., 2000) and also suggest that children's EF is organized in a similar fashion, though perhaps without a distinct inhibition component (Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; van der Sluis, de Jong, van der Leij, 2007; but also see Wiebe, Espy, & Charak, 2008, for evidence for a unitary EF construct in preschool children).

In light of this componential framework, different tasks ostensibly require different EF components. For example, the Eriksen flanker task (Eriksen & Eriksen, 1974) assesses inhibition by requiring children to inhibit attending to distracters and to focus narrowly on a target stimulus. In particular, children are instructed to press a button corresponding to the direction of a central target arrow flanked by peripheral arrows. Incongruent trials require inhibitory processes because the flanking arrows face the opposite direction of the central target arrow (e.g., > > < > >). Congruent trials (e.g., > > > > >) do not require inhibitory processes because the flanking arrows provide consistent information about how to respond. For another example, a task-switching paradigm assesses the shifting component (Tomporowski, Davis, Lambourne, Gregoski, & Tkacz, 2008). In this task, a series of numbers containing the digits 1 and 3 are presented on a computer screen (e.g., "1 1 1" or "3"). Children are asked either "How many?" or "What number?" and therefore need to shift between two cognitive processes—identifying the number and counting how many numbers are presented on the screen.

The common thread in these tasks, and other EF tasks, is that success depends on goal-directed behavior that adapts to novel task parameters, rather than on automatic behavior elicited in an associative learning manner. In light of this componential framework, researchers must pay particular attention to the tasks used to assess EF in order to answer the following: What component(s) of EF is (are) being impacted by aerobic exercise? (See Etnier & Chang, 2009 for a commentary on issues involved in studying the effects of physical activity on EF.)

Neural circuitry within the prefrontal cortex (PFC) is critical to EF (Luria, 1966; Shimamura, 2000; Stuss & Benson, 1984). Unlike other brain regions responsible for motor and sensory processing, speech and language development, and attention, the PFC matures late in adolescence (Gogtay et al., 2004; O'Hare and Sowell, 2008). During this period of immaturity, progressive and regressive changes (e.g., myelination and synaptic pruning, respectively) occur concurrently and *are driven in part by the child's experiences* (O'Hare and Sowell, 2008). This protracted period of brain development is paralleled by a protracted period of cognitive development. Because EF involves complex, non-automatic processes that coordinate lower-level cognitive processes in a goal-directed fashion, EF follows an extended developmental timetable, maturing at some point in adolescence or early adulthood (Best, Miller, & Jones, 2009). With increasing age, children and adolescents demonstrate greater competence on tasks that assess each EF component individually but also on tasks that require the coordination of multiple components (e.g., manipulating information in working memory while inhibiting interfering information) (Diamond, 2006).

This protracted cognitive and neural development may be one clue to understanding why children's EF is sensitive to the effects of aerobic exercise. Both EF and the underlying neural circuitry are still immature in late childhood and even adolescence, and therefore, certain experiences may facilitate their development or temporarily enhance their functioning. Aerobic exercise appears to be such an experience that would positively impact EF and the supporting neural circuitry.

What is the experimental evidence that aerobic exercise impacts children's EF?

There are two distinct experimental designs used to assess the effects of aerobic exercise on cognition. The first examines the effects of chronic aerobic exercise (i.e., aerobic training), in which children are randomly assigned to habitual aerobic exercise over several weeks or to a control condition of equal duration (Table 1). The purpose of the aerobic exercise program is to improve children's cardiorespiratory functioning. This improvement, in turn, may improve cognitive functioning, which is assessed after the aerobic exercise program has ended (Tomporowski, Davis, Miller, et al., 2008). The second design examines the immediate changes in cognitive functioning immediately following *acute* bouts of aerobic exercise (Table 2). These studies determine the immediate effects of exercise on cognition rather than the longer-lasting effects of chronic exercise programs (Tomporowski, 2003). Both experimental designs will be examined; however, it should be noted that the mechanisms by which

Table 1
Summary of findings of experimental studies that assess the effects of chronic exercise on children's executive function.

Authors	*n*	Sample	Exercise intervention	Duration	Tests	Results
Tuckman and Hinkle (1986)	154	4–6th grade, healthy	Aerobic running program	12 weeks for 30 min/day, 3 days/week	BG MTSP AUT	Improvements on AUT (EF) No improvements on B–G, MTSP
Hinkle et al. (1993)	85	8th grade, healthy	Aerobic running program	8 weeks for 30 min/day, 5 days/week	TTCT	Improvements on TTCT (creativity)
Davis et al. (2007, in press)	163	7–11 years, overweight	Aerobic games (HR > 150 BPM)	13 weeks for 20 or 40 min/day, 5 days/week	CAS	Dose–response improvement in EF No improvement in non-EF Math fluency improvement Increased PFC activation (fMRI)

Note. AUT = Alternate Uses Test. BG = Bender–Gestalt test. BPM = beats per minute. CAS = Cognitive Assessment System. EF = executive function. HR = heart rate. MTSP = Maze Tracing Speed Test. TTCT = Torrance Test of Creative Thinking. WJ = Woodcock–Johnson.

chronic and acute aerobic exercise affect cognition differ. These differences will be discussed in the following section.

Chronic aerobic exercise

In an early study of chronic exercise and cognition, Tuckman and Hinkle (1986) compared the effects of a 12-week aerobic running program to a standard physical education class in 4th, 5th, and 6th-grade children. The running program consisted of various running exercises that became increasingly more physiologically-demanding over the course of the program. Comparisons of post-test cognitive functioning revealed that the aerobic running program did not influence perceptual-motor skills or visual-motor coordination but did improve children's creativity as assessed by the Alternate Uses Test. In particular, this test assesses flexible and divergent thinking by asking children to name as many appropriate uses of named objects (e.g., hammer). In a subsequent study, Hinkle et al. (1993) examined the effects of a similar aerobic running program in 8th-grade children. In comparison to the control group, children assigned to aerobic running performed better on the Torrance Test of Creative Thinking. Like the Alternate Uses Test, this measure of creativity assesses flexibility and divergent thinking. Although not pure measures of EF, creativity tasks are believed to tap EF (Delis et al., 2007), and therefore, these results support the notion that EF is sensitive to the effects of chronic aerobic exercise (Tomporowski, Davis, Miller, et al., 2008).

A more recent study by Davis et al. (2007, in press) provides further evidence that EF is sensitive to aerobic training. Overweight children (⩾85th percentile BMI, aged 7–11) completed an aerobic exercise intervention involving group aerobic games (e.g., running games, modified basketball and soccer). Children were randomly assigned to one of three treatment conditions: no exercise control, 20-min exercise dose or 40-min exercise dose. Children in the 20-min and 40-min groups spent an equivalent time in the research facilities and received equal attention. Cognitive functioning was assessed via the Cognitive Assessment System (CAS; Naglieri & Das, 1997). As predicted, the aerobic training only had an effect on tasks requiring EF. Moreover, the aerobic training had a marginal positive effect on mathematics achievement. These cognitive gains were complemented by increased PFC activation, but decreased parietal activation, in a sub-sample of the children using an fMRI anti-saccade paradigm (Davis et al., in press). For both the behavioral and fMRI data, comparisons were made to control children who received no attention or intervention of any kind. Thus, these findings indicate that

Table 2
Summary of findings of experimental studies that assess the effects of acute exercise on children's executive function.

Authors	*n*	Sample	Exercise intervention	Duration	Tests	Results
Caterino and Polak (1999)	177	2nd–4th grade, healthy	Stretching and aerobic walking	15 min	WJ Test of Concentration	Improved performance only for 4th grade children
Tomporowksi, Davis, Lambourne, et al. (2008)	69	7–11 years, overweight	Treadmill walking (moderate intensity)	23 min	Task-switching	No effect in comparison to video watching rest condition
Hillman et al. (2009)	20	*M* = 9.6 years (*SD* = 0.7) healthy	Treadmill walking (60% of max HR)	20 min	Flanker task	Improved accuracy following walking Improved reading comprehension Greater P3 in fronto-central, central regions
Ellemberg and St. Louis-Deschênes (2010)	72	7 and 10 years, healthy boys	Stationary biking while watching TV (63% of max HR)	40 min	Simple & choice RT task	Decreased RT on both tasks following biking No effect on accuracy No age differences
Pesce et al. (2009)	60	11–12 years, healthy	Group games (HR = 137 BPM) Circuit training (HR = 146 BPM)	1 h	Free-recall immediate and delayed memory	Equivalent impact on delayed recall Greater impact on immediate recall following group games
Stroth et al. (2009)	35	13–15 years, healthy	Stationary biking (60% of max HR)	20 min	Go/no-go version of flanker task	No effect on behavioral or ERP data in comparison to watching a video
Budde et al. (2008)	115	13–16 years, healthy	Coordinative Exercise (HR = 122 BPM) Circuit training (HR = 122 BPM)	10 min	d2 selective attention task	Improvement in both conditions relative to pre-test Greater improvement following coordinative exercise

Note. BPM = beats per minute. EF = executive function. ERP = event-related potential. HR = heart rate. RT = reaction time.

participation in aerobic training influences EF and the underlying neural networks, but it does not rule out that other forms of exercise also may influence EF.

Acute aerobic exercise

One interesting experimental design, more often used in acute exercise studies, is to examine differences in cognitive functioning upon completing different types of exercise. In one such study (Budde et al., 2008), adolescents (aged 13–16) were randomly assigned to either a 10-min bout of a challenging bimanual coordinative exercise or to a 10-min bout of non-coordinative exercise. Heart rate monitoring ensured that both exercise conditions were of moderate aerobic intensity; however, the challenging exercise involved a series of skilled bimanual coordination tasks whereas the simpler exercise involved only repetitive motor movement. Both task accuracy and completion time on a selective attention task (selectively attend to the letter "d" while actively ignoring the orthographically similar letter "p") were better for adolescents assigned to the challenging exercise than for adolescents assigned to the simpler exercise. According to the authors, the complex coordination exercise likely required "frontal-dependent cognitive processes" (EF), which enhanced prefrontal neural functioning. The simpler, repetitive exercise ostensibly did not rely on frontal circuitry.

A second study (Pesce et al., 2009) also compared two forms of aerobic exercise of equivalent aerobic intensity: During one session preadolescent children (aged 11–12) completed 1 h of individual circuit training and during another session completed 1 h of aerobic group games. Unlike other studies, the children's motor activity was categorized in order to provide information about the social and cognitive interactions for each form of exercise. (However, the authors provide no specific description of either exercise.) Whereas circuit training contained more opportunities to learn motor skills, the group games provided more opportunities to apply those motor skills in a competitive and strategic manner. Also, the circuit training consisted solely of individual activity, and the group games consisted roughly of equal parts individual activity and group activity. After each session, children completed a list-learning procedure to assess both immediate and delayed word recall. Important to the current focus on EF, the conscious recollection of items, as is required in a word recall task, is thought to rely on PFC-mediated cognitive processes, such as strategic and effortful searches (Della Rocchetta & Milner, 1993; Moscovitch & Winocur, 2002). For immediate word recall, only the acute bout of group aerobic games enhanced memory relative to baseline memory performance. For delayed recall, both forms of exercise benefited memory performance. The authors surmise that whereas both forms of aerobic exercise led to a general arousal that may have benefited memory consolidation, only the group games condition induced a more specific cognitive activation that further enhanced immediate recall. This specific cognitive activation likely occurred through the greater opportunity for social interaction and the need to apply motor skills in a strategic fashion.

Together, these two findings raise the possibility that the degree to which the exercise requires complex, controlled, and adaptive cognition and movement may determine its impact on EF. Coordinative exercises, such as those employed by Budde et al. (2008), require substantial top-down cognitive control and the ability to override automatic behavior (Diamond, 2000, 2009). Aerobic games, such as those employed by Pesce et al. (2009), likely require cooperation with other children, strategic behavior, coordination of complex bodily movements, and adaptation to continually changing task demands. Repetitive aerobic exercises, on the other hand, likely require less cognitive engagement, particularly of EF, since there is little need to guide cognition to accomplish a challenging goal or coordinate the body to execute complex movements. These differences in EF demands may lead complex exercise to have a stronger effect on EF than simpler exercise.

Other recent experimental research has compared simple repetitive aerobic exercise (e.g., treadmill walking) to periods of rest. If complex forms of aerobic exercise facilitate EF more so than simpler forms, then differences in EF performance following simple exercise and periods of rest should be smaller. Tomporowski, Davis, Lambourne, et al. (2008) provide evidence consistent with this idea by showing that acute treadmill walking had no effect on shifting, a core EF component, in overweight children (aged 7–11). Using a within-subjects design, children completed the shifting task after a 23-min, moderate intensity treadmill walk and after watching a video of equivalent length. A task-switching paradigm (described in the previous section) assessed the shifting component of EF. The researchers found no improvements in shifting performance after walking relative to performance after watching the video. Similarly, Stroth et al. (2009) found that 20 min of stationary bicycling at moderate intensity, relative to watching a video for an equivalent time period, did not facilitate adolescents' (aged 13–15) performance on a modified go/no-go version of the flanker task that taps several aspects of EF, including selective attention, inhibition of certain responses, and the maintenance of rules in working memory.

On the other hand, Hillman et al. (2009) found that acute treadmill walking did have an effect on children's EF. Also using a within-subjects design, children (mean age = 9.6) completed an inhibition task both after 20 min of treadmill walking at moderate intensity and after 20 min of resting with no intervening activity. The Eriksen flanker task (Eriksen & Eriksen, 1974) assessed inhibition. Importantly, acute walking only facilitated response accuracy on incongruent trials, which require inhibition, suggesting a selective effect on inhibitory processes and not a more global effect on perceptual or response processes. The acute walking also had a beneficial effect on children's reading comprehension skills. These behavioral findings were corroborated by neuroelectric data via EEG assessment. Specifically, increases in P3 amplitude located in fronto-central, central, and parietal regions were observed following exercise. The authors interpreted this increased P3 response to indicate greater allocation of attentional resources to the stimulus.

Furthermore, Ellemberg and St. Louis-Deschênes (2010) found that stationary cycling for 40 min at a moderate intensity while watching an age-appropriate television show enhanced response time, but not accuracy, on simple and choice reaction time tasks. The researchers used a tightly-controlled between-subjects design, comparing exercised children to children who sat motionless on the stationary bike while watching the same television show. The researchers were also interested in detecting developmental differences and included only healthy 7- and 10-year-old males in the study. No developmental differences were detected, but subtle task differences were noted: Although reaction time was significantly faster following exercise on both tasks, the enhancement was greater for the choice reaction time task. According to the researchers, the choice reaction time task taps EF processes such as flexibility and inhibition, and the results support EF's sensitivity to acute aerobic exercise.

Considering all of these acute studies, aerobic exercise appears to enhance EF, and it may be that exercises requiring greater cognitive engagement have a stronger effect on EF than simpler exercises, requiring limited cognitive engagement. Key differences in their designs, cognitive assessments, and sample characteristics, however, make comparisons across these studies difficult but also may explain the inconsistent findings. Importantly, the impact of aerobic exercise on EF may be moderated by cognitive developmental level and by the EF component examined. That is, EF may be more sensitive to aerobic exercise at one developmental time point than at another, and one EF component may be more sensitive to acute aerobic exercise than another. As stated previously, evidence suggests that these components, though correlated, are distinct in children and follow different developmental timetables (Best et al., 2009). Combining these two possibilities, the link between aerobic exercise and EF may be moderated by both age and EF component. During late childhood, inhibition (Hillman et al., 2009) may be more more sensitive than shifting (Tomporowski, Davis, Lambourne, et al., 2008) to the effects of acute exercise, but during adolescence, it may no longer be as sensitive to those effects (Stroth et al., 2009).

To date, few studies have taken the developmental approach of considering moderation by age. One exception is the study by Ellemberg and St. Louis-Deschênes (2010). The researchers included two distinct age groups (7- and 10-year-olds) in order to test for moderation by age. Although no interaction was detected, the sample characteristics (i.e., including two distinct age groups) at least allowed for it to be examined. A second exception is a study conducted by Caterino and Polak (1999), which found that an acute bout of stretching and aerobic walking, relative to a grade-appropriate classroom activity, facilitated selective attention, assessed via the Woodcock–Johnson Test of Concentration, in 4th graders but not in 2nd or 3rd graders. However, the authors offer little explanation as to why the effect was only found in 4th graders. A related issue not addressed by most studies is the potential influence of variation in pubertal status within the sample. It is possible that variations in hormone levels could moderate the influence of aerobic exercise on cognition; however, only Hillman et al. (2009) assessed pubertal status and determined that all children within their sample were prepubescent.

Another important difference among these studies is that Budde et al. (2008), Pesce et al. (2009), and Caterino and Polak (1999) conducted applied studies, in which children were tested in groups in a school setting. The remaining studies were clinical studies, in which children were tested individually in a tightly-controlled laboratory setting. There are numerous confounds that exist in applied studies (e.g., social interaction, time of testing, variation in the precise activity of each child) that are minimized in laboratory-based, clinical studies, which require researchers to be cautious in comparing clinical and applied studies.

That being stated, even slight differences in both the exercise and control conditions among the clinical studies may account for differences in the results. For example, by having children watch an age-appropriate video while exercising, Ellemberg and St. Louis-Deschênes (2010) may have provided a more cognitively-engaging exercise condition than the other studies, which in turn, may have influenced the results. With regard to the control condition, Tomporowski, Davis, Lambourne, et al. (2008) and Stroth et al. (2009) had children watch a video while resting whereas Hillman et al. (2009) did not provide any sort of activity during the rest period. Although these procedural differences may seem trivial, they may actually be important. Whether exercise was determined to have a positive effect on EF or not was relative to the impact of the control condition on EF, rather than on some absolute change in EF performance. It is possible that a video would engage children more so than the no-activity rest condition, and this engagement could facilitate EF performance and reduce the relative impact of walking on EF. Thus, what the exercise condition is compared to needs to be carefully considered. The study by Ellemberg and St. Louis-Deschênes (2010) provides an example of how to control for subtle differences that often exist between exercise and control conditions.

Summary

In summary, these experimental studies suggest that single bouts of aerobic exercise may transiently facilitate children's EF and also that chronic participation in aerobic exercise may induce more enduring improvements to EF. Additionally, the amount of EF engagement during the exercise appears to be an important factor, at least for acute aerobic exercise. Whether this engagement is an important factor for chronic exercise remains to be tested. To date, most experimental studies have used acute exercise bouts, likely due to the greater cost and participant attrition associated with long-term interventions.

What mechanisms underlie the link between aerobic exercise and EF?

A clearer understanding of these findings, including how to reconcile discrepancies in the literature and what general conclusions to draw, requires attention to the possible mechanisms that underlie the impact exercise has on EF. There are at least three general pathways by which aerobic exercise may facilitate EF in children: (1) the cognitive demands inherent in the structure of goal-directed and engaging exercise, (2) the cognitive engagement required to execute complex motor movements, and (3) the physiological changes in the brain induced by aerobic exercise (Table 3).

Cognitive demands inherent in exercise and physical activity

An often overlooked fact is that many forms of exercise are cognitively-engaging activities. Researchers have suggested that this cognitive engagement inherent in exercise may help explain how exercise impacts cognition (Sibley & Etnier, 2003; Tomporowski, Davis, Miller, et al., 2008; Tomporowski & McCullick, 2009). Much of children's exercise comes through participation in group activities or sports that require complex cognition in order to cooperate with teammates, anticipate the behavior of teammates and opponents, employ strategies, and adapt to ever-changing task demands. Group activities such as soccer, tag, or basketball played by children in the studies conducted by Davis et al. (2007, in press) contain many of those cognitive demands. Importantly, EF tasks place similar demands on children's executive processes by requiring them to create, monitor, and modify a cognitive plan to meet task demands (Banich, 2009). Thus, aerobic games and EF tasks require a sim-

Table 3
Summary of pathways by which aerobic exercise impacts executive function.

Pathway	Exercise types	Effects on cognition and the brain
Cognitive demands inherent in engaging games	Group games	Contextual interference has robust effect on retention and transfer of skills Strategic play recruits similar cognitive processes as EF tasks Adaptive video game training enhances non-trained EF skills
Cognitive demands inherent in coordination of complex motor tasks	Group games	Contextual interference leads to greater motor skill learning
	Complex motor tasks (e.g., bimanual coordination tasks, motor skill learning)	Activation of PFC during complex motor execution Physiological changes in hippocampus and cerebellum
Physiological changes resulting from aerobic exercise	Group games	Neurogenesis in the hippocampus
	Repetitive aerobic exercise (e.g., running)	Angiogenesis and increased cerebral blood volume Up-regulation of growth factors and neurotrophins (e.g., BDNF) Immediate increase in neurochemicals (e.g., NE, DA) Enhanced learning and memory

Note. BDNF = brain-derived neurotrophic factor. DA = dopamine. EF = executive function. NE = norepinephrine. PFC = prefrontal cortex.

ilar way of thinking and similar cognitive skills. Perhaps cognitive skills acquired during aerobic games transfer to EF tasks.

If this is the case, participation in cognitively complex, yet sedentary, games should also positively impact children's EF. Research has supported this proposition by showing that computerized games created specifically to train EF are effective for young children (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; Thorell, Lindqvist, Bergman, Bohlin, & Klingberg, 2008), older children and adolescents (Klingberg, Forssberg, & Westerberg, 2002; Klingberg et al., 2005), and adults (Erickson et al., 2007; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Olesen, Westerberg, & Klingberg, 2004; Persson & Reuter-Lorenz, 2008).

Two features are germane to the current discussion. First, the computerized EF tasks used in these studies adapted to the participants' current performance, and therefore, remained engaging throughout the training program (e.g., Rueda et al., 2005). Similarly, aerobic games require adaptive and flexible play in a novel situation. Consequently, it appears that these computerized tasks and aerobic games place similar demands on cognition by requiring flexible behavior and decision-making in a novel environment. Second, the computer training not only improved performance on the trained games but also transferred to novel EF tasks, including inhibition tasks (Klingberg et al., 2002, 2005; Olesen et al., 2004), and working memory tasks (Thorell et al., 2008). In one study the benefits lasted three months after training terminated (Klingberg et al., 2005), and in other studies the behavioral improvements were accompanied by increased frontal activation on EF tasks as compared to controls (fMRI: Ericksen et al., 2007; Olesen et al., 2004; and EEG: Rueda et al., 2005). Thus, there is strong evidence that challenging, yet sedentary, games that require adaptive and goal-directed behavior can effectively train EF.

One mechanism that may explain how participation in engaging games transfers and results in enhanced EF concerns *contextual interference* (Tomporowski & McCullick, 2009): Although skill acquisition occurs more rapidly when the components of a task are presented in a simple and repetitious manner, the retention and transfer of those skills are enhanced when there is contextual interference, i.e., the components are presented in a complex and quasi-random manner (Battig, 1972). Children's participation in games, both sedentary and aerobic, often contains contextual interference. For example, in the game of basketball, the child may need to perform a bounce pass to effectively pass the ball in one specific scenario but need to lob the ball in another. The particular pass needed at that time is not predetermined and is rarely repeated over and over, but instead, is determined by a myriad of factors that converge at a particular moment. Contextual interference places demands on executive processes as a motor action plan must be created, monitored, and modified in the presence of continually changing task demands (Brady, 2008). Thus, the processing of pertinent information is likely more effortful and elaborative, leading to greater learning (Carey, Bhatt, & Nagpal, 2005). A recent fMRI study reports that this more effortful processing imposes demands on EF-related circuitry, as underscored by greater frontal activation, compared to more widespread parietal, premotor, and cerebellar activation in the absence of contextual interference (Cross, Schmitt, & Grafton, 2007).

The degree of cognitive engagement afforded by an activity surely varies across development. Forms of exercise that contain numerous rules likely are inappropriate for younger children, who may not be cognitively equipped to maintain and understand those rules. In turn, they may become frustrated by the activity and will receive no benefit. Conversely, older children may become uninterested in activities that are quickly mastered.

Cognitive demands of complex motor movement

The execution of complex motor movements also recruits neural circuitry associated with EF. Diamond (2000) reviewed several areas of research suggesting a close neural link between, and substantial co-activation of, the cerebellum, critical for complex and coordinated movement, and dorsolateral PFC (DL-PFC), critical for EF. Diamond concluded that the cerebellum seems to be important for complex cognitive functions as well as complex motor functions; likewise, the DL-PFC seems to be important for complex motor functions as well as complex cognitive functions (see also Serrien, Ivry, & Swinnen, 2007). More recently, Diamond (2009) argued that the brain, and the mind by extension, operates on a global-default mode, and that both cognitive and motor activities that rely on non-automatic and selective processing require the effortful overriding of that default. As an example of this, Diamond offers the execution of bimanual coordination tasks, during which the individual does different things with each hand simultaneously. Thus, the execution of complex motor movements appears to be an inherently cognitively-engaging task, whereas the execution of simpler repetitive exercise, such as walking once it has been mastered by the child, may be less so, instead relying on a global-default mode of operation.

Additionally, research with animals indicates that complex motor activity induces morphological changes to the brain whereas simple motor activity does not. In rodents and nonhuman primates, the execution of complex motor movement promotes neural growth in the hippocampus, cerebellum, and cerebral cortices to a greater degree than does repetitive motor movement (Carey et al., 2005; Jones, Hawrylak, Klintsova, & Greenough, 1998).

The physiological changes due to aerobic exercise

The above findings indicate that aerobic exercise engages EF and other higher-order cognitive processes by requiring goal-directed behavior and the coordination of motor movements. Additionally, the demands placed on the body's cardiovascular system while exercising induces physiological changes in the brain to impact cognition and may interact with the cognitive components of the exercise to impact cognition. Acute and chronic aerobic exercises differ in the physiological changes they induce and will be discussed separately.

Chronic aerobic exercise

Extensive research with rodents suggests that exercise induces changes in brain regions critical to learning and memory (Holmes, 2006; van Praag, 2006) that occur over several sessions of regular exercise (Cotman, Berchtold, & Christie, 2007). These changes are mediated by up-regulation of several growth factors, including insulin-like growth factor-1 (IGF-1), vascular endothelial growth factor (VEGF), and brain-derived neurotrophic factor (BDNF) (Cotman et al., 2007; Dishman et al., 2006; Holmes, 2006; van Praag, 2006). BDNF, in particular, has been shown to be an important activity-dependent modulator of synaptic transmission and, in turn, of synaptic plasticity (Schinder & Poo, 2000). Moreover, BDNF appears to mediate exercise-induced neurogenesis, i.e., the process by which new neurons proliferate and develop (Churchill et al., 2002).

Exercise-induced neurogenesis has been observed in the hippocampus of adult mice following voluntary freewheel running (van Praag, Christie, Sejnowski, & Gage, 1999)—a finding consistently replicated over the past decade that correlates with enhanced learning and memory on tasks such as the Morris water maze and radial arm maze (see van Praag (2006) for a review of these studies). A recent study manipulated the timing of a 2 week freewheel running program with respect to training on a Y-maze task to demonstrate that exercise improves both the acquisition and retention of learning (van der Borght, Havekes, Bos, Eggen, & Van der Zee, 2007). These cognitive improvements were complemented by increased hippocampal neurogenesis. Although still a matter of contention, it is thought that the resulting newborn hippocampal cells facilitate learning and memory (e.g., Cotman et al., 2007; Kramer & Erickson, 2007). Much less contentious is the fact that exercise enhances short-term and long-term potentiation—the synaptic parallel of learning—in the hippocampus through the up-regulation and interplay of IGF-1 and BDNF (Cotman et al., 2007).

Animal models of the impact of exercise on the juvenile brain are sparse (van Praag, 2009); however, the few extant studies indicate that exercise has a similar effect on the developing brain as it does on the adult brain. Regular treadmill running results in enhanced visuo-spatial memory and hippocampal cell density—due to increased cell survival—in adolescent rats (da Silva et al., 2010; Uysal et al., 2005). One study of juvenile rats discovered that the impact of exercise on neurogenesis and on the expression of growth factors (e.g., BDNF) was intensity-dependent; that is, low- and moderate-intensity exercise (as determined by running speed) had a stronger impact than high-intensity exercise of equivalent duration (Lou, Liu, Chang, & Chen, 2008). Thus, evidence that exercise positively impacts the developing brain is accumulating, and it may be that regular moderate, rather than intense, exercise is most beneficial (see also Ploughman, 2008).

Fabel and Kempermann (2008) posit that exercise causes a nonspecific neural activation that when combined with a engaging context leads to robust and enduring neurogenesis in the learning and memory centers of the brain. Thus, exercise in a complex and social environment may lead to greater morphological changes than exercise in a simpler context. Freewheel running in conjunction with group housing induces neurogenesis in the hippocampus to a greater extent than freewheel running individually (Stranahan, Khalil, & Gould, 2006). A second study (Ekstrand, Hellsten, & Tingström, 2008) reported intriguing evidence that whereas individual freewheel running promotes angiogenesis (i.e., the growth of new blood vessels linked to neurogenesis) in the hippocampus in comparison to a sedentary condition, an enriched environment promotes angiogenesis in both the hippocampus and PFC in adult rats. The enriched environment included several platforms, along with ropes, ladders, and plastic tubes to move among the platforms, and was reconstructed twice weekly in order to maintain its novelty. It may be that regular exercise in a complex and novel environment promotes EF via specific morphological changes in the PFC.

Evidence is building that exercise's impact on human cognition is mediated by similar mechanisms (Pereira et al., 2007). For example, Pereira et al. (2007) found evidence that chronic aerobic exercise increases regional cerebral blood volume (CBV) in a specific area of the hippocampus in both mice and humans. This increased CBV, thought to be associated directly with angiogenesis, was shown to be a direct correlate of neurogenesis in mice and predicted effortful memory performance in humans. Further support that aerobic exercise promotes morphological changes in humans comes from a randomized controlled trial conducted by Colcombe and colleagues (Colcombe et al., 2006). Older adults (aged 60–80) assigned to 6 months of aerobic training showed increased white and gray matter volume, based on structural MRI, compared to the no-activity control participants. This increased brain volume was most pronounced in frontal brain regions—regions implicated in EF. The authors note that the increased brain volume may reflect cellular changes in synaptic interconnections, axonal integrity, and capillary bed growth. Finally, there is some evidence that aerobic exercise induces functional changes to the brain. As reported previously, overweight children who participated in a chronic aerobic exercise intervention showed increased frontal activation, but decreased parietal activation, during an fMRI anti-saccade paradigm (Davis et al., in press). Thus, converging evidence suggests that regular aerobic exercise in humans also has a direct impact on the neural substrate underlying cognition.

Acute aerobic exercise

Aerobic exercise also induces immediate neurochemical changes (Meeusen, Piacentini, & De Meirleir, 2001) that may prime the central nervous system for either concurrent or subsequent skill acquisition. In a rodent model of ischemia, aerobic exercise immediately preceding motor skill training led to greater skill recovery than either skill training or exercise alone (Ploughman, Attwood, White, Doré, & Corbett, 2007). There was also marginally greater expression of mRNA BDNF in the exercise plus motor skill training condition, suggesting that up-regulation of growth factors may underlie the priming effect.

A study with humans further suggests that exercise has an immediate priming effect (Winter et al., 2007). Here, learning was superior following a short, intense running effort as compared to a longer, moderately intense run or period of relaxation. This behavioral effect was complemented by increases in peripheral levels of BDNF and monoamines (dopamine, norepinephrine, and epinephrine) that predicted retention of the learned material (see also Ferris, Williams, & Shen, 2007). A second human study examined whether the simultaneous engagement in exercise and a cognitive task leads to an interaction between the central and peripheral biochemical response (McMorris, Collard, Corbett, Dicks, & Swain, 2008). The authors were interested in exercise-induced acute increases in dopamine and norepinephrine concentrations that may aid cognitive performance. Although the results did not clearly indicate that the combination of exercise and a challenging EF task boosts neurochemical levels more so than repetitive exercise alone, there was evidence that the greater the norepinephrine response to the combination of exercise and EF, the greater benefit to EF task performance. These immediate neurochemical boosts may transiently enhance the neural response to challenging tasks. Already discussed, Hillman et al. (2009) reported that acute treadmill walking results in enhanced P3 amplitude in preadolescent children, likely representing increased allocation of attention. Hence, exercise not only induces long-lasting morphological changes over time but stimulates immediate chemical changes leading to an increased state of arousal that may enhance cognitive performance. Consequently, both acute and chronic exercise may facilitate EF but through different physiological pathways.

Summary

To summarize, evidence from a variety of research disciplines indicates that aerobic exercise may
impact EF through multiple pathways. Which of these pathways apply depends on the nature of the
1 exercise. Participation in aerobic games likely requires many of the same cognitive processes as more
traditional EF tasks, such as strategic and goal-directed behavior in the face of a novel game experi-
2 ence, and those skills gained during aerobic game participation may transfer to EF tasks. Aerobic
games also require skilled and complex movement, which directly relies on the prefrontal neural cir-
3 cuitry supporting EF. Finally, aerobic exercise causes not only general physiological changes to the body (e.g., increased blood flow) but also specific changes in the brain. Acute exercise promotes an immediate neurochemical response that may enhance cognitive performance, and chronic exercise induces morphological changes to brain regions critical to learning. Supporting the results of experimental studies with children, there is intriguing evidence that exercise in a cognitively-engaging context has a stronger impact on the brain. Thus, an interesting hypothesis is that exercise that impacts EF through multiple pathways would have a stronger effect than exercise that works through fewer pathways. For example, chronic participation in aerobic games ostensibly would impact EF via more pathways (i.e., goal-directed thinking, skilled and complex movement, and chronic physiological changes) than regular walking (chronic physiological changes).

How are physical activity and EF connected at earlier developmental time points?

In order to understand the link between physical activity and EF, it is necessary to look at the possible origins of this link. Several lines of research outline the potential role of movement in cognitive development starting in infancy (Adolph, 2008; Campbell, Eaton, & McKeen, 2002; Robertson & Johnson, 2009; Sommerville & Decety, 2006; Thelen & Smith, 1994). Emphasizing its importance, Piaget (1952) termed the first stage of development the *Sensorimotor Period*. More recently, the application of dynamical systems theory to developmental theory and the notion of embodied cognition (Smith, 2009; Thelen & Smith, 1994) have drawn attention to the child's body and the actions of the body when considering learning and cognitive development. Like Piagetian theory, the dynamical systems account stresses the sensorimotor processes that underlie the formation of representations; however, unlike in a Piagetian account, these representations are not part of discrete cognitive structures, but emerge through the complex and nonlinear interactions of the body, mind, and environment (Smith, 2009). Furthermore, these sensorimotor representations are not considered limitations of an immature cognitive structure. Instead, sensorimotor representations emerge at all ages and allow for coherence and stability within the individual (Smith, 2009). In line with this view, recent research provides evidence that early action experience may provide the basis for higher-order cognition, including EF, to emerge. Consideration of a subset of these studies will be helpful in understanding the more specific link between aerobic exercise and EF found in later development.

Movement–attention coupling in early infancy

Robertson and his colleagues (Friedman, Watamura, & Robertson, 2005; Robertson, Bacher, & Huntington, 2001; Robertson & Johnson, 2009; Robertson, Johnson, Masnick, & Weiss, 2007) have examined the second-by-second coupling of movement and visual attention engagement and disengagement in young infants. This research suggests that physical activity may aid in unlocking infant's sustained attention, allowing for attention to shift to another stimulus (Robertson et al., 2001; Robertson et al., 2007). The integration of movement and attention that occurs over the first few months of life may be significant to later attention and cognitive development. In a longitudinal study, Friedman et al. (2005) found that variation in movement–attention coupling in early infancy significantly correlated with parent reports of hyperactivity and inattention 8 years later. Given that childhood inattention problems (i.e., ADHD) have been linked to executive dysfunction (Barkley, 1997) and that individual differences in attention during infancy predict later EF abilities (Sethi, Mischel, Aber, Shoda, & Rodriguez, 2000), early movement–attention coupling such that motor activity is suppressed during sustained attention likely is a critical foundation to later EF development.

Infant locomotion and cognitive flexibility

By the end of the first year of life, infants' motor repertoire extends beyond actions on the immediate environment to include locomotion that allows exploration of the more distant environment. Adolph and her colleagues (e.g., Adolph, 2000; Berger & Adolph, 2003; Gill, Adolph, & Vereijken, 2009) have studied extensively infants' forms of locomotion and their adaptation of locomotion to a constantly changing environment. Adolph (2006, 2008) drew on the idea of "learning to learn" from Harry Harlow to argue that young children's exploratory motor activity places infants in novel and complex situations that train a controlled and adaptive way of thinking—that is, cognitive flexibility. Cognitive flexibility is a foundational EF (Miyake et al., 2000) that stands in contrast to simple associative learning in which a specific cue elicits a predefined response. Instead, cognitive flexibility is characterized by the ability to focus on relevant stimuli while ignoring irrelevant stimuli and the ability to form, test and alter hypotheses in a strategic manner (Adolph, 2006). Later, this way of thinking can be applied in other complex and novel problem-solving situations with similar task parameters, whether physically-based or entirely abstract. Thus, movement seems to drive cognitive development in part by requiring children to use flexible and adaptive thought processes.

A bridge crossing experiment with 16-month-old infants illustrates their adaptive locomotion and the early signs of EF (Berger & Adolph, 2003). In this experimental paradigm the demands on infants' locomotive skills are manipulated by encouraging them to cross bridges of varying widths (from narrow to wide), with or without the presence of a handrail. During difficult trials (i.e., narrow bridge crossings) infants were more likely to use a handrail, when available, and their success depended on the use of multiple strategies, strategy monitoring and updating, and the switching to more efficient strategies. Successful infants approached the task in a planful manner and used sophisticated means-end problem solving by first testing out the handrail prior to embarking onto the bridge and then using the handrail as a tool to enhance their balance while crossing the narrow bridge. Indeed, infants' strategic approach to the task bears striking similarities to older children's strategy use on traditional problem solving tasks involving math, reading, or memory skills—tasks that require planful and goal-directed executive processes. Thus, early motor exploration may form the foundation of a goal-directed, flexible way of thinking (i.e., "learning to learn") that will be critical not only to later EF during physical activity, but even to abstract problem solving.

Action experience and understanding of action goals

Infants' action experiences also impact goal-directed behavior (i.e., EF) by allowing them to understand that others' actions are intentional and goal-directed. Sommerville and Woodward (2005) used a habituation procedure to determine whether 10- and 12-month-olds focused their attention on an experimenter's action *per se* (i.e., pulling a cloth forward) or on the end goal of that action (i.e., obtaining a toy on top of the cloth). Most 12-month-olds selectively encoded the action goal. In contrast, only 10-month-olds who themselves had used goal-directed actions to obtain a toy selectively encoded the action goal. In a follow-up study, Sommerville, Hildebrand, and Crane (2008) explored whether action experience uniquely impacted infants' understanding of actions or whether simple action observation equally promoted action understanding. Ten-month-olds participated in either active training of a means-end action procedure (i.e., using a cane to pull a toy closer) or observation of that same action procedure before participating in a similar habituation paradigm. In support of the unique importance of action experience, infants who participated in the active training, but not those who participated in observation training, showed release from habituation when the action goal changed, indicating a selective encoding of action goals. Furthermore, a follow-up analysis revealed that only those infants who used planful strategies during active training showed selective goal encoding of others' actions. Thus, in line with the results of Sommerville and Woodward (2005), infants' understanding of action goals depended not only on having experience in performing similar actions but also on having competence in performing those actions. Extending that previous finding, it appears that goal-directed action competence precedes goal-directed action understanding.

Motor activity and cognition in preschoolers

Motor activity continues to be important to higher-order cognitive development during the preschool years. Campbell et al. (2002) examined whether variation in motor activity in preschool children (aged 4–6) predicted variation in behavioral control. Motor activity was measured objectively using actometers, which record the frequency of movement of the arms and legs of the child. Behavioral control was assessed using common child appropriate inhibition tasks such as the tapping task (i.e., tap twice when the experimenter taps once and vice versa). It was found that higher levels of movement predicted higher inhibition performance but not non-inhibition performance (i.e., control trial performance). The authors argued that high activity in preschoolers represents functional, exploratory activity rather than a lack of behavioral control. Similar to the arguments of Adolph (2006), Adolph (2008), movement may require constant shifts in attention and motor response (i.e., cognitive flexibility) that "may stimulate prefrontal lobe functioning and enhance young children's inhibitory ability" (p. 295).

Summary

These studies indicate that within the first few weeks of life a tight coupling of action and the rudiments of EF emerges. It appears that the complexity of the action and of the EF component increase with development. Early bursts of gross motor movement are coupled to basic attentional processes. Later, locomotion and exploration connect with adaptive and flexible ways of thinking. At the same time, toddlers' personal experiences with goal-directed actions facilitate their understanding of others' goal-directed actions. Older children's participation in structured aerobic games, which require even more complex movement and coordination, facilitates further EF development, including the sophisticated abilities to selectively attend to stimuli and to withhold prepotent responses in favor of other responses. Thus, the link between physical activity and EF found in children may be traced back to infancy.

It is likely that the proposed mechanisms mediating the specific link between habitual aerobic exercise and EF in later childhood also may help explain this early-developing link. For example, early exploration of the world often requires the effortful coordination of multiple movements, the adaption of those movements to dynamic task demands, and the connection of those movements to create a goal-directed action sequence. The regular engagement in these physical actions likely stimulates regions of the brain, inducing critical morphological and functional development. Therefore, regular engagement in physical movement in early childhood likely activates, and facilitates the development of, frontal-mediated EF.

Implications

EF is critical to nearly all forms of behavior and is a cornerstone of development. EF is important to classroom behavior (Riggs, Blair, & Greenberg, 2003) and to emotional self-regulation, which is particularly important for school readiness and success (Blair & Diamond, 2008). In fact, self-regulation (e.g., following directions and controlling attention) seems to be more closely linked to success during kindergarten than the acquisition of specific academic skills (e.g., knowing the letters of the alphabet) (Blair & Diamond, 2008). Physical activity, and aerobic exercise more specifically, have the potential to promote multiple facets of development through its direct impact on EF. Two recent studies indicate that preschool interventions that create student-centered, action-based classroom environments positively impact EF in comparison to more traditional, teacher-centered classroom environments (Diamond, Barnett, Thomas, & Munro, 2007; Lillard & Else-Quest, 2006). In turn, these student-centered, action-based classrooms may lead to increased positive play behavior (Lillard & Else-Quest).

In older children, aerobic exercise interventions may be effective in several populations. Overweight children, because they typically are inactive, arguably should be the highest priority target population of aerobic exercise interventions. In fact, because the human body evolved to support regular physical activity, some of the health problems associated with childhood overweight actually may to some extent reflect children's inactivity rather than their overweight *per se* (Booth & Lees, 2006; Vaynman & Gomez-Pinilla, 2006). Pediatric overweight has risen significantly and to alarming levels in recent years (Ogden et al., 2006), and overweight in children is related to poor academic achievement (Dwyer, Sallis, Blizzard, Lazarus, & Dean, 2001; Taras & Potts-Datema, 2005) and to sedentary behavior (Must, Bandini, & Tybor, 2007; Must & Tybor, 2005). Moreover, school time dedicated to recess has dwindled (Story, Kaphingst, & French, 2006), and few children receive the recommended amount of exercise (CDC, 2007). As already reported, Davis et al. (2007, in press) established that an aerobic exercise intervention impacted overweight children's EF math fluency despite no specific math instruction (Davis et al., in press). This outcome is consistent with the finding that EF is associated with achievement in a number of academic domains (Best et al., 2009). Sound scientific support for the beneficial effects of aerobic exercise on EF and on academic achievement by extension, as is shown here, may be instrumental in reversing current school policies that limit time allotted to regular exercise.

Children with ADHD, another population of significant public interest, may also benefit from aerobic exercise. Both an animal model of ADHD (Hopkins, Sharma, Evans, & Bucci, 2009) and an experimental study with diagnosed children (Tantillo, Kesick, Hynd, & Dishman, 2002) provide tentative evidence that exercise has an ameliorative effect on ADHD symptoms; however, much more research is needed to clarify the complicated findings of these studies. Given the proposed link between executive dysfunction and ADHD (Barkley, 1997), the possibility that aerobic exercise may reduce ADHD symptoms through its promotion of EF should be researched.

Finally, youth with various other disabilities, who often live more sedentary lifestyles, may benefit from physical activity (Ploughman, 2008). A 6-month home-based randomized controlled trial in which children completed various physical exercises to enhance fine motor skill and coordination promoted various language skills, including reading accuracy, phonological skill, and verbal working memory, in children with reading difficulty (some with diagnosed dyslexia) (Reynolds, Nicolson, &

Hambly, 2003). These cognitive gains persisted even 18 months after the termination of the intervention (Reynolds & Nicolson, 2007). In another randomized control trial, an 8-month intervention stressing various aerobic and anaerobic exercises, including the coordination of body movements, positively influenced the cognitive functioning of children with cerebral palsy (Verschuren et al., 2007). Thus, regular exercise has the potential to bolster not only children's physical health but also their cognitive health and may be effective in clinical interventions.

Advances in the video gaming industry offer a novel manner by which to implement exercise-based interventions and to increase children's physical activity while playing cognitively-engaging interactive games. Exergames (a portmanteau of "exercise" and "games") are a new generation of video games that stimulate a more active, whole-body gaming experience. Because of their recent emergence, empirical research with exergames is limited, but the few extant studies report the potential of exergames to promote physical activity. First, caloric expenditure from exergame playing is significantly greater than from sedentary video game playing (Graves, Stratton, Ridgers, & Cable, 2007) or television watching (Graf, Pratt, Hester, & Short, 2009). Second, evidence suggests that exergame-based interventions may be an effective manner to increase regular physical activity. For example, Warburton et al. (2007) reported that young adults assigned randomly to an exergame condition demonstrated greater physical activity adherence compared to young adults assigned to traditional exercise training (stationary cycling). Moreover, the exergame group showed significantly greater increases in aerobic capacity (*VO*2 max) and decreases in resting systolic blood pressure in comparison to traditional aerobic training group. Similarly, Mhurchu et al. (2008) found that children provided with exergame equipment demonstrated increased physical activity and marginally decreased waist circumferences compared to controls. Thus, there is promising early evidence that exergames can have a salutary effect of physical health by promoting physical activity.

Exergames have several attributes that make them ideal for intervention research. Exergames are relatively inexpensive, are widely available, require a small amount of space, can be played alone or with others, adjust to one's skill level, and are perceived as enjoyable by children (Papastergiou, 2009). These same attributes also may make exergames ideal for use by low-income children, who may have limited access to safe recreational space and equipment, and by children with psychosocial impediments to physical activity engagement (e.g., children, especially overweight ones, with low physical activity self-efficacy and enjoyment, or negative perceptions of exercising around others). Importantly, these games can be designed to impose significant cognitive demands on the children and to adapt to the children's performance so that children's cognitive health benefits as well. Furthermore, cognitively-engaging exergames and sedentary games can be compared in experimental research to determine whether cognitively-engaging games alone (i.e., without any aerobic component) impact cognition.

Concluding themes

Several themes emerge from this review of the benefits of aerobic exercise on children's EF. These themes provide a concise synthesis of current research in the field and also guide us in formulating future investigations.

EF is a multi-componential construct that consists of several distinct, yet interrelated, processes. Each component follows a unique developmental course, and each matures in late adolescence or in early adulthood. It is possible, therefore, that exercise would not impact each component of EF equally or that certain components are more sensitive to specific forms of aerobic exercise. In creating future research designs, attention needs to be paid to which tasks are being used to assess EF. Ideally, multiple EF tasks will be employed that have been linked to multiple EF components (e.g., the go/no-go task to assess response inhibition or a backwards number span to assess working memory) to determine whether certain components are more sensitive (Etnier & Chang, 2009). Non-EF tasks also need to be employed to further test the hypothesis that aerobic exercise has its strongest impact on EF. Finally, the cognitive and physical developmental level of the children needs to receive special attention, as the effect of exercise on EF(s) may be moderated by children's cognitive level and pubertal status.

All forms of aerobic exercise appear not to be equal in their impact on EF. From the cognitive challenges (e.g., the need to act in a goal-directed and strategic fashion) inherent in group games to the arousing effect of vigorous movement, exercise has the potential to impact EF in several ways. As recent acute studies have done (e.g., Budde et al., 2008 and Pesce et al., 2009) different forms of exercise need to be pitted against one other to test whether certain forms have a stronger impact on EF. The evidence suggests that aerobic activity alone influences EF, but that the interaction of aerobic activity and cognitive engagement has an even stronger effect. However, it is unclear whether this effect is greater than the effect of cognitively-engaging sedentary activities on EF. As mentioned above, interactive video games could provide a novel method to explore this experimentally. For example, exergames and sedentary video games with similar game play (i.e., engage similar cognitive processes) could be compared. If exergaming has a stronger effect on children's EF, then it could be concluded that the interaction of aerobic activity and cognitive engagement drives the effect. Alternatively, if exergaming and sedentary gaming have an equivalent effect on EF, then it would seem that the more important factor is that the activity, whether aerobic or sedentary, provides a context to engage EF processes.

There are also several ways in which aerobic activity can be cognitively-engaging. For example, it can provide opportunities to acquire complex motor skills or it can require children to continually adapt their strategies and behavior to changing game demands. As done by Pesce et al. (2009), detailed and objective data of what types of learning occur during different forms of exercise will be highly informative in determining how those forms of exercise are cognitively engaging. Furthermore, the social interaction that occurs during group games and other forms of exercise also may positively impact cognition. Pesce et al. (2009) assessed the amount of social interaction during group games and circuit training; unfortunately, they did not relate these data to performance on the cognitive task. One animal model (Stranahan et al., 2006) reported that rats in social isolation do not garner the same benefits from exercise that rats housed together do. The authors suggest that social interaction may buffer against the stressful aspects of exercise. Clearly, attention needs to be paid to the possibility that social interaction may explain (in full or in part) the added benefits of group games on cognition. One possibility is that trying to assess others' mental states (e.g., their intentions) and anticipate their movements during group play provides part of the benefit.

Finally, certain forms of exercise may be more beneficial to EF at one age or another. Younger children may benefit from less structured forms of exercise that involve pretend play whereas older children may benefit from more sophisticated games containing complex rule structures. Thus, the children's developmental level needs to be carefully considered to optimize their cognitive engagement.

Animal models have been instrumental in revealing the physiological mechanisms that underlie that link between exercise and EF. Exercise ultimately exerts its influence on cognition via physiological changes in the brain. In humans we can examine gross morphological and functional changes through imaging techniques (e.g., changes gray matter volume or in activation strength and location, respectively); however, to understand detailed chemical and cellular changes, animal models are required. Animal models have established that the up-regulation of BDNF and other neurotrophins is a critical pathway. This line of research will continue to expand our knowledge and fill in current gaps, such as how BDNF up-regulation leads to enhanced cognition (Holmes, 2006). Overall, the mechanisms by which exercise affects cognition can be understood only by studying them at multiple levels, from cells to social interaction.

The impact of aerobic exercise on children's EF needs to be placed within the larger context of the action–cognition interaction that persists across development. Studies reviewed here indicate a physical activity–cognition coupling that begins in early infancy and that likely promotes the rudiments of goal-directed behavior and cognition. Evidence from studies of older children's EF following aerobic exercise indicates that this coupling continues in later development. However, there has not been sufficient crosstalk between developmental psychologists, who typically conduct the former studies, and kinesiologists, who typically conduct the latter studies. Such crosstalk would be beneficial as there are several developmental issues that need to be considered. Already mentioned, whether a specific EF component is sensitive to aerobic exercise and whether exercise will be cognitively engaging may depend on the children's developmental level. Evidence suggests that the EF components are distinct, emerge at different ages, and develop at different rates (Best et al., 2009). This evidence should be considered in order to select appropriate EF tasks and forms of aerobic exercise for a certain sample of children.

Furthermore, a developmental approach to this research will aid in hypothesizing about the nature of the changes in EF resulting from aerobic exercise. An important question is whether aerobic exercise transiently facilitates EF or whether it has a more fundamental impact on development, resulting in long-term changes. This could be answered by including follow-up cognitive assessments after several months or years. It is also important to determine the size of the effect on EF. This could be addressed by including multiple ages and by comparing trained younger children to untrained older children. Rueda et al. (2005) used this approach to examine the impact of a 5-day computer training on EF. By comparing the behavioral and neuroelectric data of trained 4-year-olds to untrained 6-year-olds, the researchers determined that the training effect on EF had an effect size resembling the developmental improvements that occur from age 4 to 6. Similar research using aerobic exercise training would enhance our understanding of how it impacts development. In the other direction, kinesiology research on the benefits of physical activity can inform developmental psychology. For example, it is interesting that infant research on links between motor behavior and cognition does not address the effects of the intensity of the action. The research on aerobic exercise described earlier suggests that this is an important dimension to consider. Such research would more clearly link these two research areas.

Overall, engagement in physical activity (or more specifically aerobic exercise) is also a cognitive activity that recruits higher-order brain regions and requires adaptive thinking. Whereas physical activity may not naturally facilitate rote memorization or associative learning, it likely does facilitate the emergence and development of adaptive, goal-directed problem-solving skills, which is one of the hallmarks of human development. Aerobic exercise, then, may be an invaluable part of children's development, and these findings should persuade parents and educators to reconsider the importance of aerobic exercise. Therefore, the importance of regular physical activity to the developing body and mind cannot be overstated.

Acknowledgment

I thank Patricia Miller, Catherine Davis, Phillip Tomporowski, and Casey O'Donnell for reading and offering comments on an earlier draft.

References

Adolph, K. E. (2000). Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science, 11*, 290–295.
Adolph, K. E. (2006). Learning to learn in the development of action. In J. J. Reiser, J. J. Lockman, & C. A. Nelson (Eds.). *Action as an organizer of learning and development* (Vol. 33, pp. 91–122). Mahway, NJ: Lawrence Erlbaum Associates.
Adolph, K. E. (2008). Learning to move. *Current Directions in Psychological Science, 17*, 213–218.
Banich, M. T. (2009). Executive Function: The search for an integrated account. *Current Directions in Psychological Science, 18*, 89–94.
Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*, 65–94.
Battig, W. F. (1972). Intratask interference as a source of facilitation in transfer and retention. In R. F. Thompson & J. F. Voss (Eds.), *Topics in learning and performance* (pp. 131–159). New York: Academic Press.
Berger, S. E., & Adolph, K. E. (2003). Infants use handrails as tools in a locomotor task. *Developmental Psychology, 39*, 594–605.
Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive function after age 5: Changes and correlates. *Developmental Review, 29*, 180–200.
Blair, C., & Diamond, A. (2008). Biological processes in prevention and intervention: The promotion of self-regulation as a means of preventing school failure. *Development and Psychopathology, 20*, 899–911.
Booth, F. W., & Lees, S. J. (2006). Physically active subjects should be the control group. *Medicine & Science in Sports & Exercise, 38*, 405–406.
Brady, F. (2008). The contextual interference effect and sport skills. *Perceptual and Motor Skills, 106*, 461–472.
Budde, H., Voelcker-Rehage, C., Pietrabyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters, 441*, 219–223.
Campbell, D. W., Eaton, W. O., & McKeen, N. A. (2002). Motor activity level and behavioural control in young children. *International Journal of Behavioral Development, 26*, 289–296.
Carey, J. R., Bhatt, E., & Nagpal, A. (2005). Neuroplasticity promoted by task complexity. *Exercise and Sport Sciences Reviews, 33*, 24–31.

Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985). Physical activity, exercise, and physical fitness: Definitions and distinctions for health-related research. *Public Health Reports, 100*, 126–131.

Caterino, M. C., & Polak, E. D. (1999). Effects of two types of activity on the performance of second-, third-, and fourth-grade students on a test of concentration. *Perceptual and Motor Skills, 89*, 245–248.

Center for Disease Control and Prevention. (2007). <http://www.cdc.gov/nccdphp/dnpa/obesity/trend> Retrieved 11.02.10.

Churchill, J. D., Galvez, R., Colcombe, S., Swain, R. A., Kramer, A. F., & Greenough, W. T. (2002). Exercise, experience and the aging brain. *Neurobiology of Aging, 23*(5), 941–955.

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., et al (2006). Aerobic exercise training increases brain volume in aging humans. *Journal of Gerontology: Medical Sciences, 61*, 1166–1170.

Cotman, C. W., Berchtold, N. C., & Christie, L. (2007). Exercise builds brain health: Key roles of growth factor cascades and inflammation. *Trends in Neurosciences, 30*, 464–473.

Cross, E. S., Schmitt, P. J., & Grafton, S. T. (2007). Neural substrates of contextual interference during motor learning support a model of active preparation. *Journal of Cognitive Neuroscience, 19*, 1854–1871.

da Silva, S. G., Doná, F., da Silva Fernandes, M. J., Scorza, F. A., Cavalheiro, E. A., & Arida, R. M. (2010). Physical exercise during the adolescent period of life increases hippocampal parvalbumin expression. *Brain & Development, 32*, 137–142.

Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P. H., Yanasak, N. E. et al. (in press). Exercise improves executive function and alters neural activation in overweight children: A randomized controlled trial. *Health Psychology*.

Davis, C. L., Tomporowski, P. D., Boyle, C. A., Waller, J. L., Miller, P. H., Naglieri, J. A., et al (2007). Effects of aerobic exercise on overweight children's cognitive functioning: A randomized controlled trial. *Research Quarterly for Exercise and Sport, 78*(5).

Delis, D. C., Lansing, A., Houston, W. S., Wetter, S., Han, S. D., Jacobson, M., et al (2007). Creativity lost: The importance of testing higher-level executive functions in school-age children and adolescents. *Journal of Psychoeducational Assessment, 25*, 29–40.

Della Rochetta, A. I., & Milner, B. (1993). Strategic search and retrieval inhibition: The role of the frontal lobes. *Neuropsychologia, 31*, 503–524.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71*, 44–56.

Diamond, A. (2006). The early development of executive functions. In E. Bialystok & F. I. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 70–95). Oxford: Oxford University Press.

Diamond, A. (2009). All or none hypothesis: A global-default mode that characterizes the brain and mind. *Developmental Psychology, 45*, 130–138.

Diamond, A., Barnett, W. S., Thomas, J., & Munro, S. (2007). Preschool program improves cognitive control. *Science, 318*, 1387–1388.

Dishman, R. K., Berthoud, H., Booth, F. W., Cotman, C. W., Edgerton, V. R., Fleshner, M. R., et al (2006). Neurobiology of exercise. *Obesity, 14*, 345–354.

Dwyer, T., Sallis, J. F., Blizzard, L., Lazarus, R., & Dean, K. (2001). Relation of academic performance to physical activity and fitness in children. *Pediatric Exercise Science, 13*, 225–237.

Ekstrand, J., Hellsten, J., & Tingström, A. (2008). Environmental enrichment, exercise and corticosterone affect endothelial cell proliferation in adult rat hippocampus and prefrontal cortex. *Neuroscience Letters, 442*, 203–207.

Ellemberg, D., & St. Louis-Deschênes, M. (2010). The effect of acute physical activity on cognitive function during development. *Psychology of Sport and Exercise, 11*, 122–126.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., et al (2007). Training-induced functional activation changes in dual-task processing: An fMRI study. *Cerebral Cortex, 17*, 192–204.

Eriksen, B. A., & Eriksen, C. E. (1974). Effects of noise letters in the identification of target letters in a non-search task. *Perception & Psychophysics, 16*, 143–149.

Etnier, J. L., & Chang, Y. (2009). Executive function: A brief commentary on definitions, measurement issues, and the current state of the literature. *Journal of Sport and Exercise Psychology, 31*, 469–483.

Fabel, K., & Kempermann, G. (2008). Physical activity and the regulation of neurogenesis in the adult and aging brain. *Neuromolecular Medicine, 10*, 59–66.

Ferris, L. T., Williams, J. S., & Shen, C. (2007). The effects of acute exercise on serum brain-derived neurotrophic factor levels and cognitive function. *Medicine & Science in Sports & Exercise, 39*, 728–734.

Friedman, N. P., Miyake, A., Young, S. E., DeFries, J. C., Corley, R. P., & Hewitt, J. K. (2008). Individual differences in executive functions are almost entirely genetic in origin. *Journal of Experimental Psychology: General, 137*, 201–225.

Friedman, A. H., Watamura, S. E., & Robertson, S. S. (2005). Movement–attention coupling in infancy and attention problems in childhood. *Developmental Medicine and Child Neurology, 47*, 660–665.

Gill, S. V., Adolph, K. E., & Vereijken, B. (2009). Change in action: How infants learn to walk down slopes. *Developmental Science, 12*, 888–902.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Science USA, 101*, 8174–8179.

Graf, D. L., Pratt, L. V., Hester, C. N., & Short, K. R. (2009). Playing active video games increases energy expenditure in children. *Pediatrics, 124*, 534–540.

Graves, L., Stratton, G., Ridgers, N. D., & Cable, N. T. (2007). Comparison of energy expenditure in adolescents when playing new generation and sedentary computer games. *British Medical Journal, 335*, 1282–1284.

Hillman, C. H., Pontifex, M. B., Raine, L. B., Castelli, D. M., Hall, E. E., & Kramer, A. F. (2009). The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. *Neuroscience, 3*, 1044–1054.

Hinkle, J. S., Tuckman, B. W., & Sampson, J. P. (1993). The psychology, physiology, and the creativity of middle school aerobic exercisers. *Elementary School Guidance & Counseling, 28*, 133–145.

Holmes, P. V. (2006). Current findings in neurobiological systems' response to exercise. In L. Poon, W. Chodzo-Zajko, & P. D. Tomporowski (Eds.), *Active living, cognitive functioning, and aging* (pp. 75–89). Champaign, IL: Human Kinetics.

Hopkins, M. E., Sharma, M., Evans, G. C., & Bucci, D. J. (2009). Voluntary physical exercise alters attentional orienting and social behavior in a rat model of attention-deficit/hyperactivity disorder. *Behavioral Neuroscience, 123*, 599–606.

Huizinga, M., Dolan, C. V., & Molen, M. W. v. d. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia, 44*, 2017–2036.
Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Science USA, 105*, 6829–6833.
Jones, T. A., Hawrylak, N., Klintsova, A. Y., & Greenough, W. T. (1998). Brain damage, behavior, rehabilitation, recovery, and brain plasticity. *Mental Retardation and Developmental Disabilities, 4*, 231–237.
Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlström, K., et al (2005). Computerized training of working memory in children with ADHD—A randomized, controlled trial. *Journal of the American Academy of Child and Adolescent Psychiatry, 44*, 177–186.
Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology, 24*, 781–791.
Kramer, A. F., & Erickson, K. I. (2007). Capitalizing on cortical plasticity: Influence of physical activity on cognition and brain function. *Trends in Cognitive Sciences, 11*(8), 342–348.
Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology, 21*, 59–80.
Lillard, A., & Else-Quest, N. (2006). Evaluating Montessori education. *Science, 313*, 1893–1894.
Lou, S., Liu, J., Chang, H., & Chen, P. (2008). Hippocampal neurogenesis and gene expression depend on exercise intensity in juvenile rats. *Brain Research, 1210*, 48–55.
Luria, A. R. (1966). *Higher cortical functions in man*. NY: Basic Books.
McMorris, T., Collard, K., Corbett, J., Dicks, M., & Swain, J. P. (2008). A test of the catecholamines hypothesis for an acute exercise–cognition interaction. *Pharmacology, Biochemistry and Behavior, 89*, 106–115.
McMorris, T., & Graydon, J. (1996). Effects of exercise on soccer decision-making tasks of differing complexities. *Journal of Human Movement Studies, 30*, 177–193.
Meeusen, R., Piacentini, M. F., & De Meirleir, K. (2001). Brain microdialysis in exercise research. *Sports Medicine, 31*, 965–983.
Mhurchu, C. N., Maddison, R., Jiang, Y., Jull, A., Prapavessis, H., & Rodgers, A. (2008). Couch potatoes to jumping beans: A pilot study of the effect of active video games on physical activity in children. *International Journal of Behavioral Nutrition and Physical Activity, 5*, 1–5.
Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100.
Moscovitch, M., & Winocur, R. (2002). The frontal cortex and working with memory. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 188–209). New York: Oxford University Press.
Must, A., Bandini, L. G., & Tybor, D. J. (2007). Activity, inactivity, and screen time in relation to weight and fatness over adolescence in girls. *Obesity, 15*, 1774–1781.
Must, A., & Tybor, D. J. (2005). Physical activity and sedentary behavior: A review of longitudinal studies of weight and adiposity in youth. *International Journal of Obesity, 29*, S84–S96.
Naglieri, J. A., & Das, J. P. (1997). *Cognitive assessment system*. Itasca, IL: Riverside Publishing.
Ogden, C. L., Carroll, M. D., Curtin, L. R., McDowell, M. A., Tabak, C. J., & Flegal, K. M. (2006). Prevalence of overweight and obesity in the United States, 1999–2004. *Journal of the American Medical Association, 295*, 1549–1555.
O'Hare, E. D., & Sowell, E. R. (2008). Imaging developmental changes in gray and white matter in the human brain. In C. A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (2nd ed., pp. 23–38). Cambridge, MA: MIT Press.
Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience, 7*, 75–79.
Papastergiou, M. (2009). Exploring the potential of computer and video games for health and physical education: A literature review. *Computers & Education, 53*, 603–622.
Pereira, A. C., Huddleston, D. E., Brickman, A. M., Sosunov, A. A., Hen, R., McKhann, G. M., et al (2007). An in vivo correlate of exercise-induced neurogenesis in the adult dentate gyrus. *Proceedings of the National Academy of Sciences USA, 104*, 5638–5643.
Persson, J., & Reuter-Lorenz, P. A. (2008). Gaining control: Training executive function and far transfer of the ability to resolve interference. *Psychological Science, 19*, 881–888.
Pesce, C., Crova, C., Cereatti, L., Casella, R., & Bellucci, M. (2009). Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. *Mental Health and Physical Activity, 2*, 16–22.
Piaget, J. (1952). *The origins of intelligence in children*. New York: International Universities Press.
Ploughman, M. (2008). Exercise is brain food: The effects of physical activity on cognitive function. *Developmental Neurorehabilitation, 11*, 236–240.
Ploughman, M., Attwood, Z., White, N., Doré, J. J. E., & Corbett, D. (2007). Endurance exercise facilitates relearning of forelimb motor skill after focal ischemia. *European Journal of Neuroscience, 25*, 3453–3460.
Reynolds, D., & Nicolson, R. I. (2007). Follow-up of an exercise-based treatment for children with reading difficulties. *Dyslexia, 13*, 78–96.
Reynolds, D., Nicolson, R. I., & Hambly, H. (2003). Evaluation of an exercise-based treatment for children with reading difficulties. *Dyslexia, 9*, 48–71.
Riggs, N. R., Blair, C. B., & Greenberg, M. T. (2003). Concurrent and 2-year longitudinal relations between executive function and the behavior of 1st and 2nd grade children. *Child Neuropsychology, 9*(4), 267–276.
Robertson, S. S., Bacher, L. F., & Huntington, N. L. (2001). The integration of body movement and attention in young infants. *Psychological Science, 12*, 523–526.
Robertson, S. S., & Johnson, S. L. (2009). Embodied infant attention. *Developmental Science, 12*, 297–304.
Robertson, S. S., Johnson, S. L., Masnick, A. M., & Weiss, S. L. (2007). Robust coupling of body movement and gaze in young infants. *Developmental Psychobiology, 49*, 208–215.

Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccomanno, L., & Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proceedings of the National Academy of Science USA, 102*, 14931–14936.

Schinder, A. F., & Poo, M. (2000). The neurotrophin hypothesis for synaptic plasticity. *Trends in Neuroscience, 23*, 639–645.

Serrien, D. J., Ivry, R. B., & Swinnen, S. P. (2007). The missing link between action and cognition. *Progress in Neurobiology, 82*, 95–107.

Sethi, A., Mischel, W., Aber, J., Shoda, Y., & Rodriguez, M. (2000). The role of strategic attention deployment in development of self-regulation: Predicting preschoolers' delay of gratification from mother–toddler interactions. *Developmental Psychology, 36*, 767–777.

Shimamura, A. P. (2000). The role of the prefrontal cortex in dynamic filtering. *Psychobiology, 28*, 207–218.

Sibley, B. A., & Etnier, J. L. (2003). The relationship between physical activity and cognition in children: A meta-analysis. *Pediatric Exercise Science, 15*, 243–256.

Smith, L. B. (2009). Dynamic systems, sensorimotor processes, and the origins of stability and flexibility. In J. P. Spencer, M. S. C. Thomas, & J. L. McClelland (Eds.), *Toward a unified theory of development: Connectionism and dynamic systems theory re-considered*. Oxford: Oxford University Press.

Sommerville, J. A., & Decety, J. (2006). Weaving the fabric of social interaction: Articulating developmental psychology and cognitive neuroscience in the domain of motor cognition. *Psychonomic Bulletin & Review, 13*, 179–200.

Sommerville, J. A., Hildebrand, E. A., & Crane, C. C. (2008). Experience matters: The impact of doing versus watching on infants' subsequent perception of tool-use events. *Developmental Psychology, 44*, 1249–1256.

Sommerville, J. A., & Woodward, A. L. (2005). Pulling out the intentional structure of action: The relation between action processing and action production in infancy. *Cognition, 95*, 1–30.

Story, M., Kaphingst, K. M., & French, S. (2006). The role of schools in obesity prevention. *The Future of Children, 16*(1), 109–142.

Stranahan, A. M., Khalil, D., & Gould, E. (2006). Social isolation delays the positive effects of running on adult neurogenesis. *Nature Neuroscience, 9*, 526–533.

Stroth, S., Kubesch, S., Dieterle, K., Ruchsow, M., Heim, R., & Kiefer, M. (2009). Physical fitness, but not acute exercise modulates event-related potential indices for executive control in healthy adolescents. *Brain Research, 1269*, 114–124.

Stuss, D. T., & Benson, D. F. (1984). Neuropsychological studies of frontal lobes. *Psychological Bulletin, 95*, 3–28.

Tantillo, M., Kesick, C. M., Hynd, G. W., & Dishman, R. K. (2002). The effects of exercise on children with attention-deficit hyperactivity disorder. *Medicine & Science in Sports & Exercise, 34*, 203–212.

Taras, H., & Potts-Datema, W. (2005). Obesity and student performance at school. *Journal of School Health, 75*(8), 291–295.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

Thorell, L. B., Lindqvist, S., Bergman, S., Bohlin, G., & Klingberg, T. (2008). Training and transfer effects of executive functions in preschool children. *Developmental Science, 11*, 969–976.

Tomporowski, P. D. (2003). Cognitive and behavioral responses to acute exercise in youth: A review. *Pediatric Exercise Science, 15*, 348–359.

Tomporowski, P. D., Davis, C. L., Lambourne, K., Gregoski, M., & Tkacz, J. (2008). Task switching in overweight children: Effects of acute exercise and age. *Journal of Sport & Exercise Psychology, 30*, 497–511.

Tomporowski, P. D., Davis, C. L., Miller, P. H., & Naglieri, J. A. (2008). Exercise and children's intelligence, cognition, and academic achievement. *Educational Psychology Review, 20*, 111–131.

Tomporowski, P. D., & McCullick, B. (2009). The effects of physical activity and direct instruction on children's executive functions: Pre-requisites and considerations. Unpublished manuscript.

Tuckman, B. W., & Hinkle, J. S. (1986). An experimental study of the physical and psychological effects of aerobic exercise on schoolchildren. *Health Psychology, 5*, 197–207.

Uysal, N., Tugyan, K., Kayatekin, B. M., Acikgoz, O., Bagriyanik, H. A., Gonenc, S., et al (2005). The effects of regular aerobic exercise in adolescent period on hippocampal neuron density, apoptosis and spatial memory. *Neuroscience Letters, 383*, 241–245.

van der Borght, K., Havekes, R., Bos, T., Eggen, B. J. L., & Van der Zee, E. A. (2007). Exercise improves memory acquisition and retrieval in the Y-maze task: Relationship with hippocampul neurogenesis. *Behavioral Neuroscience, 121*, 324–334.

van der Sluis, S., de Jong, P. F., & van der Leij, A. (2007). Executive functioning in children, and its relations with reasoning, reading, and arithmetic. *Intelligence, 35*, 427–449.

van Praag, H. (2006). Exercise, neurogenesis, and learning in rodents. In E. O. Acevedo & P. Ekkekakis (Eds.), *Psychobiology of physical activity* (pp. 61–74). Champaign, IL: Human Kinetics.

van Praag, H. (2009). Exercise and the brain: Something to chew on. *Trends in Neuroscience, 32*, 283–290.

van Praag, H., Christie, B. R., Sejnowski, T. J., & Gage, F. H. (1999). Running enhances neurogenesis, learning, and long-term potentiation in mice. *Proceedings of the National Academy of Sciences, 96*, 13427–13431.

Vaynman, S., & Gomez-Pinilla, F. (2006). Revenge of the "sit": How lifestyle impacts neuronal and cognitive health through molecular systems that interface energy metabolism with neuronal plasticity. *Journal of Neuroscience Research, 84*, 699–715.

Verschuren, O., Ketelaar, M., Gorter, J. W., Helders, P. J. M., Uiterwaal, C. S., & Takken, T. (2007). Exercise training program in children and adolescents with cerebral palsy. *Archives of Pediatric and Adolescent Medicine, 161*, 1075–1081.

Warburton, D. E., Bredin, S. S., Horita, L. T., Zbogar, D., Scott, J. M., Esch, B. T., et al (2007). The health benefits of interactive video game exercise. *Applied Physiology, Nutrition, & Metabolism, 32*, 655–663.

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Developmental Psychology, 44*, 575–587.

Winter, B., Breitenstein, C., Mooren, F. C., Voelker, K., Fobker, M., Lechtermann, A., et al (2007). High impact running improves learning. *Neurobiology of Learning and Memory, 87*, 597–609.