PRESCHOOLERS EXHIBIT SIMILAR LEARNING BUT GREATER ON-TASK BEHAVIOR FOLLOWING PHYSICALLY ACTIVE LESSONS ON THE APPROXIMATE NUMBER SYSTEM

By

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PUBLIC ABSTRACT

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Previous studies demonstrate variable effects of physically active learning on cognition, academic achievement, and classroom behavior. Moreover, understanding of how the dual-task nature of incorporating physical activity with instructional activities may immediately impact upon learning remains in question. The present study examined the acute effects of physically active instruction on acuity of the approximate number system and on-task behavior in preschool-aged children. Using a randomized within-participants repeated-measures crossover design, children completed a computerized approximate number system acuity task before and after engaging in either 20-min of either physically active or conventional sedentary instruction during two separate, counterbalanced sessions. The conventional sedentary instruction consisted of activities previously demonstrated to strengthen approximate number representations at very light intensity corresponding to 21% heart rate reserve whereas the physically active instruction consisted of comparable activities integrated with physical activity at light-to-moderate intensity corresponding to ≥ 38% heart rate reserve. Findings revealed that following a single bout of physically active instruction at low-to-moderate intensity, preschool-aged children exhibited enhanced on-task behavior relative to following conventional sedentary instruction. Although no physical activity-related effects were observed for median reaction time or response accuracy (as indices of approximate number system acuity), preschoolers accrued 931.3 ± 8.2 more steps and an additional 9 minutes at or above light intensity activity during the physically-active

instruction. Accordingly, these findings provide evidence to suggest that physically active learning is an appealing approach that does not compromise instructional time, may reduce the need for redirecting off-task behavior, and ultimately enables children to accrue the many benefits associated with increased physical activity.

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KEY ABBREVIATIONS

ANS	Approximate Number System
BMI	Body Mass Index
HRR	Heart Rate Reserve
VO_{2max}	Maximum Aerobic Capacity
VO_2peak	Peak Oxygen Uptake

CHAPTER 1

Introduction

Physical activity recommendations have suggested that intervening during the school day may be an ideal means of increasing physical activity to address the growing trend of children adopting a predominately sedentary lifestyle (2018 Physical Activity Guidelines Advisory Committee, 2018). Such recommendations are based upon the observation that children spend between 25-32 hours weekly in out-of-home early childcare settings (Katzmarzyk et al., 2016), with a vast majority of their time spent in sedentary activities (Hnatiuk et al., 2014), and classroom lessons are the least active segment of a child's day (Bailey et al., 2012; Nettlefold et al., 2011). Thus, overall levels of childhood physical activity could be enhanced by integrating physical activity within educational contexts through either implementing physical activity breaks during the day or incorporating physical activity into instructional time. Although such approaches are effective for enhancing physical activity (Daly-Smith et al., 2018), and a growing body of evidence has demonstrated cognitive enhancements following physical activity engagement (2018 Physical Activity Guidelines Advisory Committee, 2018; Pontifex et al., 2019), a critical limitation is our understanding of how the dual-task nature of incorporating physical activity with instructional activities may have immediate impacts upon learning.

Compelling evidence from cross-sectional studies and a growing number of randomized controlled trials have demonstrated that physical activity engagement — and relatedly, superior aerobic fitness — is associated with higher academic achievement particularly in areas related to reading and mathematics (Brignac et al., 2011; Castelli et al., 2007; Davis & Cooper, 2011; Donnelly et al., 2016; Donnelly & Lambourne, 2011; Eveland-Sayers et al., 2009; Keating et al., 2019; Kwak et al., 2009; Logi Kristjánsson et al., 2010; London & Castrechini, 2011; Morita et al., 2016; Ruiz et al., 2010; Scudder et al., 2014; Suchert et al., 2016; Vasold et al., 2019). Thus, it should come as no surprise that providing greater opportunities to engage in physical activity during the school day has served to enhance scholastic outcomes. For instance, the provision of one additional hour of physical education during the school day in grades 2-6 was associated with superior grades across language, mathematics, and science compared to students provided with greater academic instruction time (Shephard et al., 1994). Likewise, modifying instructional programming to replace academic instruction with physical activity opportunities (e.g., swimming, gymnastics, outdoor activities, etc.) served to increase the number of students successfully passing qualifying exams, relative to a school following traditional instructional approaches (Hervet, 1952; see Shephard, 1997). Enhancements in scholastic performance resulting from physical activity have even been observed during the period immediately following physical activity. Specifically, in contrast to concerns regarding difficulty getting students to re-engage with academics following activity breaks, growing evidence suggests that children exhibit improved on-task behavior and greater capacity to solve arithmetic problems during a one-minute timed test following 10- and 20-min physically active classroom breaks relative to a 10-min sedentary break (Howie et al., 2014, 2015). Similarly, Pontifex and colleagues (2013) observed enhancements in reading and arithmetic performance on the Wide Range Achievement test following a 20-minute bout of activity. Such acute and chronic engagement in physical activity further appears to positively impact not only scholastic performance, but also improve a range of high level cognitive operations, including cognitive control and memory (Colcombe et al., 2006; Dickinson et al., 2016; Eggermont et al., 2009; Etnier et al., 2014; Hillman et al., 2009; Kamijo & Takeda, 2009, 2010; Pesce et al., 2009; Pirrie & Lodewyk, 2012; Pontifex et al., 2014, 2011, 2013; Voss et al., 2011). Accordingly, recommendations for implementing activity breaks during the school day to increase physical activity appear to be well-justified given that such interventions also appear to relate to immediate and long-term benefits for cognition and scholastic achievement.

However, physical activity integrated within instructional contexts could conceptually be implemented in ways that may offer negligible benefits or may even hinder learning. For instance, findings from Howie and colleagues (2015) indicated that physical activity periods lasting less than 10 minutes were not associated with enhancements in scholastic performance relative to sedentary periods. Such findings suggest that implementing short physical activity opportunities as placeholder or transition activities within instructional contexts (i.e., having students march while spelling words until an instructor can rotate around to the group of students) may do little for scholastic/cognitive performance. Similarly, although such activities eventually would amass over the course of the day, prior work by Pontifex and colleagues (2016) has observed that the accumulation of physical activity over the course of a 12-hour period (even within particular intensities) is unrelated to long-term memory and in some cases may even be detrimental to the consolidation of long-term memory during that period. Yet, promisingly, an emerging body of preliminary evidence has suggested that full integration of physical activity and instruction may provide long-term benefits to scholastic performance. Specifically, daily physically active learning interventions lasting from 4 weeks to 6 months have been associated with improved retention on assessments of literacy (Kirk et al., 2014), foreign language (Mavilidi et al., 2015), geography (Mavilidi et al., 2016), science (Mavilidi et al., 2017), and math (Mavilidi et al., 2018) in preschool-aged children relative to conventional sedentary approaches immediately and up to 4 to 6 weeks following cessation of the intervention. Further, small to moderate positive effects of physically active academic lessons on mathematics and language achievement scores have been observed immediately following cessation of two- (Mullender-Wijnsma et al., 2016) and three-year interventions (Donnelly et al., 2009), with gains in mathematics performance retained up to 7 months later (Mullender-Wijnsma et al., 2019).

However, given such findings, it is important to acknowledge that the positive effects of physically active instructional approaches observed across a longer period of time may reflect the enhancements of other mental processes — including attention, classroom behavior, and aspects of cognitive control — which enable greater scholastic performance even if the implementation of physically active instructional approaches is actually detrimental. That is, full integration of physical activity and instruction inherently results in a dual-task situation where the student is tasked with managing cognitive and energetic demands placed upon their system by both the physical activity and the instruction. In such an instance, the load theory of attention (Lavie, 2005; Lavie et al., 2004) can be extended to suggest that when the cognitive and energetic demands are high, the resource-limited nature of attention would result in focusing on only one aspect of the instructional activity (i.e., either the physical activity or the instructional content). If such activities are unable to be differentiated, then attention and performance would overall be reduced. Whereas if the cognitive and energetic demands are too low, the student may appear to be more distractible given the greater perceptual stimuli available in this context and the involuntary nature of perception. Thus, under higher- and lower- demands, physically active instructional approaches might negatively impact the students' learning. However, others have argued that cognitively engaging physical activity may actually result in greater cognitive enhancements following an activity than those observed when participating in non-cognitively engaging physical activities (Best, 2010; Pesce, 2012; Pesce et al., 2013). In this way, integrating physical activities with learning could result in impairments (through cognitive load) or improvements (through cognitive engagement). Thus, further research is necessary to better understand the immediate effects of physically active lessons on scholastic performance to ensure that such approaches are not detrimental to educational outcomes.

The present investigation, thus, sought to address this limitation in the literature by determining the extent to which incorporating physical activity within instructional periods impacts upon scholastic performance. Although the vast majority of literature in children in this area has focused upon preadolescent populations (Daly-Smith et al., 2018), changes induced by physically active lessons could be masked or prompted as a byproduct of other compensatory cognitive operations given the complexity of academic performance. Accordingly, focusing on a preschool-aged population offers an ideal opportunity to assess changes in scholastic performance free of potential confounds associated with high-level cognitive operations that are not yet fully operational (A. Diamond, 2002). Early mathematical competence is a particularly relevant construct in this population — serving as a superior predictor of overall academic achievement and success than literacy skills (Duncan, Dowsett, Claessens, Magnuson, Huston, Klebanov, Pagani, Feinstein, Engel, Brooks-Gunn, et al., 2007; Jordan et al., 2009) — and as an important determinant of career success, income, and psychological well-being in later life (Paglin & Rufolo, 1990; Parsons & Bynner, 2005; Rivera-Batiz, 1992).

One such aspect that forms the foundation for quantitative knowledge is the approximate number system, which has received substantial contemporary attention given its role underlying later mathematical achievement (Bonny & Lourenco, 2013; Mazzocco, Feigenson, & Halberda, 2011). The approximate number system is involved with the mental representation of numerosity (i.e., thinking about quantities; such as determining which container hold more grapes — regardless of grape size), and is functionally distinct from the symbolic representation of numbers (Feigenson et al., 2004). Recent investigations suggest that individual differences in the approximate number system may underlie respective differences in mathematical achievement (Mazzocco, Feigenson, & Halberda, 2011; Mazzocco et al., 2011). In a longitudinal investigation, the acuity of ninth grade students' approximate number system correlated with standardized mathematical achievement scores, extending all the way back to kindergarten even when controlling for intelligence, general cognitive abilities (i.e., working memory and visuospatial reasoning), and lexical access (Halberda et al., 2008). Interestingly, converging evidence indicates that the approximate number system is malleable such that even brief periods (i.e., 20 min) of training improve the acuity of this core number system (Hyde et al., 2014), with lasting impacts on subsequent math and arithmetic skills in school-aged children and adults (Honoré & Noël, 2016; Hyde et al., 2014; Park & Brannon, 2013).

Accordingly, utilizing a rigorous randomized within-participants repeated-measures crossover design with a sample of preschool-aged children, the present investigation assessed changes in the acuity of the approximate number system prior to and following a 20-min bout of either conventional sedentary instruction or physically active instruction, during two separate counterbalanced sessions. This approach enabled the characterization of the extent to which integrating physical activity with early numeracy instruction interferes with or enhances acquisition of approximate number representations. It was hypothesized that physically active learning would serve to improve precision of the approximate number system (i.e., shorter reaction time and increased response accuracy) relative to conventional sedentary learning.

Aims and Hypotheses

Aim 1. To determine the extent to which integrating physical activity with early numeracy instruction interferes with or enhances acquisition of approximate number representations (as indexed by median reaction time and response accuracy) in preschool-aged children.

Hypothesis 1. Shorter reaction time and increased response accuracy will be observed following physically active instruction relative to following conventional sedentary instruction, as an indication of physically active instruction-induced enhancements.

Aim 2. To determine the immediate effects of physically active instruction on time-on-task as indexed by frequency of experimenter redirection.

Hypothesis 2. Following a single bout of physically active instruction, children will exhibit enhanced time-on-task as indexed by requiring fewer experimenter redirections relative to following the conventional sedentary instruction.

CHAPTER 2

Review of Literature

Approximate Number System

Mathematical competence includes foundational skills such as verbal counting, simple arithmetic, and numerical comparison, which serve as better predictors of overall academic achievement and success than literacy skills (Duncan, Dowsett, Claessens, Magnuson, Huston, Klebanov, Pagani, Feinstein, Engel, & Brooks-Gunn, 2007; Jordan et al., 2009). One of the most important determinants of mathematical competence is our primitive number sense (i.e., the approximate number system). The approximate number system is the core internal number sense and forms the basis for more complex manipulations of symbolic mathematical competencies that follow formal instruction. This nonverbal ability to represent number and to estimate quantity is shared with non-human animals and is present as early as infancy (Feigenson et al., 2004). Moreover, acuity of the approximate number system predicts later math achievement and has been postulated as an underlying factor contributing to individual differences in mathematical competence (Dehaene, 2011; Feigenson et al., 2004; Libertus et al., 2011). Imprecision of this system is related to later math difficulties as well as the risk of developing math-related learning disabilities, such as dyscalculia (Feigenson et al., 2004; M. M. M. Mazzocco et al., 2011a). The approximate number system influences basic whole number competencies, that is, understanding the meaning of numbers and number relationships (Dehaene, 2011; Feigenson et al., 2004). This foundational number sense is important for learning advanced mathematics because math difficulties are cumulative such that difficulties with whole numbers, for example, will lead to difficulties with fractions and poor math achievement, thereby closing off a wide range of vocations in science, technology, engineering, and mathematics disciplines.

The approximate number system is regarded as the most basic system for representing and processing numerical magnitude. Accordingly, two fundamental features underlie this system: the numerical distance effect and the numerical ratio effect. The numerical distance effect suggests that the capacity to estimate numerical magnitude for symbolic (i.e., Arabic numerals) depends on the numerical distance between the numbers being compared (see Figure 1). For instance, when the numerical distance between pairs of numbers is small (e.g., 1 or 2), reaction time is slower and more errors are likely to be made relative to when pairs of numbers are separated by a large numerical distance (e.g., 8 or 9; Moyer & Landauer, 1967). This effect has been replicated in numerous studies since Moyer and Landauer's original report (Ansari et al., 2006; Ashkenazi et al., 2009; Dehaene et al., 1990; Holloway & Ansari, 2009).

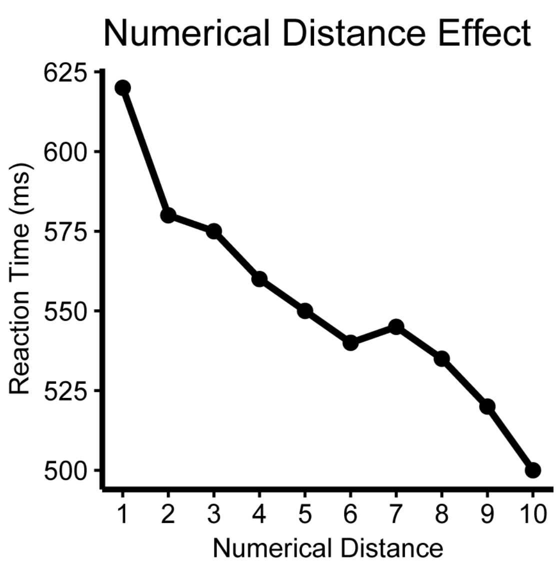

Figure 1. Numerical distance effect: Adapted from Ansari (2012).

Another robust effect is the numerical ratio effect (see Figure 2). The numerical ratio effect describes the slowing of reaction time when the numerical ratio between a pair of quantities (i.e., nonsymbolic stimuli) is large; the larger the ratio of the quantities, the more difficult the discrimination. For instance, when comparing quantities of 1 vs. 2 and 8 vs. 9, both pairs are separated by a numerical distance of 1, but the ratio (smaller/larger) for 1 vs. 2 is 0.5 whereas the ratio for 8 vs. 9 is 0.89. Accordingly, the reaction time is slower for comparing quantities of 8 vs. 9 relative to comparing 1 vs. 2. That is, the discriminability of two numbers is proportional to their numerical ratio.

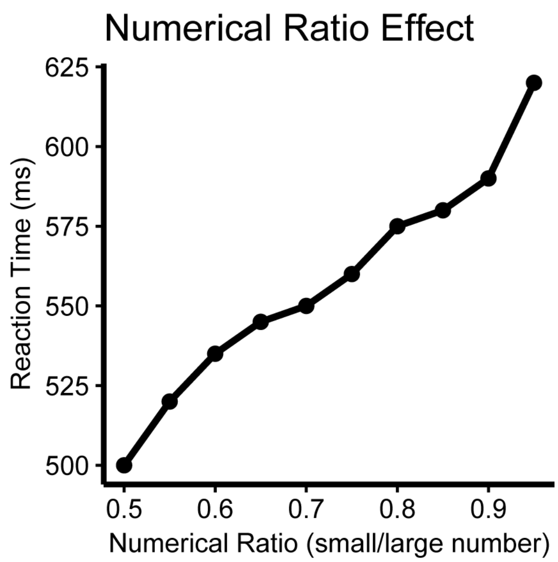

Figure 2. Numerical Ratio Effect: Adapted from Ansari (2012).

The numerical distance and numerical ratio effects are the standard tools for assessing the representation and processing of numerical magnitude—or acuity of the approximate number system. Namely, these effects are thought to reflect the approximate number system because the neural representations of numbers that are closer together are more similar than the neural representations of those numbers that are further apart. In other words, these effects represent an approximate number system of numerical magnitude. Conventionally, numerical representation and processing of numerical magnitude have been thought of as numbers represented along a continuum on a mental number line (however it is important to note that this is strictly a model representation and does not imply a linear representation of numerical magnitude in the brain). In this way, numbers closer together on the number line (i.e., separated by a smaller number size) have more overlap and are represented similarly, making them more difficult to discriminate between than numbers further apart on the number line (see Figure 3). For instance, if each number is represented by a Gaussian distribution, discriminating between 1 vs. 2 is more difficult than discriminating between 1 vs. 5 because the numerical representations have more overlap, thereby illustrating the numerical distance effect.

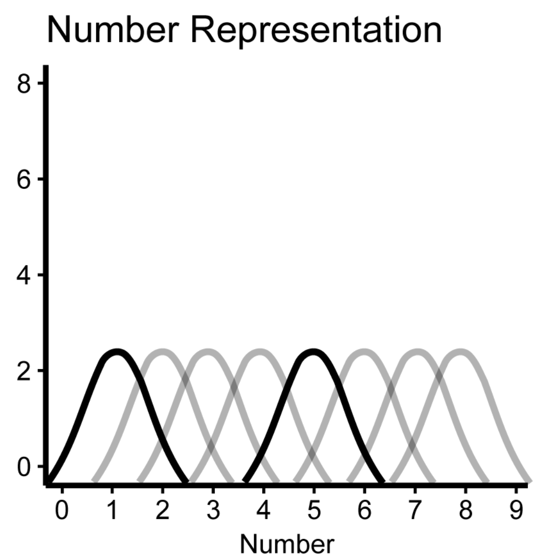

Figure 3. Number representation of the approximate number system: Adapted from Ansari (2012).

In other words, the approximate number system follows Weber's law: the discriminability between two numerosities varies as a function of the distance or ratio between them (Feigenson et al., 2004). Additionally, the precision of this core number sense increases with development such that successful discrimination of numerosity improves for smaller ratios with maturation, which allows for this system to become integrated with the symbolic number system used for mathematical computation and reasoning as individuals enter school (Feigenson et al., 2004).

Neuroimaging Evidence of the Approximate Number System

In addition to the behavioral evidence, recent progress has been made in characterizing neural circuits underlying numerical magnitude processing. Evidence from neuroimaging studies suggests that regions of the intraparietal sulcus are critical for numerical magnitude processing (Ansari & Dhital, 2006), and these language-independent areas are related to visuospatial abilities (Dehaene et al., 1999). Additionally, evidence demonstrates that children rely more heavily on prefrontal brain regions—typically associated with inhibitory control—during early mathematics learning (Houdé, Rossi, Lubin, & Joliot, 2010). Only later do children exhibit the involvement of specialized mathematical processing areas, such as the intraparietal sulcus (Houdé et al., 2010). Interestingly, activation of the intraparietal sulcus has also been related to acuity of the approximate number system (Ansari, 2008). Convergent evidence supports the association of intraparietal sulcus activation with numerical distance. That is, greater intraparietal sulcus activation is observed for number pairs separated by a small distance relative to number pairs separated by a large distance (Ansari, 2008; Dehaene et al., 2003; Nieder & Dehaene, 2009). Moreover, neuroelectric indices of numerical estimation are influenced by numerical distance and numerical size between nonsymbolic displays, with stimulus identification taking longer for pairs separated by a large distance and for nonsymbolic arrays that are greater in size; however, much further research is warranted to understand neuroelectric indices of the approximate number system (Dehaene, 1996; Heine et al., 2011).

Evidence from non-human animal studies sheds light on the neuronal coding of numerical magnitude. That is, single neuron recordings in monkeys actively discriminating numerosity reveal that numerosity-selective neurons are tuned to the number of items in a visual display such that maximal neuronal activity is observed when the neuron's preferred quantity is viewed, and a progressive drop off occurs as the quantity moves away from that preferred number (Nieder et al., 2002). For instance, a neuron that prefers four dots also responds to the presentation of three and five dots, but slightly less than to four dots and even less when presented with two and seven dots. In other words, the further the numerical distance between the neuron's preferred numerosity and the nonsymbolic dot display presented, the lower the neuronal firing rate. Taken together, the evidence suggests that numerical magnitude is encoded and processed at the single neuron level in the brain and exhibits the numerical size and numerical distance effects associated with the approximate number system.

Approximate Number System across Development

Studies have also demonstrated that this primitive number system is present in infants. For instance, 6-month old infants exhibit a sense of numerosity as evidenced by mean gaze time to large numerosity displays following habituation (Xu & Spelke, 2000; Xu et al., 2005). These findings demonstrate that infants have the capacity to discriminate between nonsymbolic dot arrays differing in numerical size, suggesting that the representation of numerical magnitude develops spontaneously and exists prior to the development of verbal counting or formal arithmetic skills. Furthermore, Lipton and Spelke (2003) demonstrated the early development of approximate number system precision using an auditory numerical comparison task in infants. Their findings demonstrated that infants as young as 6-months old discriminated 16 from 8 sounds, but these same infants could not discriminate between 8 and 12 sounds. However, at 9-months old, these infants were able to discriminate between 8 and 12 sounds but not between 8 and 10 sounds on the same task. Taken together, the evidence suggests the existence of an approximate number system for numerical magnitude processing—as early as infancy—prior to formal schooling and independent of language competencies. Accordingly, education builds upon this primitive system to allow for higher-level mathematical skills and symbolic representations.

Formal schooling builds upon early numeracy skills, such as verbal counting, which rely upon the acuity of the approximate number system. Extant evidence suggests that children ages 3-4 years old recognize numerical equivalence—the ability to match the number 4 to a nonsymbolic array of 4 dots—without mastering verbal counting (Mix, 1999a, 1999b; Mix et al., 1996). Moreover, verbal counting success is linked to the acuity of the approximate number system (Mix, 1999b) such that the comparison of different quantities may lead to improvements in linguistic counting ability (Mix, 1999a). Some findings have suggested behavioral performance on numerical matching tasks (i.e., matching auditory numerical stimuli to visual numerical stimuli) is slightly above chance in 3-year olds whereas 4-year olds perform above chance, suggesting performance on such tasks relies upon development (Mix et al., 1996). Therefore, these visual-auditory numerical matching tasks may be related to mastery of the linguistic counting system. Such findings relate to performance on nonsymbolic magnitude comparison tasks because the ability to discriminate between numerical magnitudes independent of visual properties of the task (i.e., overall size) is influenced by the ability to use cardinality and mastery of the verbal counting system (Brannon & Van de Walle, 2001; Rousselle et al., 2004). Thus, performance on nonsymbolic magnitude comparison tasks may also be modulated by development and understanding of early numeracy concepts such as ordinality, cardinality, and linguistic counting. Children who do not understand such numeracy concepts may rely heavily on perceptual features of the stimuli (i.e., size and area) to discriminate numerosities.

The reliance upon perceptual features of the stimuli weakens with older age. One possible explanation is the rapid development of inhibitory control during ages 3-5 years old, which helps children ignore distracting task-irrelevant information (such as incongruency between numerosity and size of stimuli).

In contrast, some evidence has found that there is no relationship between nonsymbolic magnitude comparison and number or counting knowledge in 3-5-year-old children (Soltész et al., 2010), which is consistent with other studies in school-aged children (Holloway & Ansari, 2009; Landerl & Kölle, 2009; Rousselle & Noël, 2007). Such evidence suggests that nonsymbolic numerical skills and symbolic/counting knowledge develop in isolation from 4-8 years old. Before the age of 4 years old, evidence does not exclude that there may be a relationship between non-symbolic magnitude comparison and counting knowledge (Brannon & Van de Walle, 2001; Rousselle et al., 2004). Indeed, 4-year olds have exhibited a congruency effect such that they rely upon the perceptual properties of stimuli and perform slightly above chance on more difficult numerical ratios (i.e., 5 vs. 7 instead of 5 vs. 15; Soltész, Szűcs, & Szűcs, 2010). Taken together, the evidence suggests that the acquisition of symbolic numerical representations relies upon acuity of the approximate number system, and this system may form the foundation for linguistic counting ability.

Assessing the Approximate Number System

One paradigm that is used to assess the acuity of the approximate number system is nonsymbolic numerical comparison tasks (Ansari, 2008; Dehaene & Akhavein, 1995; Halberda et al., 2008). In these tasks, participants compare the relative magnitude of two numerical stimuli that can be either symbolic (e.g., Arabic numerals) or nonsymbolic (e.g., dot or square arrays). However, the approximate number system is thought to be directly measured using nonsymbolic numerical comparison since nonsymbolic stimuli are language-independent and symbolic numerals require additional processing that is mapped onto nonsymbolic representations (Price et al., 2012). This distinction is important for examining number sense in this age group since language skills may be so varied and rely upon growth in literacy skills, such a letter knowledge (K. E. Diamond et al., 2008). This paradigm is simplistic in that it has been used with a variety of nonsymbolic stimuli (e.g., dots, squares, crayons; Ansari & Dhital, 2006; Halberda et al., 2008; Mazzocco, Feigenson, & Halberda, 2011b) and participant populations (e.g., infants, preschoolers, school-age children, adolescents, adults; Halberda & Feigenson, 2008; Halberda et al., 2008; Mazzocco et al., 2011b; Xu & Spelke, 2000). However, this paradigm requires that the visual properties of the two nonsymbolic stimuli being compared are not confounded (Gebuis & Reynvoet, 2011). That is, many visual properties of the stimuli need to be controlled (Inglis & Gilmore, 2014; Price et al., 2012). For instance, some variables (e.g., the total area covered by the nonsymbolic dot arrays and the density of the dot arrays) remain equal while other variables (e.g., diameter of each dot and total surface area) vary randomly for half the trials, and these properties are reversed on the other half of the trials (Gebuis & Reynvoet, 2011). For instance, for half the trials the larger numerosity is larger in surface area whereas for the other half of the trials, the larger numerosity is smaller in surface area. Additionally, this task requires the manipulation of numerical size and ratio effects by equally distributing nonsymbolic arrays across small (e.g., distances of 1, 2, and 3) and large numerical distances (e.g., distances of 5, 6, and 7; Ansari & Dhital, 2006). By controlling these properties, participants are forced to rely on more than one single visual property of the stimuli (e.g., dot size) to approximate numerical magnitude. To this end, individuals completing these tasks will switch between different visual properties to discriminate the numerosities isolating engagement of the approximate number system.

Numerical comparison tasks elicit a key metric of the approximate number system: the numerical distance effect (Moyer & Landauer, 1967), exhibiting a monotonic increase in reaction time and error rates as the numerical distance between nonsymbolic numerosities decrease. Accordingly, individuals exhibit faster reaction times and more accurate responses when comparing the numerical magnitudes of 2 vs. 9 relative to comparing 8 vs. 9. Additionally, this task elicits the numerical ratio effect, with a monotonic increase in reaction time and errors as the ratio between the two quantities being compared increases. These two effects are highly correlated and are thought to reflect the noise within internal representations of numbers (Dehaene & Akhavein, 1995).

Different conditions of nonsymbolic numerical comparison tasks have been used (Price et al., 2012) such that presentation of the numerosities being compared can occur sequentially (e.g., the dot arrays to be compared to one another are presented one at a time), simultaneously (e.g., the dot arrays to be compared appear on the screen side-by-side at the same time), or intermixed (e.g., the dot arrays to be compared are presented mixed with one another; see Figure 4). Each of these presentations differs in the additional cognitive processing demands, such as increased working memory demands in the sequential condition and visual resolution of overlapping comparators in the intermixed condition (Price et al., 2012). The paired presentation condition places the least demand on extraneous cognitive processes and produces the strongest numerical ratio effects relative to the other conditions since the two numerosities are spatially separate—alleviating working memory demands—thereby isolating the effects on the acuity of the approximate number system (Price et al., 2012). Taken together, the extant evidence suggests that to create nonsymbolic stimuli for numerical comparison tasks, visual properties should be varied so that participants do not rely on a sole visual cue from trial to trial and the condition for presentation should be considered (Smets et al., 2015). Recent research suggests use of the simultaneous presentation with numbers outside the subitizing range to isolate assessment of the approximate number system (Inglis & Gilmore, 2014).

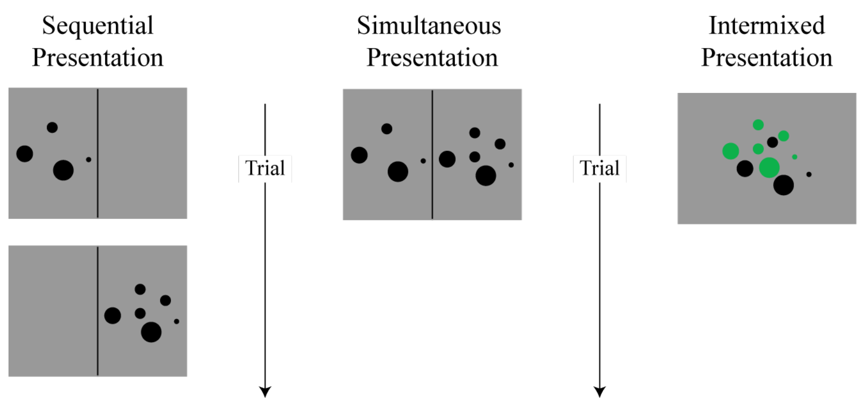

Figure 4. Different conditions of nonsymbolic numerical comparison tasks.

Sequential presentation (Figure 4 left) presents each dot array to be compared one after the other. Simultaneous presentation (Figure 4 middle) presents the dot arrays side by side at the same time. Intermixed presentation (Figure 4 right) presents the dot arrays differing in color overlapping on the same frame. Simultaneous and intermixed presentations place larger demands for inhibitory control whereas the sequential presentation places larger demands on working memory.

The approximate number system has traditionally been measured through numerical comparison paradigms (Ansari, 2008; Dehaene & Akhavein, 1995; Halberda et al., 2008). The reaction time numerical ratio effect demonstrates significant validity ($r = .52$, $p = .001$) and high reliability, $r = .78$, $p = .001$ (Price et al., 2012). Moreover, significant validity ($r = .39$, $p < .05$) and reliability ($r = .47$, $p = .005$) for examining ratio effects from behavioral performance from paired presentation of nonsymbolic comparison tasks has been demonstrated (Price et al., 2012). However, due to high variability in response performance in young children, the reliability and validity of such effects remains in question (Libertus et al., 2011). With young children, response accuracy is regarded as a more reliable index of the precision of the approximate number system (Inglis & Gilmore, 2014; Wang et al., 2016).

Development of the Approximate Number System

During the course of human development, the approximate number system becomes more precise. Developmental changes occur in basic numerical magnitude processing, with numerical size and distance having a greater influence on younger children's acuity of nonsymbolic numerical processing relative to older children (Halberda & Feigenson, 2008; Huntley-Fenner & Cannon, 2000). That is, precision of the approximate number system increases with age and years of education. Conversely, the effects of numerical size and numerical ratio diminish with age and years of education (see Figure 5).

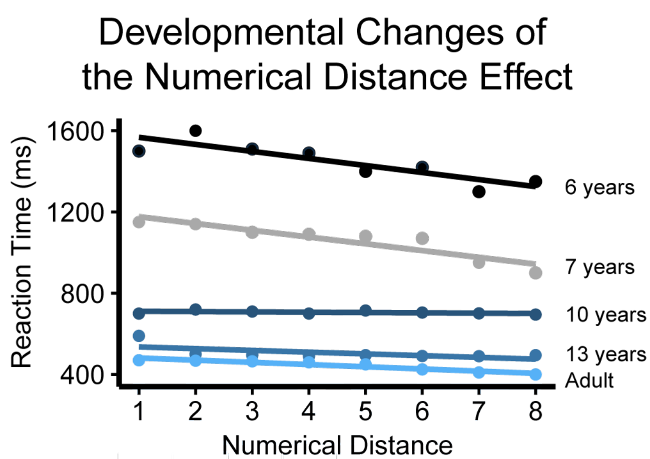

Figure 5. Developmental changes in numerical magnitude processing. Adapted from (Skuler & Mierkiewicz, 1977).

Developmental changes in the numerical distance effect are thought to reflect changes in numerical magnitude representation and processing. Namely, approximate representations of numerical magnitude become less overlapping over developmental time, thereby allowing for faster access and enhanced ability to discriminate between numerical magnitudes that are closer together (Ansari, 2012). In other words, if numbers are represented along a mental number line, development may sharpen the representational distribution of the curves, leading to less overlap in numerical magnitudes that are in close proximity to one another along the number line.

Developmental Changes in Numerical Magnitude Representation

Additionally, evidence from numerical estimation tasks that require children to verbally estimate the magnitude of rapidly presented dot arrays without counting demonstrates that variability in the estimation of non-symbolic arrays decreases with age (Huntley-Fenner, 2001). Another plausible explanation for the developmental changes associated with numerical magnitude representation and processing is a shift from a logarithmic internal numerical representation to a linear representation (Siegler & Booth, 2004). That is, a logarithmic representation conceives of numerical magnitude by amplifying the distance between numerical magnitudes in the middle and upper ends of the range so that the psychological distance between estimations of 5 and 10 is larger than the estimations for the distance between 65 and 70 (Siegler & Booth, 2004). However, a developmental shift from logarithmic internal representation to linear representation would indicate that the psychological distance for the estimation of the distance between 5 and 10 is the same as the estimation for the distance between 65 and 70. Although the developmental shift from logarithmic to linear internal numerical magnitude representation is gradual, there is a period in which children are characterized by a mixture of both logarithmic and linear internal representations. For instance, Siegler and Booth (2004) found that between the ages of 6 to 8 years old, children demonstrate patterns of numerical estimation that progress from logarithmic (i.e., age 6; kindergarten) to a mixture of logarithmic and linear (i.e., age 7; grade one) to a strictly linear pattern (i.e., age 8; grade two). In other words, as children increase with age and acquire symbolic mathematical competence, their internal representation of number transitions from logarithmic to linear.

Additional neuroimaging evidence demonstrates functional neuroanatomical differences in adults relative to children during numerical magnitude processing (Ansari et al., 2005). That is, tasks eliciting numerical distance effects during symbolic number processing in adults activate parietal areas, including the intraparietal sulcus and precuneus (Ansari et al., 2005). However, children exhibit activation primarily in frontal regions in addition to parietal regions, suggesting they rely more heavily on attentional control networks. Accordingly, this evidence suggests that a critical shift from frontal to parietal areas occurs from age 9 to 20 years, supporting the notion that numerical magnitude processing becomes more automatic with age thereby requiring less involvement of frontal regions related to attention, working memory, and cognitive control operations (Ansari et al., 2005).

One explanation for children's involvement of frontal regions is that they require aspects of cognitive control to discriminate between numerical magnitude representations that have greater overlap than adults (Ansari, 2012). In other words, children primarily involve frontal regions for discriminating numerosity represented in parietal regions. This developmental shift also coincides with the rapid development of inhibitory aspects of cognitive control during the preschool years (Davidson et al., 2006; Jones et al., 2003). Although less relevant for acute physical activity study paradigms, evidence from the physical activity cognition literature supports larger volumes in areas of the brain underlying cognitive control and memory performance in children higher in aerobic fitness (Chaddock et al., 2010, 2011; Chaddock-Heyman et al., 2014). Given that extant evidence supports enhancements in aspects of cognitive control and attention following 20-mins of moderately intense aerobic physical activity (McGowan et al., 2019; Pontifex et al., 2019), it follows that acute physical activity may enhance young children's approximate number sense by enhancing their attentional and inhibitory control, which they engage for tasks involving nonsymbolic magnitude comparison. However, recent evidence has demonstrated that the approximate number system is malleable and susceptible to training (DeWind & Brannon, 2012; Hyde et al., 2014; Park & Brannon, 2013; Wang et al., 2016). Although the exact sources of failures in the approximate number system remain to be fully understood, evidence suggests that training of this system—through activities that engage nonsymbolic number understanding—improves acuity of this core system of number sense, which translates to improvements in math and arithmetic abilities in both children and adults (Honoré & Noël, 2016; Hyde et al., 2014; Park & Brannon, 2013).

Extant evidence supports the relationship between acuity of the approximate number system and later math achievement. Although the mechanisms underlying individual differences in the internal number representation remain in question, some evidence suggests that deficits in visuospatial working memory, visuospatial short-term memory, and inhibitory control may explain decrements to the approximate number system (Ashkenazi et al., 2013; Sowinski et al., 2015; Szucs et al., 2013). However, other studies have found no such working memory deficits (Landerl et al., 2004). The nature of the task and the amount of attentional control required may influence the inconsistent results, so children with numerical magnitude processing difficulties may perform at similar levels as more advanced children on tasks assessing visuospatial working memory and visuospatial short-term memory, but they may perform poorly on complex mathematical tasks requiring high attentional control (Passolunghi & Mammarella, 2012).

Therefore, it is plausible that impaired working memory and attentional control may lead to difficulty maintaining and manipulating numerical representations during nonsymbolic magnitude comparison tasks. As such, acute physical activity may serve to transiently improve aspects of cognitive control and attentional control, thereby influencing acuity of the approximate number system during early childhood when children rely heavily on inhibition and attention to perform such tasks. Although there is no clear conclusion or explanation for imprecision of the approximate number system, converging evidence demonstrates that children from low-income families consistently underperform on nonsymbolic magnitude tasks and are at greater risk of developing later math difficulties (Dyson et al., 2013; Fuhs & McNeil, 2013). Namely, children from these households may have less exposure to early numeracy concepts, such as counting, and may have decrements in working memory and inhibitory control—manifesting in decreased acuity of the approximate number system. Indeed, early exposure to quantitative knowledge in the home environment—such as number talk—and increased physical activity participation may serve to influence acuity of the approximate number system for these individuals.

Training of the Approximate Number System

A growing body of evidence has investigated the influence of training the primitive number sense in school-aged children and adults (Hyde et al., 2014; Park & Brannon, 2013, 2014). Findings have revealed that engagement of this system during daily practice of nonsymbolic magnitude tasks over weeks as well as during a brief 20-min session improves performance on subsequent symbolic arithmetic tasks (Hyde et al., 2014; Park & Brannon, 2013, 2014). These studies have primarily trained the approximate number system through tablet-based nonsymbolic arithmetic tasks (Park & Brannon, 2013, 2014) that closely resemble the same nonsymbolic magnitude assessments used to index acuity of this system. Therefore, it remains unclear whether children simply demonstrate improvements due to practicing the task or as a function of more fine-tuned approximate number representations following the tablet game. Practically speaking, numerical training may be a viable means for helping children with minimal background in math, as is the case with many low-income families, allowing them to catch up to their peers as early as possible. However, an investigation examining the influence of nonsymbolic numerical training on math abilities in preschoolers observed a global effect on performance on the Test of Early Mathematics Achievement, so it remains a question to what precise domains of early quantitative knowledge are influenced by this type of training (Park et al., 2016). Nonetheless, such findings suggest that targeting the approximate number system in preschoolers could be effective for improving school readiness, even for short durations (e.g., 20 min).

Although the training programs have varied across studies, both nonsymbolic and symbolic numerical training conditions have resulted in greater gains in magnitude processing in preschoolers relative to reading control conditions, with symbolic training leading to larger improvements in arithmetic (Honoré & Noël, 2016). To date, most studies have used longitudinal designs, with only one study using brief nonsymbolic number training in first-grade students (Hyde et al., 2014). Findings revealed even a singular session engaging the approximate number system resulted in improvements in subsequent symbolic mathematics, and these improvements were specific to mathematics because no differences were observed on a comparable sentence completion task (Hyde et al., 2014). However, to what degree different methods for training this system result in changes to acuity of the approximate number system in preschoolers remains a question. Moreover, a critical limitation to translating these findings into early learning contexts is that these studies have exclusively used computerized games (almost identical to the approximate number system task) that allow children to practice nonsymbolic array comparison. Therefore, it remains a question whether children simply gain additional practice with the task rather than fine-tune their internal representation of numerical magnitude (i.e., acuity of the approximate number system). Moreover, such interventions are not viable solutions for early mathematics learning, especially when implementing tablet-based learning at the school- or even classroom-level is impractical and expensive. Instead, examining other methods for training the approximate number system, such as integrating acute physical activity with activities aimed at enhancing number sense (and reflective of the preschool context), may be a more viable means to optimize mathematical learning in the preschool classroom while also helping to shape physically active behaviors for life.

Acute Physical Activity and Cognition in Children

A growing body of evidence supports the positive effects of single bouts of aerobic physical activity on cognitive function in school-age children (see Pontifex et al., 2019). However, a vast majority of the acute physical activity-cognition literature has examined the changes in cognitive control following single bouts of aerobic physical activity at moderate intensity in college-aged young adults (Pontifex et al., 2019), with only a few studies examining these effects in preschool-aged children (Mierau et al., 2014; Palmer et al., 2013).

Of the extant literature examining the effects of acute physical activity on cognition in school-aged children, performance on standardized achievement tests has been used as the outcome. While such an approach may be lucrative to administrators, this approach fails to evaluate specific academic domains of cognition. To this end, the extant literature has done little to contribute to understanding what academic contexts acute physical activity may optimize learning. For example, the degree to which acute physical activity influences specific aspects of mathematics, such as ordinality, counting, or magnitude estimation remains to be elucidated. Therefore, to better understand the effects of short bouts of aerobic physical activity on academic-specific aspects of cognition, further research is warranted—especially during the early years—with particular attention to evaluating important foundational concepts, such as numeracy. A shift in research approaches is needed to transition from measuring changes in aspects of cognition postulated to relate to academic achievement (i.e., inhibitory control) to examine to what degree specific domains of academic cognition are affected by single bouts of aerobic physical activity (i.e., magnitude comparison, numeracy). These findings will inform activity-promoting interventions that can be integrated into the classroom to optimize learning across the curriculum. For instance, does acute physical activity integrated with number sense activities help children improve their understanding of magnitude or is this skill better learned using traditional methods that purport the benefits of using manipulatives? Understanding which aspects of mathematical cognition are optimized by acute physical activity approaches will help inform evidence-based learning interventions that will help all children reach their full academic potential. Moreover, gaining a better understanding of these effects during the early years is critical for hastening of intervention and improving school readiness, especially before children at risk of developing math difficulties fall too far behind their peers.

Nonetheless, one study has examined the influence of single bouts of aerobic physical activity on sustained attention and response inhibition in a small sample (i.e., 17) of preschoolers ages 4-5 years using the Picture Deletion Task for Preschoolers (PDTP; Palmer et al., 2013).

Findings included fewer errors following the physical activity relative to the sedentary condition and enhanced time-on-task. In addition to behavioral performance, a growing body of evidence has examined neuroelectric indices of attention to gain greater insight into these covert cognitive processes. For instance, Mierau (2014) observed improved alpha power in a sample of 10 boys ages 5-6 years—thought to reflect a state of physical relaxation following acute physical activity. However, the limitations of these studies (i.e., small sample size and only using boys) constrain the conclusions that can be drawn regarding the more general influence of acute aerobic physical activity on cognitive function in preschoolers.

Despite evidence supporting the facilitative effects of single bouts of physical activity on cognition in school-aged children (Pontifex et al., 2019), the degree to which these same effects are evident during the early years remains a question. Moreover, these single bouts of aerobic physical activity may be more easily integrated into play-based learning contexts—characteristic of the preschool classroom—providing a means to explore and to participate in activities that engage diverse mathematical concepts (Ginsburg et al., 2008; Parks & Blom, 2014). Although less studied in the acute physical activity-cognition literature, a related body of knowledge has examined how physically active academic learning influences academic achievement.

Physically-Active Lessons and Academic Achievement

Related to the body of literature examining the influence of acute physical activity on cognition is a growing body of evidence investigating the effects of physically active academic lessons. Academic lessons incorporating physical activity have resulted in improved early literacy skills in preschoolers (Kirk et al., 2014) as well as immediate and delayed retention on tests of foreign language, geography, and science (Mavilidi et al., 2015, 2016, 2017). However, to what degree physically active learning improves mathematics remains a question. Following a two-year active academic lesson intervention, improved math and spelling scores were observed in second- and third-grade students (Marijke J. Mullender-Wijnsma et al., 2016). However, no such positive effects have been observed for executive functions following a two-year intervention using physically active academic lessons (Greeff et al., 2016). However, improved math scores have been observed in children ages 9-12 years following physical activity breaks integrated into the classroom (Howie et al., 2015). Small to moderate positive effects of physically active academic lessons on achievement scores have been observed in school-aged children, even when teachers did not implement these lessons daily (Bartholomew & Jowers, 2011). Similar effect sizes have been observed for timed math tests and language test scores, equating to about four months more learning gains following a two-year physically active academic lesson intervention (Mullender-Wijnsma, Hartman, de Greeff, et al., 2016).

A recent study used a cluster randomized controlled trial in childcare centers to examine the effects of a 4-week program that integrated movements with symbolic number understanding across four conditions: task-relevant physical activity, task nonrelevant physical activity, observing physical activity, or conventional sedentary teaching (Mavilidi et al., 2018). The task-relevant physical activity consisted of hopping, jumping, or stepping on numbers as children counted on a line of numbers ranging 1 to 20 whereas the task nonrelevant physical activity involved children running laps around the room, the observing physical activity involved children observing the task-relevant physical activity condition and counting alongside their peers, and the conventional sedentary teaching involved sitting and counting while looking at the number line. However, it is important to note that a critical limitation to the comparison of the sedentary teaching relative to the task-relevant physical activity condition is that these two conditions vary greatly in the degree to which children were able to engage with the number line, which may have limited the degree to which the sedentary teaching condition engaged numerical understanding. A composite score was created from children's performance on math outcomes included counting from 1 to 20, number line estimation, block counting, symbolic numerical comparison, and numerical identification was measured at pretest, following the four-week intervention, and six weeks following cessation of the intervention. Findings demonstrated greater average activity counts per minute as measured using accelerometry between physically-active and sedentary conditions; however, there were no differences in activity counts between the two physically active conditions. Moreover, the integrated physical activity condition resulted in higher scores at all three times points of testing (pretest, posttest, and delayed posttest) relative to the three other conditions. Specifically, the integrated physical activity condition performed better on the counting and numerical identification tasks, so this intervention appeared to target symbolic numeracy skills.

A critical limitation, however, is that these interventions used broad assessments of achievement, which may fail to capture the precise mathematical domains influenced by such approaches. Despite increasing physical activity levels (Norris, Shelton, Dunsmuir, Duke-Williams, & Stamatakis, 2015), studies have only observed improved standardized test scores (Donnelly et al., 2009; Reed et al., 2010), with no such improvements observed for reading comprehension (Helgeson, 2013) or knowledge of math content (Graham et al., 2014). Moreover, findings cannot be generalized beyond a narrow age range, which includes children ages 9 to 12 years old. Collectively, findings from the physically active learning literature are promising for indicating a positive influence of physically active lessons on improved academic performance. However, we cannot conclude that such approaches will lead to benefits in all academic realms of cognition. Instead, further research is warranted to identify which aspects of cognition related to math and reading are selectively improved by integrating physical activity with academic lessons. Scarce evidence elucidates the relationship between physical activity and specific aspects underlying academic subject performance such as mathematics (i.e., counting), especially during the preschool years. Moreover, such interventions may help to close the achievement gap for children with little opportunities for physical activity outside the classroom.

Classroom Activity Breaks and Cognition

Another related area of research is that of classroom physical activity breaks (i.e., activity breaks). This approach integrates short bursts of moderately-intense physical activity throughout the day as a means to address physical inactivity because schools have reduced allotted time to physical education. At present, this body of literature supports the improvement in classroom behavior following short physical activity breaks at moderate intensity. However, variability in experimental designs, outcome measures, and intervention characteristics limit the conclusions that can be drawn on the effects of such classroom breaks on cognition (Daly-Smith et al., 2018). Overall, classroom activity breaks generally use whole-body aerobic activities (i.e., running, jogging on the spot) and durations range from 4 to 20 minutes (Daly-Smith et al., 2018). Despite increasing the duration of classroom activity breaks, Howie et al. (2014, 2015) observed no differences in the amount of moderate-to-vigorous physical activity accrued (~ 4.3 mins), suggesting children may fatigue. Overall, physical activity breaks appear to support enhanced time-on-task following physical activity breaks relative to control conditions (Grieco et al., 2009, 2016; Mahar et al., 2006; M. J. Mullender-Wijnsma et al., 2016).

Of the domains of cognition that have been assessed in some classroom activity break studies, there emerges no single construct that dominates the literature. Following physical activity breaks, immediate visual recall is improved and delayed recall has been observed to be greater 3 days postintervention (Daly-Smith et al., 2018). However, other studies have observed no such positive effects on cognition, with 4 studies observing improved cognitive function and 13 studies observing no change in cognitive function following classroom activity breaks. However, comparison of these findings with the vast body of acute physical activity-cognition literature is limited by the diverse domains of cognition assessed (e.g., working memory, inhibition, executive function, attention, word recall). Low-to-medium quality study designs dominate the physical activity break and classroom break literature, with diversity in mode, duration, and intensity of intervention as well as assessing different aspects of cognition with tasks that conflate multiple cognitive domains. Future investigations should use higher quality experimental designs and take into consideration task impurity to improve confidence in the observed outcomes (Daly-Smith et al., 2018).

Load Theory of Selective Attention and Cognitively-Engaging Physical Activity

When considered within the framework of the load theory of attention (Lavie, 2005; Lavie et al., 2004), physical activity integrated with instructional contexts could conceptually be implemented in ways that may hinder learning. In such an instance, the load theory of attention suggests that when cognitive and energetic demands are high, the resource-limited nature of attention would result in focusing on only one aspect of the instructional activity (i.e., either the physical activity or the instructional content). Consequently, attention and performance would overall be reduced because of the interference placed on differentiating between the two activities. Whereas if the cognitive and energetic demands are low, the student may appear more distractible given the greater perceptual stimuli available in this context and the involuntary nature of perception. Thus, under higher- and lower- demands, physically active instructional approaches may negatively impact students' learning. However, others have argued that cognitively-engaging physical activity may actually result in greater cognitive enhancements following an activity than those observed when participating in non-cognitively engaging physical activities (Best, 2010; Pesce, 2012; Pesce et al., 2013).

Recent interest in the cognitively-engaging physical activity hypothesis has suggested that the cognitive demands during acute physical activity may influence the cognitive benefits observed (Best, 2010; Pesce, 2012; Pesce et al., 2013). That is, cognitively-engaging acute physical activity (e.g., playing games or learning subject material) may result in greater gains in cognition relative to traditional forms of acute aerobic physical activity (e.g., treadmill walking or cycling). These gains may be attributed to the engagement of neural networks underlying cognitive control in cognitively-engaging physical activity, which traditional acute physical activity modalities fail to do since the task demands are automated (Best, 2010; Schmidt et al., 2015). For schools, gaining a better understanding of how cognitively-engaging acute physical activity can be integrated during academic learning time is timely given recent educational directives asserting the primacy of achievement on standardized achievement tests. While the potential for acute physical activity breaks integrated into classroom learning is attractive to educational practitioners, it is impractical to incorporate treadmills or cycle ergometers on a whole-class or even school-level basis. Therefore, a more practical solution may be understanding for what academic realms of cognition (e.g., numeracy) acute aerobic physical activity optimizes learning.

To date, evidence has supported the notion that cognitively-engaging acute physical activity results in greater gains in aspects of cognitive control relative to traditional acute physical activity and non-physical activity control conditions (Ellemberg & St-Louis-Deschênes, 2010; Ishihara et al., 2017; Pesce et al., 2013; Schmidt et al., 2015). While no single cognitively-engaging acute physical activity condition has emerged, the level of cognitive engagement has varied from video watching (Ellemberg & St-Louis-Deschênes, 2010) to gameplay (Ishihara et al., 2017; Pesce et al., 2013; Schmidt et al., 2015) to video game-based physical activity (Benzing et al., 2016). Regardless of methodological differences, results have shown that physical activity conditions that are more cognitively challenging are more efficacious for enhancing attention and aspects of cognitive control. Even though further research is warranted, these findings are promising for the application of such acute physical activity conditions to enhance academic learning. Not only does cognitively-engaging acute physical activity manifest in larger immediate cognitive gains than traditional acute physical activity, but such an approach may be a more viable and sustainable solution for integrating acute physical activity with academic learning in the classroom setting (Schmidt et al., 2015). Nonetheless, the degree to which such cognitively-engaging physical activity acutely impacts academic domains of cognition remains a question.

However, some evidence suggests that cognitive engagement integrated with physical activity may hinder children's cognitive control (Egger et al., 2018; Gallotta et al., 2015, 2012) or may result in no changes to aspects of cognitive control (Best, 2012; van den Berg et al., 2016). However, procedural differences (i.e., physical activity intensity and duration) and individual differences (i.e., age, sex, fitness level, academic achievement) across these studies may explain the inconsistent findings. In particular, the absence of positive effects of physical activity on cognitive control in these studies has been attributed to the light intensity of the physical exertion as recent reviews have supported moderate intensity as optimal for enhancing cognition (Chang et al., 2012; Pontifex et al., 2019). Nonetheless, scarce evidence exists to elucidate the impact of cognitively-engaging physical activity on cognition in young children as a majority of these studies have been conducted in school-age children.

Measuring Physical Activity Intensity During the Intervention

A recent review of physically-active lessons and classroom breaks highlighted objective measurement of physical activity intensity as a consideration for future research study design given that a number of studies to date have failed to objectively measure physical activity during the intervention (Daly-Smith et al., 2018). Although there are a number of different techniques that have been used to assess physical activity in a variety of populations, this discussion will be limited to heart rate monitors and pedometers as they were used in the present study. As an objective physiological indicator of the effect of physical activity, heart rate monitors provide a valid measure of heart rate in children, which has been shown to be linearly related to VO_{2max} and energy expenditure during physical activity (Durant et al., 1993; Welk et al., 2000). Although heart rate monitoring is highly correlated with direct observation ($r = .79$), it is weakly correlated under control conditions ($r = .49$). However, this type of error does not affect estimates of total activity (e.g., minutes spent above a certain threshold) and is considered a strong predictor for energy expenditure in children (Eston et al., 1998; Livingstone et al., 1992). For mathematical tasks, heart rate also reliably captures task-related physiological response, which is of interest for elucidating individuals susceptible to math anxiety, for instance (Goodie et al., 2000). Such a physiological response during cognitive task performance cannot be captured by other physical activity measurement methods.

Pedometers, also used in the present study, provide an objective indicator of step count thereby indexing the volume of activity (Corder et al., 2007; Freedson & Miller, 2000). In terms of practicality, pedometers may offer the best solution for a low-cost objective monitoring tool.

In particular, pedometry is particularly useful for large population studies, such is the case with randomized-controlled trials in schools. However, pedometers fail to capture non-ambulatory activities (Corder et al., 2007; Freedson & Miller, 2000), which can be problematic for physical activity recording during seated or rest conditions. Pedometers were selected for use in the present study to serve as an easily interpreted step count to demonstrate to teachers how they could increase children's physical activity volume if integrating the physically-active numeracy conditions weekly in their classroom. Moreover, pedometers can be used as a motivational tool in intervention studies by giving a target goal to be performed during the intervention (Corder et al., 2007; Freedson & Miller, 2000).

Summary

To date, evidence supports the positive effects of acute aerobic physical activity on aspects of cognitive control in college-aged young adults (Pontifex et al., 2019). Moreover, acute aerobic physical activity has demonstrated improved academic achievement on broad standardized assessments in school-aged children. However, the extant literature has failed to capture the precise domains of subject-specific cognition influenced by acute physical activity as well as elucidate physical activity-induced changes in cognition during the early years. A more promising and sustainable solution may be integrating acute physical activity with academic learning (i.e., cognitively-engaging physical activity) to improve number sense in preschoolers (as indexed by the acuity of the approximate number system), which underlies all later more complex mathematical understanding. Moreover, recent evidence suggests that acute physical activity may selectively enhance cognition for children performing at the lowest levels (Drollette et al., 2014; Resaland et al., 2016) with cognitively-engaging physical activity showing greater gains than traditional acute aerobic physical activity (Benzing et al., 2016; Pesce et al., 2013;

Schmidt et al., 2015). Accordingly, given the supposition that preschool children are at the lowest level of numeracy, this population may be uniquely suited for accruing the benefits of cognitively-engaging acute physical activity to manifest in improvements in the precision of the approximate number system. To this end, integrating academic learning with acute physical activity may be a viable solution for promoting numeracy skills during the early years without compromising instructional time and allowing for children to accrue the many benefits associated with increased physical activity. Such findings will inform classroom-based activity-promoting interventions to optimize student learning and school readiness, which is particularly important for children from low-income families who are less exposed to math at home.

CHAPTER 3

Methodology

Participants

A final sample of 51 preschool-aged children (*M* = 4.7 ± 0.8 years, 25 females; 24% nonwhite) participated in this investigation at Michigan State University. An initial sample of 60 participants was recruited; however, nine preschool-aged children were excluded for noncompliance (i.e., not participating in any of the intervention activities and/or not performing the approximate number system task). See Figure 6A for a CONSORT flow diagram of enrollment. The present study was approved by the Institutional Review Board at Michigan State University. Parents/guardians of all participants provided written informed consent and participants provided verbal and written assent prior to participation in the study. All parents/guardians reported participants being free of neurological disorders or physical disabilities and indicated normal or corrected-to-normal vision. Demographic characteristics are provided in Table 1. Figure 6A is a CONSORT flow chart showing retention of participants through each testing period. Figure 6B shows a schematic diagram depicting within-participants counterbalanced cross-over study design.

Table 1. Participant demographics (mean ± SD).

Measure	All participants	Females	Males
N	51	25	26
Age (years)	4.7 ± 0.8	4.7 ± 0.9	4.6 ± 0.7
Nonwhite (%)	24	12	12
Weight-for-stature (percentile)	55.0 ± 29.2	50.1 ± 28.7	59.3 ± 29.5
At least one guardian with post-secondary education (%)	96%	92%	100%
Both guardians with post-secondary education (%)	59%	60%	58%

Note: Weight-for-Stature based on Child Growth Standards ages 2-5 years (World Health Organization, 2007).

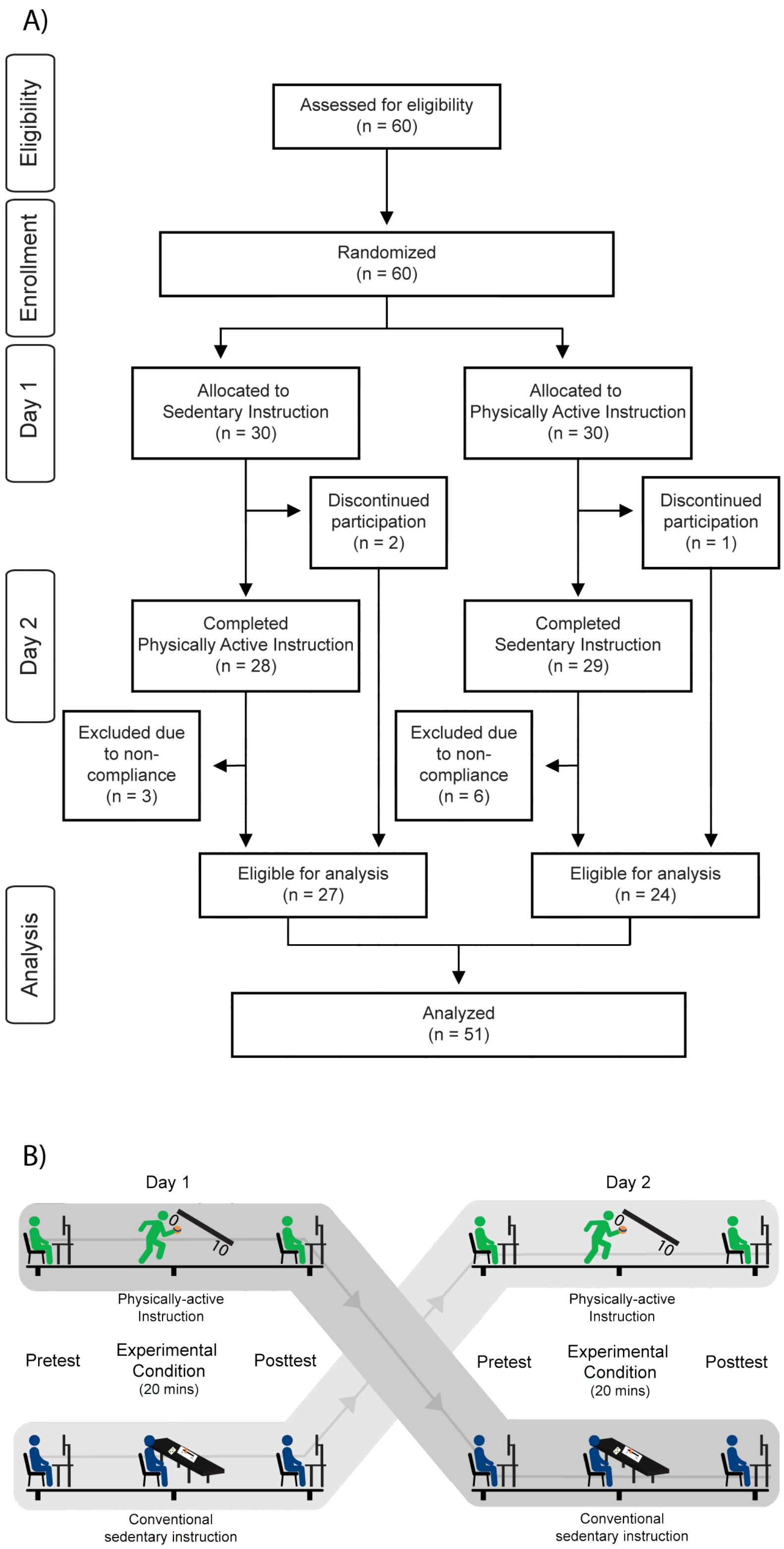

Figure 6. Illustration of study retention and experimental design.

Approximate Number System Acuity Task

Acuity of the approximate number system was assessed using a nonsymbolic magnitude comparison paradigm (Moyer & Landauer, 1967). Participants were instructed to respond as accurately as possible with a button press (6.4 cm wired response buttons Model: Buddy Button; AbleNet, Roseville, MN) to indicate which of two schools of fish contained a greater number of fish. The two schools of fish were presented simultaneously on a grey background with button-response mappings appearing below the arrays to alleviate working memory demands (Price et al., 2012), see Figure 7. The number of fish in each school ranged from 2 to 20. The magnitude of the difference between schools of fish ranged from 0.19 to 0.89 (smaller school / bigger school) and were equally distributed across three levels of difficulty: very easy difference ratios (≤ 0.30; i.e., 4 fish in one school vs 16 fish in the other school), easy difference ratios (0.33 to 0.5; i.e., 6 fish in one school vs 12 fish in the other school), and hard difference ratios (≥ 0.67; i.e., 10 fish in one school vs 11 fish in the other school). The side with the greater number of fish was counterbalanced across trials.

Consistent with previous investigations using this task in preschool-aged children (Libertus et al., 2013), the size of the fish were equally distributed across small (39 pixels), medium (60 pixels), and large (81 pixels) fish and the surface density of the fish were counterbalanced such that all sizes of fish occurred with equal probability within arrays of greater or less numbers. This approach ensured that children engaged the approximate number system rather than responded to other characteristics of the stimulus presentation (i.e., luminance, individual fish size). Further, to encourage children to use approximation rather than counting, stimuli were presented focally for a variable stimulus duration ranging from 1,250 to

3,000 ms with a fixed 1,000 ms post-response interval, consistent with previous task parameters used in this age group (Halberda & Feigenson, 2008).

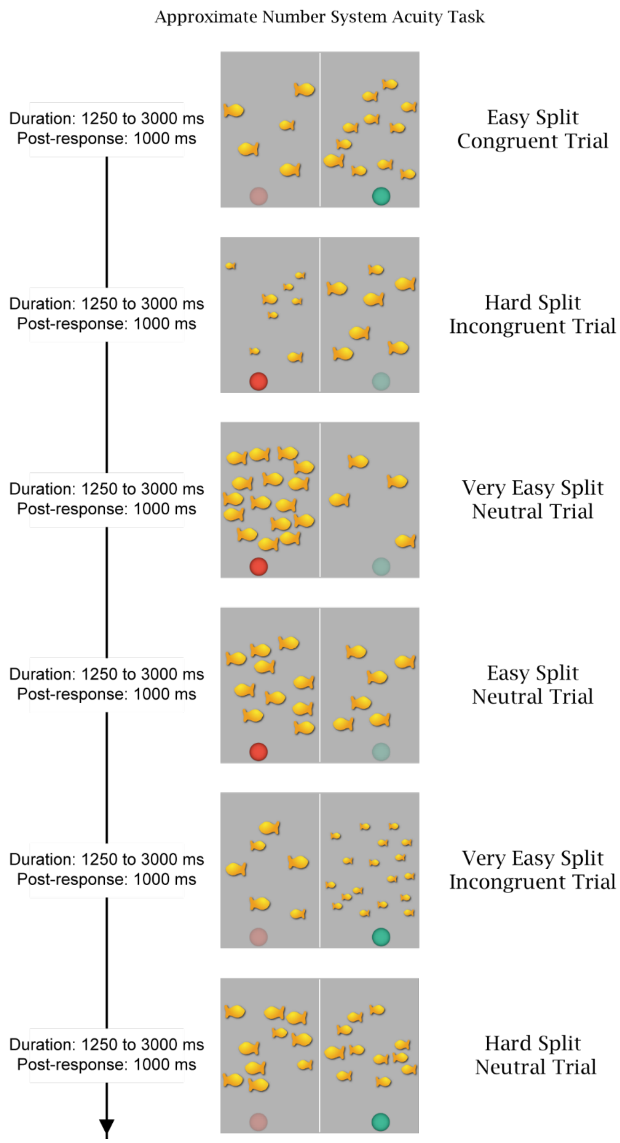

Figure 7. Illustration of the approximate number system task. For reference, the correct response to each stimulus is depicted.

At each measurement period, children completed 12 practice trials followed by 72 task trials (grouped into three blocks of 24 trials with a short break between each block). Stimuli were presented focally on a grey background on an Inspiron 5447 Dell Inc. laptop using Psychopy, 1.83.4 (Peirce, 2009). Reaction time was quantified using median speed of responding following the onset of the stimulus only for correct trials (Whelan, 2008; Wilkinson et al., 2006). Response accuracy was quantified as the proportion of correct responses relative to the number of trials administered (excluding practice trials). Finally, beyond behavioral performance metrics, on-task behavior was quantified by a trained observer separate from the experimenter administering the approximate number task. Observers were given a detailed definition of off-task behavior: the number of times participants required experimenter redirection during the execution of the task (i.e., pressing both buttons at the same time, diverting eye contact away from the laptop screen, talking to the experimenter). Both experimenter and observer were blind to the experimental condition at pretest.

Physical Activity Measurement

During the experimental conditions, children wore a heart rate monitor (Model: H7; Polar Electro, Kepele, Finland) to continuously record heart rate as an objective physiological index of the intensity of the physically active lesson (Durant et al., 1993; Welk et al., 2000). Additionally, children's physical activity was measured using a uni-axial spring-levered pedometer (Model: Yamax Digi-Walker SW-200; Yamasa Tokei Keiki Co Ltd., Japan) worn on the right hip to record number of steps. To maintain consistency with the acute physical activity cognition literature, the physically active instruction condition was intended to encourage participation at moderate-to-vigorous intensity (Pontifex et al., 2019).

To prepare heart rate data for analysis, a 20-point (10-second) box-car moving average was used to smooth the final time series data. Such an approach assumes that the average of adjacent points is a better measure of the signal than any of the individual points. Percent of heart rate reserve was calculated using the formula ($HR_{average}$ – Resting HR/Age-predicted HR_{max} – Resting

HR)*100 where $HR_{average}$ was the average across the smoothed time series data during each period (i.e., pretest, experimental condition, and posttest). Age-predicted HR_{max} was calculated using the equation 205.8 – (0.685*Age) from Robergs & Landwher (2002) and has been shown to closely predict HRmax in children ages 7-17 years old (Mahon et al., 2010). Resting heart rate was quantified as the lowest 1-minute period during non-task related or instructional periods.

Procedure

Using a randomized within-participants cross-over design (see Figure 6B), participants visited the laboratory on two separate days (mean days apart 6.9 ± 5.9; mean time of day difference 33.7 ± 156.0 min). During the first visit, following consent/assent, participants' parents/guardians completed the Physical Activity Readiness Questionnaire (Thomas et al., 1992). Children were then counterbalanced into two different session orders (Day 1: conventional sedentary instruction, Day 2: physically active instruction or Day 1: physically active instruction, Day 2: conventional sedentary instruction, see Figure 6B) to ensure any observed effects were unrelated to the specific order in which participants received the experimental conditions (Pontifex et al., 2019). Throughout the experimental conditions, the experimenter viewed a timer and transitioned to activities to maintain each activity for approximately 6 min. The 20 min experimental condition included transition time to maintain consistency with early learning classroom settings in which such transitions frequently occur. Assessment of the acuity of the approximate number system was performed on a laptop before and immediately following cessation of each 20 minute experimental condition (see Table 2).

Table 2. Mean (± SD) values for experimental session characteristics.

Measure	Physically active	Conventional Sedentary	*t*	*p*	d_s *[95% CI]*
Pretest assessment					
Heart rate (bpm)	105.6 ± 13.1	103.9 ± 12.4	0.7	0.5	0.1 [-0.3 to 0.5]
Heart rate reserve (%)	19.0 ± 12.8	18.2 ± 11.6	0.3	0.8	0.1 [-0.3 to 0.5]
Time preceding experimental condition (min)	7.2 ± 3	6.1 ± 8.3	0.9	0.39	0.3 [-0.1 to 0.6]
Experimenter redirection (n)	3.3 ± 3	3.2 ± 3.4	0.3	0.8	0.04 [-0.3 to 0.3]
Experimental condition					
Heart rate (bpm)	127.5 ± 10.8	106.8 ± 10.5	9.1	< 0.001*	1.9 [1.4 to 2.5]
Heart rate reserve (%)	37.9 ± 10.6	20.9 ± 10.6	7.6	< 0.001*	1.6 [1.1 to 2.1]
Percent of heart rate max	63.2 ± 5.3	53.1 ± 5.1	9.1	< 0.001	1.9 [1.4 to 2.1]
Steps (n)	987.4 ± 332.3	56.1 ± 64.3	19.1	< 0.001*	3.91 [3.2 to 4.6]
Session Duration (min)	20.1 ± 1.2	20.2 ± 1.7	0.1	0.95	0.01 [-0.4 to 0.4]
Post-test assessment					
Heart rate (bpm)	109.8 ± 10.7	105 ± 12.7	2.0	0.05	0.4 [0 to 0.8]
Heart rate reserve (%)	22.8 ± 11.0	18.6 ± 14.5	1.6	0.1	0.3 [-0.1 to 0.7]
Time following experimental condition (min)	2.7 ± 1.7	3 ± 2.1	0.8	0.4	0.2 [-0.23 to 0.56]
Experimenter redirection (n)	2.5 ± 2.8	5 ± 3.6	5.3	< 0.001*	0.7 [0.4 to 1.0]

Note. The t-tests reflect the differences between physically active and seated control at each time point for each measure of interest. * denotes the *t*-test was significant at $p < 0.05$. Age-predicted HR_{max} was calculated using the equation 205.8 – (0.685*Age) from Robergs & Landwher (2002).

Conventional sedentary instruction. To maximize the external validity of the present investigation, the control condition replicated activities previously utilized within the literature to strengthen the acquisition of number sense in preschoolers (Link et al., 2013; Park & Brannon, 2014; Wang et al., 2016). During the conventional sedentary instruction condition, participants were asked to first perform a number line estimation activity using flashcards depicting quantities of animals ranging from 1 to 10 and moving a plastic figurine along a line to the point corresponding to the quantity on the flashcard (the line only had landmarks for 0 and 10). Next, participants viewed flashcards depicting symbolic and nonsymbolic quantities ranging from 1 to 10 and were asked to decide if the quantity was less than or greater than 5. Finally, participants completed the Counting Bears (Seyline, Frisco, TX) activity which showed participants flashcards depicting symbolic and nonsymbolic quantities and asked participants to count the number of bears corresponding to the number on the flashcard. Over the course of the 20 minute conventional sedentary instruction condition (M = 20.2 ± 1.7 min), participants accumulated 4.5 minutes [95% CI: 2.0 to 6.9] of activity at or above a light intensity (at or above 30% of heart rate reserve); mean heart rate = 107.0 [95% CI: 103.9 to 110.1], heart rate reserve = 20.9 Percent [95% CI: 17.7 to 24.1].

Physically active instruction. During physically active instruction, participants engaged in similar activities to those utilized in conventional sedentary instruction with the incorporation of physically active components. For the number line estimation activity, participants ran to the position corresponding to the quantity on the flashcard on a 10 m long number line (the line only had landmarks for 0 and 10). For the less-than greater than 5 activity, children responded by throwing a foam ball or bean bag into a hula hoop target laid on the ground corresponding to less than or greater than 5. For the counting activity, participants progressed through a series of six hula hoops which each contained a nonsymbolic quantity. In each hula hoop, participants had to bounce and two-hand catch a ball the number of times corresponding to the magnitude prompt. Following bouncing the ball in each hula hoop, children were asked to bounce pass the ball with the experimenter while ordering the quantities from least to greatest. Over the course of the 20 minute physically active condition (M = 20.1 ± 1.2 min), participants accumulated 13.5 minutes

[95% CI: 11.6 to 15.3] of activity at or above a light intensity (at or above 30% of heart rate reserve); mean heart rate = 127.8 bpm [95% CI: 124.6 to 131.0], heart rate reserve = 37.9 Percent [95% CI: 34.7 to 41.2].

Power Analysis

Given a sample size of 51 participants and a beta of 0.20 (i.e., 80% power), the present research design theoretically has sufficient sensitivity to detect repeated measures, within-between interactions as computed using G*Power 3.1.2.9 exceeding $d = 0.40$. For post-hoc comparisons, assuming a two-sided alpha, the design has sufficient sensitivity to detect *t*-test differences exceeding $d = 0.40$ for dependent means and $d = 0.80$ for independent means. A recent study has observed training effects of approximate mental representations on nonsymbolic magnitude comparison in first graders with an effect size of $d = 0.63$ (Obersteiner et al., 2013). Thus, the present design provides sufficient sensitivity to address the aims of the present investigation.

Statistical Analysis

Data were analyzed using multi-level modeling as this approach is robust to unbalanced data (i.e., missing observations), accounts for a number of sources of variability (Goldstein, 2011; Volpert-Esmond et al., 2018), and is preferable for repeated-measures designs (Quené & Van den Bergh, 2004). This approach maximized experimental power by allowing participants with incomplete data due to discontinued participation to be retained within analysis (three participants did not complete both experimental sessions, see Figure 1a). Analyses were conducted with $\alpha = .05$ and Benjamini-Hochberg false discovery rate control = 0.05 for post-hoc breakdowns.

To determine the extent to which the acuity of the approximate number system was differentially impacted by physically active instructional methods relative to conventional sedentary instruction, analysis of performance on the approximate number system task was conducted separately for median reaction time and response accuracy using a 2 (Mode: conventional sedentary instruction, physically active instruction) × 2 (Time: pretest, posttest) × 3 (Ratio: very easy, easy, hard) univariate multi-level model including a random intercept for Participant, Participant × Mode, Participant × Time, and Participant × Ratio interactions. Frequency of experimenter redirection during the approximate number system task as an index of on-task behavior was analyzed using a 2 (Mode: conventional sedentary instruction, physically active instruction) × 2 (Time: pretest, posttest) univariate multi-level model including a random intercept for Participant, Participant × Mode, and Participant × Time interactions. All analyses were performed in R using the lme4 (Bates, Mächler, Bolker, & Walker, 2015), lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017), and emmeans (Lenth, Love, & Herve, 2017) packages in R version 3.6 (R Core Team, 2013) with Kenward-Roger degrees of freedom approximations. For each inferential finding, Cohen's f^2 and d with 95% confidence intervals were computed as standardized measures of effect size, using appropriate variance corrections for repeated-measures comparisons (d_{rm}; Lakens, 2013).

CHAPTER 4

Results

Task Performance

Reaction time. Analysis of median reaction time revealed no main effects or interactions with Mode, F's (2,49) ≤ 0.6, p's ≥ 0.434, f^2's ≤ 0.02 [95% CI: 0 to 0.08], see Figure 8, suggesting that there was no difference between the physically active instructional method relative to conventional sedentary instruction. However, a main effect of Time was observed for median reaction time indicating that learning occurred as participants responded faster at posttest (859.6 ± 235.1 ms) relative to pretest (912.3 ± 238.3 ms), $F(1, 50) = 15.1$, $p < 0.001$, $d_{rm} = 0.29$ [95% CI: 0.13 to 0.44] (see Table 3). Further, a main effect of Ratio was observed, $F(2, 99) = 23.9$, $p < 0.001$, $f^2 = 1.15$ [95% CI: 0.60 to 2.27], with median reaction time slowing with increased task difficulty: very easy ratios exhibited the fastest reaction time (834.1 ± 203.9 ms), followed by easy (897.5 ± 228.9 ms), then hard (926.3 ± 268.4 ms) ratios, t's (99) ≥ 2.1, p's ≤ 0.037, d_{rm}'s ≥ 0.17 [95% CI: 0.01 to 0.75], see Figure 9.

Response accuracy. Analysis of response accuracy revealed no main effects or interactions with Mode, F's (2,49) ≤ 1.0, p's ≥ 0.38, f^2's < 0.01 [95% CI: 0 to 0.03], see Figure 8, suggesting that there was no difference between the physically active instructional method relative to conventional sedentary instruction. However, a main effect of Ratio was observed, $F(2, 100) = 499.9$, $p < 0.001$, $f^2 = 1.97$ [95% CI: 1.15 to 3.82], see Figure 9, which was superseded by a Time × Ratio interaction, $F(2, 338) = 3.5$, $p = 0.03$, $f^2 = 0.01$ [95% CI: 0.00 to 0.07]. Post-hoc decomposition of this interaction revealed that response accuracy was maintained from pretest to posttest for very easy and easy ratios, t's(155) = 0.3, p's ≥ 0.3, d_{rm}'s = 0.03 [95% CI: -0.16 to 0.28]. Whereas a slight reduction in response accuracy for the hard ratio — that did not remain significant following false discovery rate control (Benjamini-Hochberg critical alpha = 0.022) — was observed at posttest (45.4 ± 11.6 %) relative to pretest (48.2 ± 11.3 %), $t(155) = 2.1$, $p = 0.037$, $d_{rm} = 0.35$ [95% CI: 0.02 to 0.68], see Table 3.

Experimenter redirection. Analysis of experimenter redirection as an index of on-task behavior revealed a main effect of Mode, $F(1, 48) = 10.2$, $p = 0.003$, $f^2 = 0.30$ [95% CI: 0.06 to 0.69], which was superseded by a Mode × Time interaction, $F(1, 49) = 20.7$, $p < 0.001$, $f^2 = 0.61$ [95% CI: 0.24 to 1.29], see Figure 8. Post-hoc decomposition of this interaction revealed that participants required similar frequency of experimenter redirection at pretest for both the physically active (3.3 ± 3.0) and conventional sedentary instruction (3.2 ± 3.4) conditions, $t(91) = 0.3$, $p = 0.8$, $d_{rm} = 0.04$ [95% CI: -0.26 to 0.34]. Following the conventional sedentary instruction condition, participants required greater frequency of redirection (5.0 ± 3.6) relative to pretest, $t(97) = 4.3$, $p < 0.001$, $d_{rm} = 0.50$ [95% CI: 0.26 to 0.74]. Following the physically active instruction condition, participants required fewer experimenter redirections (2.5 ± 2.8) relative to pretest, $t(97) = 2.0$, $p = 0.043$, $d_{rm} = 0.29$ [95% CI: 0.01 to 0.58], see Table 3. Though this difference did not remain significant following false discovery rate control (Benjamini-Hochberg critical alpha = 0.040), fewer experimenter redirections were required following the physically active instruction condition relative to following the conventional sedentary instruction condition, $t(91) = 5.3$, $p < 0.001$, $d_{rm} = 0.70$ [95% CI: 0.42 to 0.97].

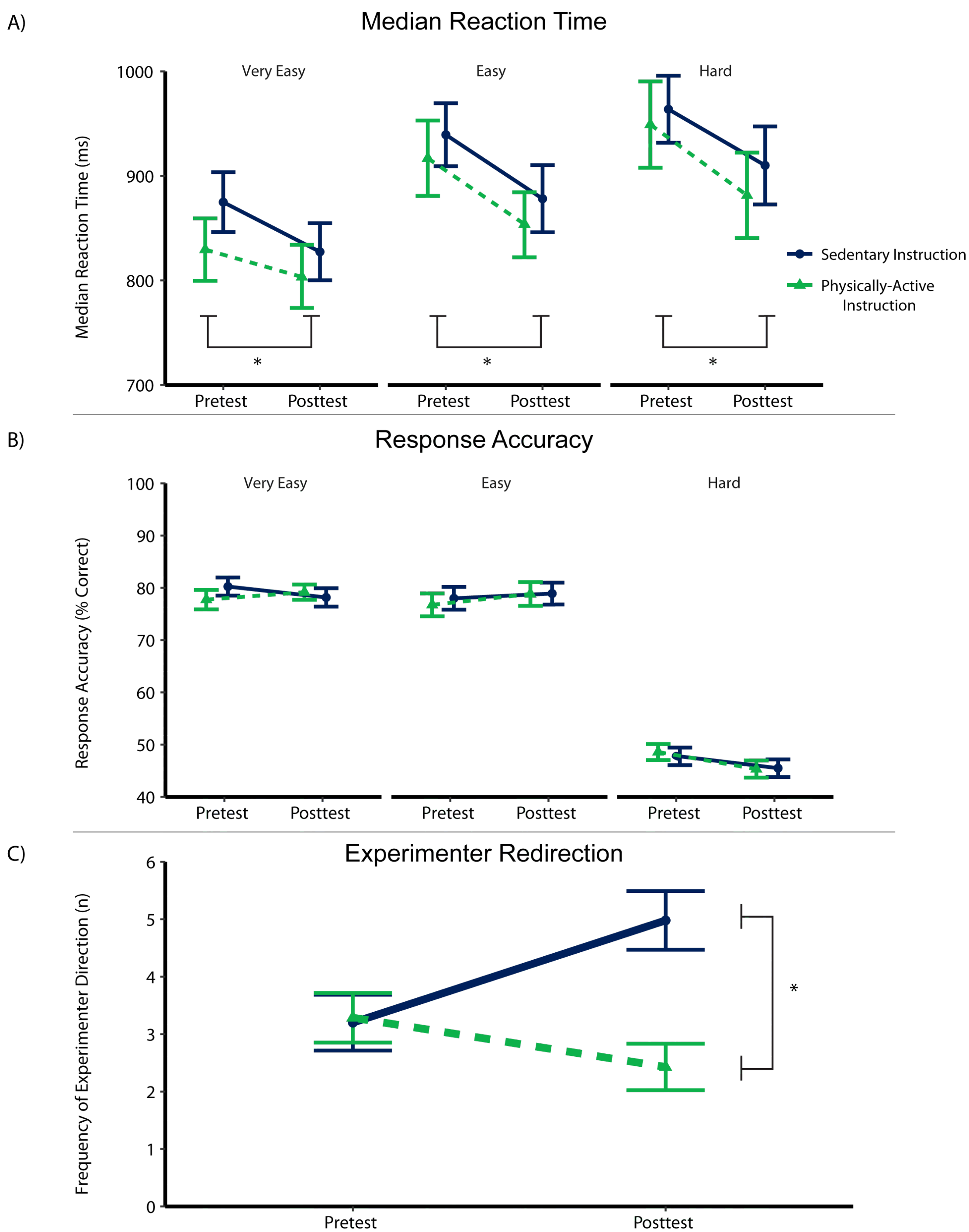

Figure 8. Illustration of the effects of mode and time for median reaction time (top), response accuracy (middle), and experimenter redirection (bottom).

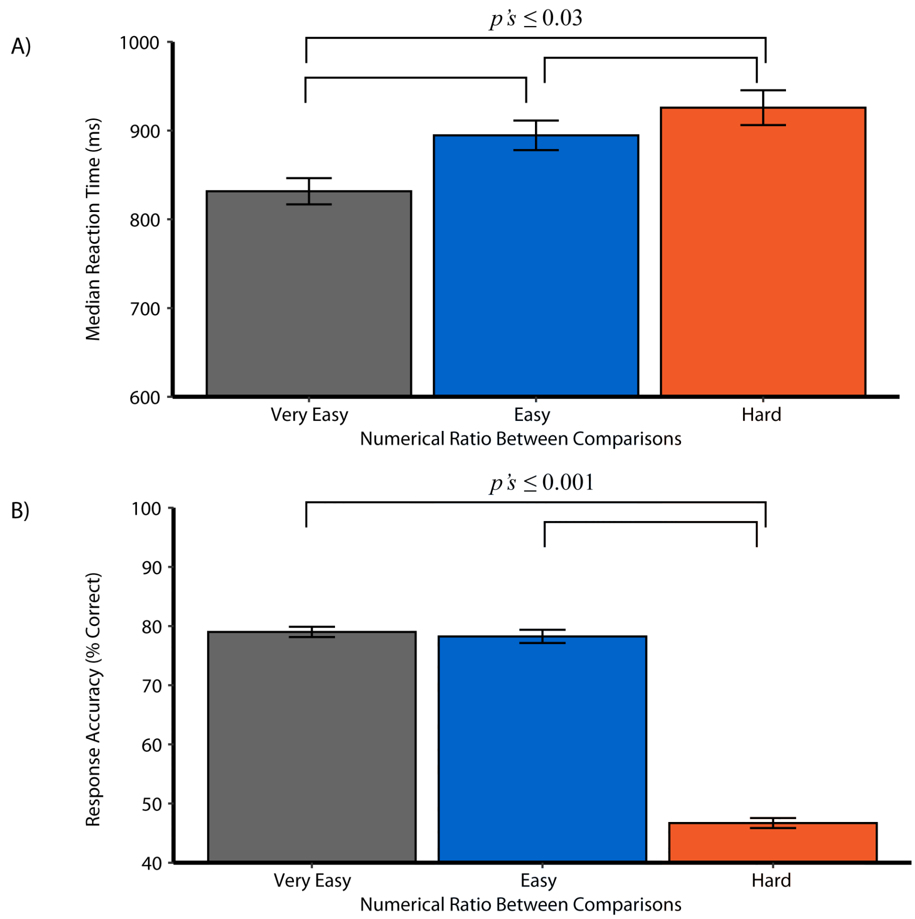

Figure 9. Mean (± SE) task performance by numerical ratio for (A) median reaction time and (B) response accuracy.

Steps. Analysis of steps recorded on a pedometer revealed children accrued a greater number of steps during the physically-active condition (987.4 ± 332.3) relative to the conventional sedentary condition (56.1 ± 64.3), $t(92) = 19.1$, $p < 0.001$, $d_s = 3.91$ [95% CI: 3.19 to 4.55], see Table 2; see Figure 10.

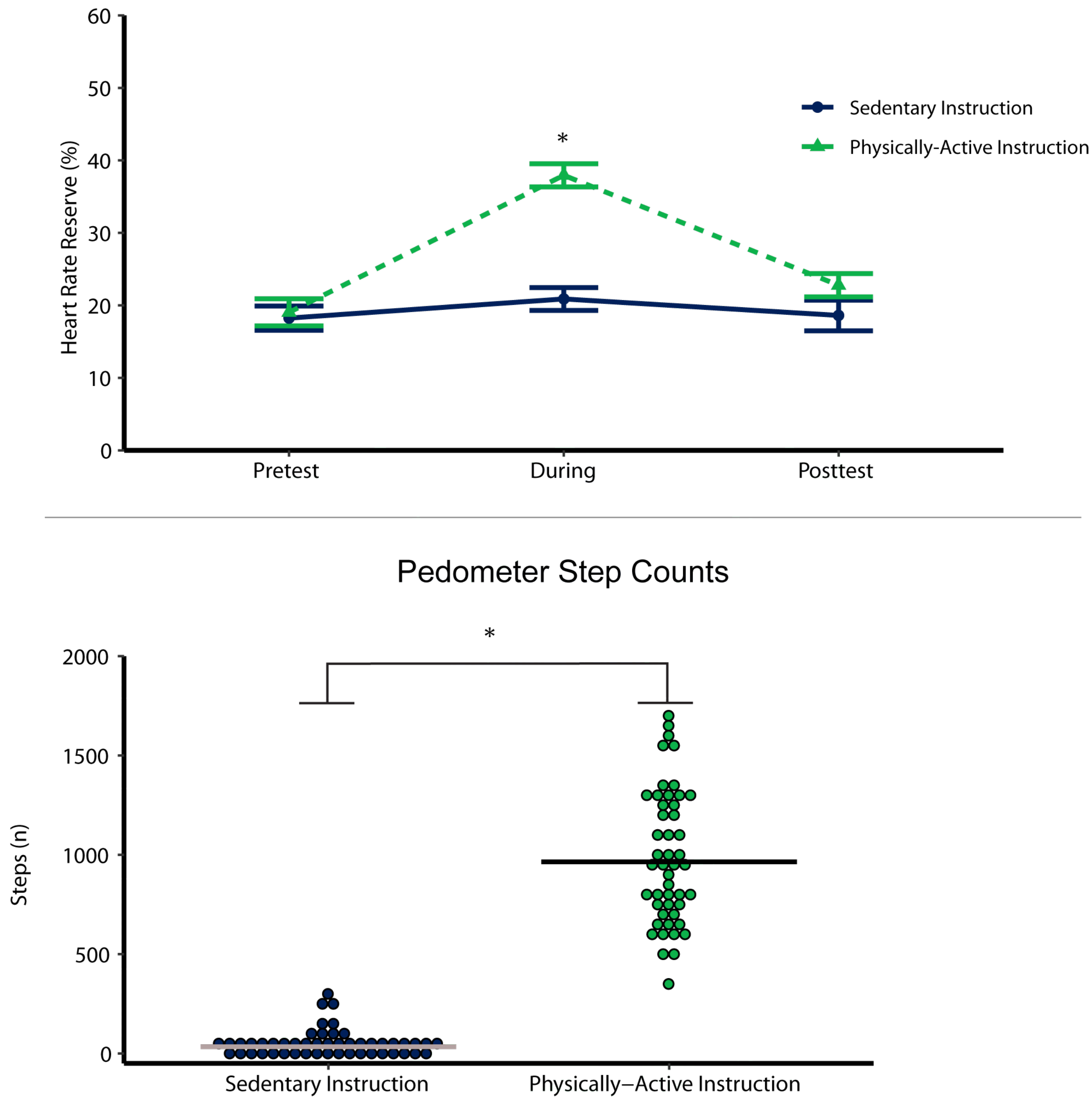

Figure 10. Illustration of heart rate intensity (top) and pedometer step counts (bottom) during each experimental condition. Mean step counts for each condition is noted with a grey line for the seated control condition and black line for the physically active condition.

Table 3. Statistical summary of post-hoc comparisons at pre-test relative to post-test for each mode.

	Pre-test	**Post-test**	***t***	***p***	**d_{rm} [95% CI]**
Median reaction time (ms)					
Physically active	899.1 ± 258.1	848.8 ± 239.1	3.0	0.003*	0.2 [0.1 to 0.6]
Missing cases (#)	1	2			
Seated Control	925.5 ± 216.7	870.4 ± 231.1	3.4	0.001*	0.4 [0.14 to 0.6]
Missing cases (#)	1	1			
Response accuracy (% correct)					
Physically active	67.7 ± 18.9	67.6 ± 20.4	0.1	0.9	0.01 [-0.2 to 0.2]
Missing cases (#)	1	2			
Seated Control	68.8 ± 19.9	67.6 ±20.4	1.0	0.3	0.1 [-0.1 to 0.4]
Missing cases (#)	1	1			
Experimenter redirection (n)					
Physically active	3.3 ± 3.0	2.5 ± 2.8	2.0	0.043†	0.3 [0.01 to 0.6]
Missing cases (#)	2	2			
Seated Control	3.2 ± 3.4	5.0 ± 3.6	4.3	0.001*	0.5 [0.01 to 0.6]
Missing cases (#)	1	1			

Note. The *t*-tests reflect the differences between pre-test and post-test for each experimental condition for each dependent variable. * denotes the *t*-test was significant at $p < 0.05$. † denotes difference did not remain significant following false discovery rate control (Benjamini-Hochberg critical alpha = 0.04).

CHAPTER 5

Discussion

Promoting physical activity in children, particularly in preschool-aged children, has the potential to reduce chronic disease burden and disorders caused by physical inactivity over the course of the lifespan. Given that classroom lessons are the least active segment of a child's day (Bailey et al., 2012; Nettlefold et al., 2011) and children attend some form of out-of-home childcare or school from 3-5 years of age until 16-18 years of age (McFarland et al., 2017), these contexts are promising points of contact for promoting health behaviors in this population. Given that classroom lessons are teacher-directed and non-discretionary, they provide an ideal opportunity for increasing physical activity levels. Therefore, understanding the extent to which physical activity integrated with academic instruction (i.e., numeracy) presents a dual-task environment that either impedes or enhances children's learning is paramount to wide-implementation of such physically-active learning approaches to promote health behaviors that optimize brain health and cognition.

The aim of the present investigation was to provide new insight into the extent to which integrating physical activity with early numeracy instruction interferes with or enhances acquisition of approximate number representations in preschool-aged children. Findings revealed that following a single bout of physically active learning at a relatively low intensity, preschool-aged children exhibited enhanced time-on-task as indexed by requiring fewer experimenter redirections relative to following the sedentary control learning condition, confirming the second *a priori* hypothesis. Contrary to the first *a priori* hypothesis, however, no physical activity-related effects were observed for median reaction time or response accuracy (as indices of approximate number system acuity). This lack of findings was obtained in spite of the observation that median reaction time and response accuracy modulated over time and performance was proportional to task difficulty, underscoring the validity of our modified approximate number system acuity task.

Task Manipulation Check

Previous research has shown changes in task performance specific to reaction time and response accuracy when comparing trials with smaller numerical ratios relative to trials with larger numerical ratios (i.e., quantities being compared are closer together such as 6 vs. 7 instead of farther apart such as 6 vs. 15; Ansari, 2012; Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Libertus et al., 2011; Mazzocco, Feigenson, & Halberda, 2011). Specifically, slower reaction time and poorer response accuracy were observed for smaller numerical ratios (i.e., hard ratios) relative to the larger ratios (i.e., easy and massive ratios), indicating an increase in processing time during trials requiring greater acuity of the approximate number system (ANS). This effect is thought to reflect the influence of the ANS on the mapping of symbolic representations to nonsymbolic representations of number (Gilmore et al., 2011). That is, greater ANS acuity would lead to stronger mapping of symbolic representations (i.e., numerals and ordinality) onto nonsymbolic representations (i.e., magnitude arrays). Although these findings are standard for this task, they demonstrate effective implementation of the task. Moreover, although no single paradigm has emerged for this task, these findings suggest that paired presentation of the magnitudes being compared is effective in alleviating working memory demands and isolating effects on acuity of the approximate number system in preschool-aged children. Using a novel stimulus that maintains children's interest (i.e., goldfish) and incorporating a novel task condition (i.e., massive difference ratios) do not influence the replication of robust ratio effects in nonsymbolic magnitude comparison tasks, suggesting effective implementation of the modified nonsymbolic magnitude task used in the present study.

Task Performance and Physical Activity

Findings from the present investigation are consistent with the extant literature observing that physically active lessons can create a substantive change in physical activity behaviors (Mahar et al., 2006; Norris, Shelton, Dunsmuir, Duke-Williams, & Stamatakis, 2015). Prior work by Mahar and colleagues (2006), has observed that school-aged children in grades K through 4 who engaged in the Energizers classroom-based physically active lessons accumulated almost 800 additional steps over the course of an entire school day relative to students engaged in conventional instructional approaches. Although physical activity was only assessed throughout the 20 minute intervention period within the present investigation, the physically active learning condition provided preschoolers with an additional 931.3 ± 8.2 steps (see Figure 4). Viewed within the framework of recommendations that preschool-aged children accumulate at least 10,000 steps per day (Cardon & De Bourdeaudhuij, 2007; Craemer et al., 2015; Tudor-Locke et al., 2011), integrating physical activity with educational content in the present study accounted for 10% of the daily recommended steps and represented a 1,600% increase in steps relative to the conventional sedentary instructional approach. Clearly, integrating physical activity within the classroom provides benefits for avoiding sedentary behavior. However, an important point of clarification is that the overall intensity of this physical activity was quite low, with preschool children accumulating just over 9 additional minutes of physical activity at or above a light intensity (at or above 30% of heart rate reserve) as a result of integrating physical activity with learning.

Novel to the present investigation was the assessment of the extent to which integrating physical activity and educational instruction has immediate impacts upon learning, specifically focusing upon changes in the acuity of the approximate number system — which serves as the foundations for mathematical achievement later in life. In contrast to the first hypothesis, behavioral metrics of performance on the nonsymbolic magnitude comparison paradigm were not observed to modulate in response to physically active learning in our preschool-aged sample. Thus, while integrating physical activity with early numeracy instruction was not associated with superior performance following the instructional period, such integration of activity and instruction was notably not associated with any deleterious effects either. Speculatively then, such a finding could reflect the stability of neural mechanisms underlying the acquisition of such skills, which enable individuals during early childhood to be robust against the influence of interfering distractors. Alternatively, it may be that the intensity of the physical activity was insufficient to incur potential enhancements in cognition and achievement or that the beneficial after-effects of the bout of physical activity counteracted the negative influence of the dual-task environment. Another important distinction of the present study from other physically-active learning investigations is that the physically-active instruction intentionally aligned with the learning goals of the lesson (i.e., engaging the approximate number system). That is, children were engaging approximate number representations while at the same time engaging in physical activity. Unlike implementing short physical activity opportunities as placeholder or transition activities within instructional contexts (i.e., having students march while spelling words until an instructor can rotate around to the group of students; Howie et al., 2014, 2015), the physically active instruction in the present study may have resulted in the same gains in the approximate number system as the conventional sedentary instruction because there was comparable duration of direct instruction. If the physical activity was implemented without integration of academic content, the same gains in approximate number representations may not have been obtained. Nevertheless, the present findings would appear to suggest that physically active learning does not detract from the acquisition of approximate number representations in young children.

Importantly, however, while performance on the nonsymbolic magnitude comparison paradigm was not impacted by the physically active instruction, such instructional approaches do appear to offer benefits relative to educational outcomes—thereby supporting the second hypothesis. Specifically, children exhibited greater on-task behavior following the physically active learning condition relative to following the conventional sedentary instruction condition—as evidenced by reduced experimenter redirection. Accordingly, such findings appear in line with the burgeoning body of literature demonstrating enhancements in attention following physical activity engagement (Pontifex et al., 2019). When viewed within the broader context of this literature, it may be that the enhancements in scholastic performance observed following long-term implementation of integrated physically active lessons may not result from the lesson period per-se, but rather reflect similar attentional control changes as those observed following classroom movement breaks. That is, following the activity period, children are able to engage attention towards subsequent instructional periods to a greater extent. From an educator perspective, such approaches reduce the need for redirecting off-task behavior, thereby increasing classroom efficiency and overall instruction time. Thus, acute bouts of physical activity enable subsequent transient enhancements in engagement to optimize the learning environment, and over repeated engagement, structural and functional neural adaptations are incurred to support such enhanced brain function. In such a context then, further research is necessary to examine the benefit of accumulating very light intensity physical activity for physical and brain health through the integration of physical activity and educational content relative to the potential of greater amounts of moderate-to-vigorous intensity activity accumulated through classroom movement breaks (Howie et al., 2014, 2015).

Limitations & Future Directions

Despite the methodological strengths of the present investigation, there are a number of limitations that warrant further discussion. First, it is important to acknowledge the potentially wide developmental range of the approximate number system within the sample population; although the randomized within-subjects crossover design mitigates many of these concerns, physical activity-induced changes in number sense may be more readily apparent in populations exhibiting greater homogeneity in development of this internal number system, in children who are lowest performing (Drollette et al., 2014), or in children with low behavioral self-regulation, which has been found to predict emergent math skills in preschoolers (Blair, 2002; McClelland et al., 2007). Additionally, the present investigation only focused upon changes in the acuity of the approximate number system within a very short period following the lesson period. Thus, further research is necessary to better understand more protracted effects of physically active instructional approaches and the effect of repeated exposure to such approaches in other outcomes relating to brain health in young children. Such knowledge will contribute to a greater understanding of how best to integrate physical activity during the school day to promote activity and enhance learning in educational contexts. Additionally, the intensity of the physically active instruction may be underestimated due to the small number of studies on using heart rate to measure physical activity in young children and the lack of research in using heart rate to describe physical activity intensity in children younger than 6 years old. However, %HRR is closely equivalent to % VO_2peak in children and has been identified as a practical variable for prescribing physical activity intensity for children (Hui & Chan, 2006). Finally, the generalizability of the present findings to classroom settings is limited given that the study was lab-based and testing occurred with children on individual basis. Promisingly, enhanced time-on-task was observed following participation in a single bout of physically active learning consistent with previous classroom-based findings. It is important to highlight that observers were not blind to experimental condition at posttest, yet a detailed definition of off-task behavior was provided and observers were coding experimenter behavior instead of children's behavior potentially so future research is needed to confirm or refute these findings.

Conclusion

Collectively, findings from this rigorous, randomized within-subjects cross-over investigation indicate that a single bout of physically active learning at low-to-moderate intensity promotes greater on-task behavior despite not enhancing learning of emerging numeracy in preschool-aged children. Moreover, such integrated learning resulted in a greater number of steps taken relative to conventional seated learning approaches. Thus, the present findings support the notion that such physically active learning approaches may be feasible in early childcare settings. Because educational administrators assert the primacy of performance on standardized achievement tests, physically active learning is an appealing approach that does not compromise instructional time, may reduce the need for redirecting off-task behavior, and ultimately enables children to accrue the many benefits associated with increased physical activity.

Investigations of the acute effects of physical activity integrated with academic learning during early childhood are rare and relatively new concepts. The current study used an acute physical activity paradigm—observed to influence inhibitory aspects of cognitive control—in an attempt to better understand the potential for improvement of acuity of the approximate number system in young children. Despite finding no physical activity-related effects on reaction time and response accuracy as indices of approximate number system acuity, time-on-task was enhanced following a single bout of physically active learning relative to following conventional seated learning approaches. These findings are the first to provide support that integrating physical activity with instruction does not hinder learning of foundational academic concepts in preschool-aged children, refuting the possibility that under high cognitive and energetic demands, attention resources are thus limited, resulting in focusing on only one aspect of the instructional activity (i.e., either the physical activity or the instructional content). Accordingly, this novel finding suggests that physically active lessons appear to not immediately hinder educational outcomes associated with academic instructional goals.

In light of the present study's findings, there remain a number of future directions to explore. This study focused on acuity of the approximate number system—as a foundational aspect underlying later mathematics achievement. However, young children rely more heavily on areas of the brain subserving cognitive control and attention when performing basic mathematical computation (i.e., arithmetic). Thus, these high-level cognitive operations may be particularly important for mathematical competence in young children. As such, such physically active instructional approaches may be well suited for acutely improving attentional control (Pontifex et al., 2019) to enhance classroom behavior and thereby offering benefits related to intended educational outcomes. Given that neuroelectric indices may be more sensitive to detecting such enhancements beyond overt behavioral measures, future research may opt to use event-related potentials and other neuroimaging methods to confirm or refute the present study's findings. Given that ANS acuity in young children may be moderated by attentional and interference control as well as rely heavily upon prefrontal cortex function—an area of the brain influenced by physical activity (Chaddock et al., 2010, 2011; Chaddock-Heyman et al., 2014)—future research should examine the impact of acute aerobic physical activity on inhibitory aspects of cognitive control and attention in preschool-aged children given this robust finding in other age groups so as to determine how these changes influence ANS acuity. Future research may opt to examine other aspects of physically active lessons, such as intensity, duration, and activity modality (e.g., aerobic vs. coordinative vs. resistance) and how varying such characteristics influence cognition and educational outcomes in young children.

As this is the first study to explore the immediate effects of physically active instruction on acuity of the approximate number system during early childhood, the methodological limitations observed throughout this study will serve to strengthen the overall design of future projects. The observed effect sizes relative to the influence of acute physical activity on cognition in preschool-aged children will help to determine ample power for future studies, thereby strengthening the literature base in this age group as a whole. Finally, the support for feasibility of the current protocols within this age group will provide the means for other researchers to begin exploring the effects of acute physical activity in young children on emerging numeracy and related educational outcomes. This line of inquiry is timely as it has the potential to impact public health issues related to childhood inactivity, educational policy, and the design of activity-promoting interventions targeting brain health and physical literacy during early childhood. Accordingly, these contributions provide a foundation for future work in this area.

APPENDICES

Appendix A: IRB Approval Letter

MICHIGAN STATE
UNIVERSITY

Initial Study APPROVAL
Revised Common Rule

March 21, 2019

To: Matthew B Pontifex

Re: **MSU Study ID:** STUDY00002242
IRB: Biomedical and Health Institutional Review Board
Principal Investigator: Matthew B Pontifex
Category: Expedited 4, 7
Submission: Initial Study STUDY00002242
Submission Approval Date: 3/21/2019
Effective Date: 3/21/2019
Study Expiration Date: **None; however modification and closure submissions are required (see below).**

Title: Effects of activity on number sense in preschoolers

This submission has been approved by the Michigan State University (MSU) BIRB. The submission was reviewed by the Institutional Review Board (IRB) through the Non-Committee Review procedure. The IRB has found that this study protects the rights and welfare of human subjects and meets the requirements of MSU's Federal Wide Assurance (FWA00004556) and the federal regulations for the protection of human subjects in research (e.g., 2018 45 CFR 46, 21 CFR 50, 56, other applicable regulations).

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How to Access Final Documents
To access the study's final materials, including those approved by the IRB such as consent forms, recruitment materials, and the approved protocol, if applicable, please log into the Click™ Research Compliance System, open the study's workspace, and view the "Documents" tab. To obtain consent form(s) stamped with the IRB watermark, select the "Final" PDF version of your consent form(s) as applicable in the "Documents" tab. Please note that the consent form(s) stamped with the IRB watermark must typically be used.

Expiration of IRB Approval: The IRB approval for this study does not have an expiration date. Therefore, continuing review submissions to extend an approval period for this study are not required. **Modification and closure submissions are still required (see below).**

Modifications: Any proposed change or modification with certain limited exceptions discussed below must be reviewed and approved by the IRB prior to implementation of the change. Please submit a Modification request to have the changes reviewed.

Appendix B: Dissertation Funding Sources

Dissertation Funding Sources

1. **Summer Research Renewable Fellowship – 2018/2019**
   College of Education, Michigan State University
   Funded - $12,000
   Use: Study coordinator assistantship support

2. **Dissertation Development Fellowship – 2018**
   Department of Kinesiology, Michigan State University
   Funded - $4,000
   Use: Participant compensation and study equipment.

3. **Dissertation Development Fellowship - 2017**
   Department of Kinesiology, Michigan State University
   Funded - $3,000
   Use: Participant compensation and study equipment.

REFERENCES

REFERENCES

2018 Physical Activity Guidelines Advisory Committee. (2018). *2018 Physical activity guidelines advisory committee scientific report*.

Ansari, D. (2008). Effects of development and enculturation on number representation in the brain. *Nature Reviews Neuroscience*, *9*(4), 278.

Ansari, D. (2012). *The foundations of numerical and mathematical abilities: A literature review*. World Bank.

Ansari, D., & Dhital, B. (2006). Age-related changes in the activation of the intraparietal sulcus during nonsymbolic magnitude processing: An event-related functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience*, *18*(11), 1820–1828.

Ansari, D., Dhital, B., & Siong, S. C. (2006). Parametric effects of numerical distance on the intraparietal sulcus during passive viewing of rapid numerosity changes. *Brain Research*, *1067*(1), 181–188. https://doi.org/10.1016/j.brainres.2005.10.083

Ansari, D., Garcia, N., Lucas, E., Hamon, K., & Dhital, B. (2005). Neural correlates of symbolic number processing in children and adults. *NeuroReport*, *16*(16), 1769. https://doi.org/10.1097/01.wnr.0000183905.23396.f1

Ashkenazi, S., Mark-Zigdon, N., & Henik, A. (2009). Numerical distance effect in developmental dyscalculia. *Cognitive Development*, *24*(4), 387–400. https://doi.org/10.1016/j.cogdev.2009.09.006

Ashkenazi, S., Rosenberg-Lee, M., Metcalfe, A. W., Swigart, A. G., & Menon, V. (2013). Visuo–spatial working memory is an important source of domain-general vulnerability in the development of arithmetic cognition. *Neuropsychologia*, *51*(11), 2305–2317.

Bailey, D. P., Fairclough, S. J., Savory, L. A., Denton, S. J., Pang, D., Deane, C. S., & Kerr, C. J. (2012). Accelerometry-assessed sedentary behaviour and physical activity levels during the segmented school day in 10–14-year-old children: The HAPPY study. *European Journal of Pediatrics*, *171*(12), 1805–1813. https://doi.org/10.1007/s00431-012-1827-0

Bartholomew, J. B., & Jowers, E. M. (2011). Physically active academic lessons in elementary children. *Preventive Medicine*, *52*, S51–S54. https://doi.org/10.1016/j.ypmed.2011.01.017

Benzing, V., Heinks, T., Eggenberger, N., & Schmidt, M. (2016). Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. *PLoS ONE*, *11*(12). https://doi.org/10.1371/journal.pone.0167501

Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review*, *30*(4), 331–551. https://doi.org/10.1016/j.dr.2010.08.001

Best, J. R. (2012). Exergaming immediately enhances children's executive function. *Developmental Psychology*, *48*(5), 1501–1510. https://doi.org/10.1037/a0026648

Blair, C. (2002). School readiness: Integrating cognition and emotion in a neurobiological conceptualization of children's functioning at school entry. *American Psychologist*, *57*(2), 111.

Bonny, J. W., & Lourenco, S. F. (2013). The approximate number system and its relation to early math achievement: Evidence from the preschool years. *Journal of Experimental Child Psychology*, *114*(3), 375–388. https://doi.org/10.1016/j.jecp.2012.09.015

Brannon, E. M., & Van de Walle, G. A. (2001). The development of ordinal numerical competence in young children. *Cognitive Psychology*, *43*(1), 53–81. https://doi.org/10.1006/cogp.2001.0756

Brignac, A., Bellar, D., Judge, L. W., Smith, J., Mazerat, N., & Trosclair, D. (2011). The relationship of BMI to grade point average, age and multiple fitness tests. *The Journal of Strength & Conditioning Research*, *25*, S121.

Cardon, G., & De Bourdeaudhuij, I. (2007). Comparison of pedometer and accelerometer measures of physical activity in preschool children. *Pediatric Exercise Science*, *19*(2), 205–214.

Castelli, D. M., Hillman, C. H., Buck, S. M., & Erwin, H. E. (2007). Physical fitness and academic achievement in third- and fifth-grade students. *Journal of Sport & Exercise Psychology*, *29*, 239–252.

Chaddock, L., Erickson, K. I., Prakash, R. S., Kim, J. S., Voss, M. W., VanPatter, M., Pontifex, M. B., Raine, L. B., Konkel, A., Hillman, C. H., Cohen, N. J., & Kramer, A. F. (2010). A neuroimaging investigation of the association between aerobic fitness, hippocampal volume, and memory performance in preadolescent children. *Brain Research*, *1358*, 172–183. https://doi.org/10.1016/j.brainres.2010.08.049

Chaddock, L., Pontifex, M. B., Hillman, C. H., & Kramer, A. F. (2011). A review of the relation of aerobic fitness and physical activity to brain structure and function in children. *Journal of the International Neuropsychological Society*, *17*(06), 975–985. https://doi.org/10.1017/S1355617711000567

Chaddock-Heyman, L., Erickson, K. I., Holtrop, J. L., Voss, M. W., Pontifex, M. B., Raine, L. B., Hillman, C. H., & Kramer, A. F. (2014). Aerobic fitness is associated with greater white matter integrity in children. *Frontiers in Human Neuroscience*, *8*, 1–7. https://doi.org/10.3389/fnhum.2014.00584

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, *1453*(Supplement C), 87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., Elavsky, S., Marquez, D. X., Hu, L., & Kramer, A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *61*(11), 1166–1170.

Corder, K., Brage, S., & Ekelund, U. (2007). Accelerometers and pedometers: Methodology and clinical application. *Current Opinion in Clinical Nutrition & Metabolic Care*, *10*(5), 597. https://doi.org/10.1097/MCO.0b013e328285d883

Craemer, M. D., Decker, E. D., Bourdeaudhuij, I. D., Verloigne, M., Manios, Y., & Cardon, G. (2015). The translation of preschoolers' physical activity guidelines into a daily step count target. *Journal of Sports Sciences*, *33*(10), 1051–1057. https://doi.org/10.1080/02640414.2014.981850

Daly-Smith, A. J., Zwolinsky, S., McKenna, J., Tomporowski, P. D., Defeyter, M. A., & Manley, A. (2018). Systematic review of acute physically active learning and classroom movement breaks on children's physical activity, cognition, academic performance and classroom behaviour: Understanding critical design features. *BMJ Open Sport & Exercise Medicine*, *4*(1), e000341. https://doi.org/10.1136/bmjsem-2018-000341

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078. https://doi.org/10.1016/j.neuropsychologia.2006.02.006

Davis, C. L., & Cooper, S. (2011). Fitness, fatness, cognition, behavior, and academic achievement among overweight children: Do cross-sectional associations correspond to exercise trial outcomes? *Preventive Medicine*, *52*, S65–S69. https://doi.org/10.1016/j.ypmed.2011.01.020

Dehaene, S. (1996). The organization of brain activations in number comparison: Event-related potentials and the additive-factors method. *J. Cognitive Neuroscience*, *8*(1), 47–68. https://doi.org/10.1162/jocn.1996.8.1.47

Dehaene, S. (2011). *The number sense: How the mind creates mathematics*. OUP USA.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and levels of representation in number processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(2), 314.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(3), 626–641. https://doi.org/10.1037/0096-1523.16.3.626

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*(3–6), 487–506. https://doi.org/10.1080/02643290244000239

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science*, *284*(5416), 970–974.

DeWind, N. K., & Brannon, E. M. (2012). Malleability of the approximate number system: Effects of feedback and training. *Frontiers in Human Neuroscience*, *6*. https://doi.org/10.3389/fnhum.2012.00068

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. *Principles of Frontal Lobe Function*, 466–503.

Diamond, K. E., Gerde, H. K., & Powell, D. R. (2008). Development in early literacy skills during the pre-kindergarten year in Head Start: Relations between growth in children's writing and understanding of letters. *Early Childhood Research Quarterly*, *23*(4), 467–478. https://doi.org/10.1016/j.ecresq.2008.05.002

Dickinson, B. D., Duncan, M. J., & Eyre, E. L. J. (2016). Exercise and academic achievement in children: Effects of acute class-based circuit training. *Human Movement*, *17*, 4–7. https://doi.org/10.1515/humo-2016-0007

Donnelly, J. E., Greene, J. L., Gibson, C. A., Smith, B. K., Washburn, R. A., Sullivan, D. K., DuBose, K., Mayo, M. S., Schmelzle, K. H., Ryan, J. J., Jacobsen, D. J., & Williams, S. L. (2009). Physical Activity Across the Curriculum (PAAC): A randomized controlled trial to promote physical activity and diminish overweight and obesity in elementary school children. *Preventive Medicine*, *49*(4), 336–341. https://doi.org/10.1016/j.ypmed.2009.07.022

Donnelly, J. E., Hillman, C. H., Castelli, D., Etnier, J. L., Lee, S., Tomporowski, P., Lambourne, K., & Szabo-Reed, A. N. (2016). Physical activity, fitness, cognitive function, and academic achievement in children: A systematic review. *Medicine and Science in Sports and Exercise*, *48*(6), 1223–1224. https://doi.org/10.1249/MSS.0000000000000966

Donnelly, J. E., & Lambourne, K. (2011). Classroom-based physical activity, cognition, and academic achievement. *Preventive Medicine*, *52*, S36–S42.

Drollette, E. S., Scudder, M. R., Raine, L. B., Moore, R. D., Saliba, B. J., Pontifex, M. B., & Hillman, C. H. (2014). Acute exercise facilitates brain function and cognition in children who need it most: An ERP study of individual differences in inhibitory control capacity.

Developmental Cognitive Neuroscience, *7*, 53–64. https://doi.org/10.1016/j.dcn.2013.11.001

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., & Brooks-Gunn, J. (2007). School readiness and later achievement. *Developmental Psychology*, *43*(6), 1428.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, *43*(6), 1428–1446. http://dx.doi.org.proxy2.cl.msu.edu/10.1037/0012-1649.43.6.1428

Durant, R. H., Baranowski, T., Davis, H., Rhodes, T., Thompson, W. O., Greaves, K. A., & Puhl, J. (1993). Reliability and variability of indicators of heart-rate monitoring in children. *Medicine and Science in Sports and Exercise*, *25*(3), 389–395.

Dyson, N. I., Jordan, N. C., & Glutting, J. (2013). A number sense intervention for low-income kindergartners at risk for mathematics difficulties. *Journal of Learning Disabilities*, *46*(2), 166–181.

Egger, F., Conzelmann, A., & Schmidt, M. (2018). The effect of acute cognitively engaging physical activity breaks on children's executive functions: Too much of a good thing? *Psychology of Sport and Exercise*, *36*, 178–186. https://doi.org/10.1016/j.psychsport.2018.02.014

Eggermont, L. H. P., Milberg, W. P., Lipsitz, L. A., Scherder, E. J. A., & Leveille, S. G. (2009). Physical Activity and Executive Function in Aging: The MOBILIZE Boston Study. *Journal of the American Geriatrics Society*, *57*(10), 1750–1756. https://doi.org/10.1111/j.1532-5415.2009.02441.x

Ellemberg, D., & St-Louis-Deschênes, M. (2010). The effect of acute physical exercise on cognitive function during development. *Psychology of Sport and Exercise*, *11*(2), 122–126. https://doi.org/10.1016/j.psychsport.2009.09.006

Eston, R. G., Rowlands, A. V., & Ingledew, D. K. (1998). Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities. *Journal of Applied Physiology*, *84*(1), 362–371.

Etnier, J. L., Labban, J. D., Piepmeier, A. T., Davis, M. E., & Henning, D. A. (2014). Effects of an acute bout of exercise on memory in 6th grade children. *Pediatric Exercise Science*, *26*, 250–258. https://doi.org/10.1123/pes.2013-0141

Eveland-Sayers, B. M., Farley, R. S., Fuller, D. K., Morgan, D. W., & Caputo, J. L. (2009). Physical fitness and academic achievement in elementary school children. *Journal of Physical Activity and Health*, *6*(1), 99–104. https://doi.org/10.1123/jpah.6.1.99

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*(7), 307–314.

Freedson, P. S., & Miller, K. (2000). Objective monitoring of physical activity using motion sensors and heart rate. *Research Quarterly for Exercise and Sport*, *71*(sup2), 21–29.

Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: Contributions of inhibitory control. *Developmental Science*, *16*(1), 136–148.

Gallotta, M. C., Emerenziani, G. P., Franciosi, E., Meucci, M., Guidetti, L., & Baldari, C. (2015). Acute physical activity and delayed attention in primary school students. *Scandinavian Journal of Medicine & Science in Sports*, *25*(3), e331–e338. https://doi.org/10.1111/sms.12310

Gallotta, M. C., Guidetti, L., Franciosi, E., Emerenziani, G., Bonavolontà, V., & Baldari, C. (2012). Effects of varying type of exertion on children's attention capacity. *Medicine & Science in Sports & Exercise*, *44*(3), 550–555. https://doi.org/10.1249/MSS.0b013e3182305552

Gebuis, T., & Reynvoet, B. (2011). Generating nonsymbolic number stimuli. *Behavior Research Methods*, *43*(4), 981–986.

Gilmore, C., Attridge, N., & Inglis, M. (2011). Measuring the approximate number system. *The Quarterly Journal of Experimental Psychology*, *64*(11), 2099–2109. https://doi.org/10.1080/17470218.2011.574710

Ginsburg, H. P., Lee, J. S., & Boyd, J. S. (2008). *Mathematics Education for Young Children: What It Is and How to Promote It. Social Policy Report. Volume 22, Number 1*. Society for Research in Child Development. https://eric.ed.gov/?id=ED521700

Goldstein, H. (2011). *Multilevel statistical models* (Vol. 922). John Wiley & Sons.

Goodie, J. L., Larkin, K. T., & Schauss, S. (2000). Validation of Polar heart rate monitor for assessing heart rate during physical and mental stress. *Journal of Psychophysiology*, *14*(3), 159–164. https://doi.org/10.1027//0269-8803.14.3.159

Graham, D. J., Lucas-Thompson, R. G., & O'Donnell, M. B. (2014). Jump In! An investigation of school physical activity climate, and a pilot study assessing the acceptability and feasibility of a novel tool to increase activity during learning. *Frontiers in Public Health*, *2*. https://doi.org/10.3389/fpubh.2014.00058

Greeff, D., W, J., Hartman, E., Mullender-Wijnsma, M. J., Bosker, R. J., Doolaard, S., & Visscher, C. (2016). Long-term effects of physically active academic lessons on physical fitness and executive functions in primary school children. *Health Education Research*, *31*(2), 185–194. https://doi.org/10.1093/her/cyv102

Grieco, L. A., Jowers, E. M., & Bartholomew, J. B. (2009). Physically active academic lessons and time on task: The moderating effect of body mass index. *Medicine & Science in Sports & Exercise*, *41*(10), 1921–1926. https://doi.org/10.1249/MSS.0b013e3181a61495

Grieco, L. A., Jowers, E. M., Errisuriz, V. L., & Bartholomew, J. B. (2016). Physically active vs. sedentary academic lessons: A dose response study for elementary student time on task. *Preventive Medicine*, *89*, 98–103.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the "Number Sense": The Approximate Number System in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, *44*(5), 1457.

Halberda, J., Mazzocco, M. M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, *455*(7213), 665–668. https://doi.org/10.1038/nature07246

Heine, A., Tamm, S., Wißmann, J., & Jacobs, A. M. (2011). Electrophysiological correlates of non-symbolic numerical magnitude processing in children: Joining the dots. *Neuropsychologia*, *49*(12), 3238–3246. https://doi.org/10.1016/j.neuropsychologia.2011.07.028

Helgeson, J. L. (2013). *The Impact of Physical Activity on Academics in English Classes at the Junior High School Level* [Ph.D., Northcentral University]. http://search.proquest.com/docview/1461555818/abstract/EADE9B5D7E9B4B00PQ/1

Hervet, R. (1952). Vanves, son experience, ses perspectives. *Revue Institut Sports*, *24*, 4–6.

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*, *159*(3), 1044–1054. https://doi.org/10.1016/j.neuroscience.2009.01.057

Hnatiuk, J. A., Salmon, J., Hinkley, T., Okely, A. D., & Trost, S. G. (2014). A review of preschool children's physical activity and sedentary time using objective measures. *American Journal of Preventive Medicine*, *47*(4), 487–497. https://doi.org/10.1016/j.amepre.2014.05.042

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology*, *103*(1), 17–29. https://doi.org/10.1016/j.jecp.2008.04.001

Honoré, N., & Noël, M.-P. (2016). Improving preschoolers' arithmetic through number magnitude training: The impact of non-symbolic and symbolic training. *PloS One*, *11*(11), e0166685.

Houdé, O., Rossi, S., Lubin, A., & Joliot, M. (2010). Mapping numerical processing, reading, and executive functions in the developing brain: An fMRI meta-analysis of 52 studies including 842 children. *Developmental Science*, *13*(6), 876–885.

Howie, E. K., Beets, M. W., & Pate, R. R. (2014). Acute classroom exercise breaks improve on-task behavior in 4th and 5th grade students: A dose–response. *Mental Health and Physical Activity*, *7*(2), 65–71. https://doi.org/10.1016/j.mhpa.2014.05.002

Howie, E. K., Schatz, J., & Pate, R. R. (2015). Acute effects of classroom exercise breaks on executive function and math performance: A dose-response study. *Research Quarterly for Exercise and Sport*, *86*(3), 217–224. https://doi.org/10.1080/02701367.2015.1039892

Hui, S. S., & Chan, J. W. (2006). The relationship between heart rate reserve and oxygen uptake reserve in children and adolescents. *Research Quarterly for Exercise and Sport*, *77*(1), 41–49.

Huntley-Fenner, G. (2001). Children's understanding of number is similar to adults' and rats': Numerical estimation by 5–7-year-olds. *Cognition*, *78*(3), B27–B40.

Huntley-Fenner, G., & Cannon, E. (2000). Preschoolers' magnitude comparisons are mediated by a preverbal analog mechanism. *Psychological Science*, *11*(2), 147–152.

Hyde, D. C., Khanum, S., & Spelke, E. S. (2014). Brief non-symbolic, approximate number practice enhances subsequent exact symbolic arithmetic in children. *Cognition*, *131*(1), 92–107.

Inglis, M., & Gilmore, C. (2014). Indexing the approximate number system. *Acta Psychologica*, *145*, 147–155. https://doi.org/10.1016/j.actpsy.2013.11.009

Ishihara, T., Sugasawa, S., Matsuda, Y., & Mizuno, M. (2017). Improved executive functions in 6–12-year-old children following cognitively engaging tennis lessons. *Journal of Sports Sciences*, *35*(20), 2014–2020. https://doi.org/10.1080/02640414.2016.1250939

Jones, L. B., Rothbart, M. K., & Posner, M. I. (2003). Development of executive attention in preschool children. *Developmental Science*, *6*(5), 498–504. https://doi.org/10.1111/1467-7687.00307

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology*, *45*(3), 850.

Kamijo, K., & Takeda, Y. (2009). General physical activity levels influence positive and negative priming effects in young adults. *Clinical Neurophysiology*, *120*(3), 511–519. https://doi.org/10.1016/j.clinph.2008.11.022

Kamijo, K., & Takeda, Y. (2010). Regular physical activity improves executive function during task switching in young adults. *International Journal of Psychophysiology*, *75*, 304–311.

Katzmarzyk, P. T., Denstel, K. D., Beals, K., Bolling, C., Wright, C., Crouter, S. E., McKenzie, T. L., Pate, R. R., Saelens, B. E., & Staiano, A. E. (2016). Results from the United States of America's 2016 report card on physical activity for children and youth. *Journal of Physical Activity and Health*, *13*(11 Suppl 2), S307–S313.

Keating, X. D., Shangguan, R., Xiao, K., Gao, X., Sheehan, C., Wang, L., Colburn, J., Fan, Y., & Wu, F. (2019). Tracking changes of Chinese pre-service teachers' aerobic fitness, body mass index, and grade point average over 4-years of college. *International Journal of Environmental Research and Public Health*, *16*(6). https://doi.org/10.3390/ijerph16060966

Kirk, S. M., Vizcarra, C. R., Looney, E. C., & Kirk, E. P. (2014). Using physical activity to teach academic content: A study of the effects on literacy in Head Start preschoolers. *Early Childhood Education Journal*, *42*(3), 181–189. https://doi.org/10.1007/s10643-013-0596-3

Kwak, L., Kremers, S. P. J., Bergman, P., Ruiz, J. R., Rizzo, N. S., & Sjöström, M. (2009). Associations between physical activity, fitness, and academic achievement. *The Journal of Pediatrics*, *155*(6), 914-918.e1. https://doi.org/10.1016/j.jpeds.2009.06.019

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition*, *93*(2), 99–125.

Landerl, K., & Kölle, C. (2009). Typical and atypical development of basic numerical skills in elementary school. *Journal of Experimental Child Psychology*, *103*(4), 546–565. https://doi.org/10.1016/j.jecp.2008.12.006

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, *9*(2), 75–82. https://doi.org/10.1016/j.tics.2004.12.004

Lavie, N., Hirst, A., Viding, E., & Fockert, J. W. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology*, *133*, 339–354.

Libertus, M. E., Feigenson, L., & Halberda, J. (2011). Preschool acuity of the approximate number system correlates with school math ability. *Developmental Science*, *14*(6), 1292–1300. https://doi.org/10.1111/j.1467-7687.2011.01080.x

Libertus, M. E., Feigenson, L., & Halberda, J. (2013). Is approximate number precision a stable predictor of math ability? *Learning and Individual Differences*, *25*, 126–133.

Link, T., Moeller, K., Huber, S., Fischer, U., & Nuerk, H.-C. (2013). Walk the number line – An embodied training of numerical concepts. *Trends in Neuroscience and Education*, *2*(2), 74–84. https://doi.org/10.1016/j.tine.2013.06.005

Lipton, J. S., & Spelke, E. S. (2003). Origins of number sense: Large-number discrimination in human infants. *Psychological Science*, *14*(5), 396–401.

Livingstone, M. B., Coward, Wa., Prentice, A. M., Davies, P. S., Strain, J. J., McKenna, P. G., Mahoney, C. A., White, J. A., Stewart, C. M., & Kerr, M. J. (1992). Daily energy expenditure in free-living children: Comparison of heart-rate monitoring with the doubly labeled water (2H218O) method. *The American Journal of Clinical Nutrition*, *56*(2), 343–352.

Logi Kristjánsson, Á., Dóra Sigfúsdóttir, I., & Allegrante, J. P. (2010). Health behavior and academic achievement among adolescents: The relative contribution of dietary habits, physical activity, body mass index, and self-esteem. *Health Education & Behavior*, *37*(1), 51–64. https://doi.org/10.1177/1090198107313481

London, R. A., & Castrechini, S. (2011). A longitudinal examination of the link between youth physical fitness and academic achievement. *Journal of School Health*, *81*(7), 400–408. https://doi.org/10.1111/j.1746-1561.2011.00608.x

Mahar, M. T., Murphy, S. K., Rowe, D. A., Golden, J., Shields, A. T., & Raedeke, T. D. (2006). Effects of a classroom-based program on physical activity and on-task behavior. *Medicine & Science in Sports & Exercise*, *38*, 2086–2094. https://doi.org/10.1249/01.mss.0000235359.16685.a3

Mahon, A. D., Marjerrison, A. D., Lee, J. D., Woodruff, M. E., & Hanna, L. E. (2010). Evaluating the prediction of maximal heart rate in children and adolescents. *Research Quarterly for Exercise and Sport*, *81*(4), 466–471.

Mavilidi, M.-F., Okely, A., Chandler, P., Domazet, S. L., & Paas, F. (2018). Immediate and delayed effects of integrating physical activity into preschool children's learning of numeracy skills. *Journal of Experimental Child Psychology*, *166*, 502–519.

Mavilidi, M.-F., Okely, A. D., Chandler, P., Cliff, D. P., & Paas, F. (2015). Effects of integrated physical exercises and gestures on preschool children's foreign language vocabulary learning. *Educational Psychology Review*, *27*(3), 413–426.

Mavilidi, M.-F., Okely, A. D., Chandler, P., & Paas, F. (2016). Infusing physical activities into the classroom: Effects on preschool children's geography learning. *Mind, Brain, and Education*, *10*(4), 256–263. https://doi.org/10.1111/mbe.12131

Mavilidi, M.-F., Okely, A. D., Chandler, P., & Paas, F. (2017). Effects of integrating physical activities into a science lesson on preschool children's learning and enjoyment. *Applied Cognitive Psychology*, *31*(3), 281–290.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development*, *82*(4), 1224–1237.

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011a). Impaired Acuity of the Approximate Number System Underlies Mathematical Learning Disability (Dyscalculia). *Child Development*, *82*(4), 1224–1237. https://doi.org/10.1111/j.1467-8624.2011.01608.x

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011b). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PLOS ONE*, *6*(9), e23749. https://doi.org/10.1371/journal.pone.0023749

McClelland, M. M., Cameron, C. E., Connor, C. M., Farris, C. L., Jewkes, A. M., & Morrison, F. J. (2007). Links between behavioral regulation and preschoolers' literacy, vocabulary, and math skills. *Developmental Psychology*, *43*(4), 947.

McFarland, J., Hussar, B., de Brey, C., Snyder, T., Wang, X., Wilkinson-Flicker, S., Gebrekristos, S., Zhang, J., Rathbun, A., & Barmer, A. (2017). The Condition of Education 2017. NCES 2017-144. *National Center for Education Statistics*.

McGowan, A. L., Chandler, M. C., Brascamp, J. W., & Pontifex, M. B. (2019). Pupillometric indices of locus-coeruleus activation are not modulated following single bouts of exercise. *International Journal of Psychophysiology*, *140*, 41–52. https://doi.org/10.1016/j.ijpsycho.2019.04.004

Mierau, A., Hülsdünker, T., Mierau, J., Hense, A., Hense, J., & Strüder, H. K. (2014). Acute exercise induces cortical inhibition and reduces arousal in response to visual stimulation in young children. *International Journal of Developmental Neuroscience*, *34*, 1–8. https://doi.org/10.1016/j.ijdevneu.2013.12.009

Mix, K. S. (1999a). Similarity and Numerical Equivalence: Appearances Count. *Cognitive Development*, *14*(2), 269–297. https://doi.org/10.1016/S0885-2014(99)00005-2

Mix, K. S. (1999b). Preschoolers' recognition of numerical equivalence: Sequential sets. *Journal of Experimental Child Psychology*, *74*(4), 309–332. https://doi.org/10.1006/jecp.1999.2533

Mix, K. S., Huttenlocher, J., & Levine, S. C. (1996). Do preschool children recognize auditory-visual numerical correspondences? *Child Development*, *67*(4), 1592–1608. https://doi.org/10.1111/j.1467-8624.1996.tb01816.x

Morita, N., Nakajima, T., Okita, K., Ishihara, T., Sagawa, M., & Yamatsu, K. (2016). Relationships among fitness, obesity, screen time and academic achievement in Japanese adolescents. *Physiology & Behavior*, *163*, 161–166. https://doi.org/10.1016/j.physbeh.2016.04.055

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*.

Mullender-Wijnsma, M. J., Hartman, E., de Greeff, J. W., Doolaard, S., Bosker, R. J., & Visscher, C. (2016). Physically active math and language lessons improve academic achievement: A cluster randomized controlled trial. *Pediatrics*, *137*(3), e20152743.

Mullender-Wijnsma, M. J., Hartman, E., de Greeff, J. W., Doolaard, S., Bosker, R. J., & Visscher, C. (2019). Follow-up study investigating the effects of a physically active academic intervention. *Early Childhood Education Journal*. https://doi.org/10.1007/s10643-019-00968-y

Mullender-Wijnsma, Marijke J., Hartman, E., Greeff, J. W. de, Doolaard, S., Bosker, R. J., & Visscher, C. (2016). Physically active math and language lessons improve academic achievement: A cluster randomized controlled trial. *Pediatrics*, peds.2015-2743. https://doi.org/10.1542/peds.2015-2743

Nettlefold, L., McKay, H. A., Warburton, D. E. R., McGuire, K. A., Bredin, S. S. D., & Naylor, P. J. (2011). The challenge of low physical activity during the school day: At recess, lunch and in physical education. *British Journal of Sports Medicine*, *45*(10), 813–819. https://doi.org/10.1136/bjsm.2009.068072

Nieder, A., & Dehaene, S. (2009). Representation of number in the brain. *Annual Review of Neuroscience*, *32*, 185–208.

Nieder, A., Freedman, D. J., & Miller, E. K. (2002). Representation of the quantity of visual items in the primate prefrontal cortex. *Science*, *297*(5587), 1708–1711.

Norris, E., Shelton, N., Dunsmuir, S., Duke-Williams, O., & Stamatakis, E. (2015a). Physically active lessons as physical activity and educational interventions: A systematic review of methods and results. *Preventive Medicine*, *72*, 116–125. https://doi.org/10.1016/j.ypmed.2014.12.027

Norris, E., Shelton, N., Dunsmuir, S., Duke-Williams, O., & Stamatakis, E. (2015b). Virtual field trips as physically active lessons for children: A pilot study. *BMC Public Health*, *15*(1), 366. https://doi.org/10.1186/s12889-015-1706-5

Obersteiner, A., Reiss, K., & Ufer, S. (2013). How training on exact or approximate mental representations of number can enhance first-grade students' basic number processing and arithmetic skills. *Learning and Instruction*, *23*, 125–135. https://doi.org/10.1016/j.learninstruc.2012.08.004

Paglin, M., & Rufolo, A. M. (1990). Heterogeneous human capital, occupational choice, and male-female earnings differences. *Journal of Labor Economics*, *8*(1, Part 1), 123–144. https://doi.org/10.1086/298239

Palmer, K. K., Miller, M. W., & Robinson, L. E. (2013). Acute exercise enhances preschoolers' ability to sustain attention. *Journal of Sport & Exercise Psychology*, *35*(4), 433–437.

Park, J., Bermudez, V., Roberts, R. C., & Brannon, E. M. (2016). Non-symbolic approximate arithmetic training improves math performance in preschoolers. *Journal of Experimental Child Psychology*, *152*, 278–293. https://doi.org/10.1016/j.jecp.2016.07.011

Park, J., & Brannon, E. M. (2013). Training the approximate number system improves math proficiency. *Psychological Science*, *24*(10), 2013–2019.

Park, J., & Brannon, E. M. (2014). Improving arithmetic performance with number sense training: An investigation of underlying mechanism. *Cognition*, *133*(1), 188–200. https://doi.org/10.1016/j.cognition.2014.06.011

Parks, A. N., & Blom, D. C. (2014). Helping young children see math in play. *Teaching Children Mathematics*, *20*(5), 310–317. https://doi.org/10.5951/teacchilmath.20.5.0310

Parsons, S., & Bynner, J. (2005). *Does numeracy matter more?*

Passolunghi, M. C., & Mammarella, I. C. (2012). Selective spatial working memory impairment in a group of children with mathematics learning disabilities and poor problem-solving skills. *Journal of Learning Disabilities*, *45*(4), 341–350.

Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, *2*, 10. https://doi.org/10.3389/neuro.11.010.2008

Pesce, C. (2012). Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *Journal of Sport and Exercise Psychology*, *34*(6), 766–786.

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*(1), 16–22. https://doi.org/10.1016/j.mhpa.2009.02.001

Pesce, C., Crova, C., Marchetti, R., Struzzolino, I., Masci, I., Vannozzi, G., & Forte, R. (2013). Searching for cognitively optimal challenge point in physical activity for children with typical and atypical motor development. *Mental Health and Physical Activity*, *6*(3), 172–180. https://doi.org/10.1016/j.mhpa.2013.07.001

Pirrie, A. M., & Lodewyk, K. R. (2012). Investigating links between moderate-to-vigorous physical activity and cognitive performance in elementary school students. *Mental Health and Physical Activity*, *5*(1), 93–98. https://doi.org/10.1016/j.mhpa.2012.04.001

Pontifex, M. B., Gwizdala, K. L., Parks, A. C., Pfeiffer, K. A., & Fenn, K. M. (2016). The association between physical activity during the day and long-term memory stability. *Scientific Reports*, *6*, 38148. https://doi.org/10.1038/srep38148

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise*, *40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Pontifex, M. B., Parks, A. C., O'Neil, P. C., Egner, A. R., Warning, J. T., Pfeiffer, K. A., & Fenn, K. M. (2014). Poorer aerobic fitness relates to reduced integrity of multiple memory systems. *Cognitive, Affective, & Behavioral Neuroscience*, *14*(3), 1132–1141. https://doi.org/10.3758/s13415-014-0265-z

Pontifex, M. B., Raine, L. B., Johnson, C. R., Chaddock, L., Voss, M. W., Cohen, N. J., Kramer, A. F., & Hillman, C. H. (2011). Cardiorespiratory fitness and the flexible modulation of cognitive control in preadolescent children. *Journal of Cognitive Neuroscience*, *23*(6), 1332–1345.

Pontifex, M. B., Saliba, B. J., Raine, L. B., Picchietti, D. L., & Hillman, C. H. (2013). Exercise improves behavioral, neurocognitive, and scholastic performance in children with ADHD. *The Journal of Pediatrics*, *162*(3), 543–551. https://doi.org/10.1016/j.jpeds.2012.08.036

Price, G. R., Palmer, D., Battista, C., & Ansari, D. (2012). Nonsymbolic numerical magnitude comparison: Reliability and validity of different task variants and outcome measures, and their relationship to arithmetic achievement in adults. *Acta Psychologica*, *140*(1), 50–57. https://doi.org/10.1016/j.actpsy.2012.02.008

Quené, H., & Van den Bergh, H. (2004). On multi-level modeling of data from repeated measures designs: A tutorial. *Speech Communication*, *43*(1–2), 103–121.

Reed, J. A., Einstein, G., Hahn, E., Hooker, S. P., Gross, V. P., & Kravitz, J. (2010). Examining the impact of integrating physical activity on fluid intelligence and academic performance in an elementary school setting: A preliminary investigation. *Journal of Physical Activity and Health*, *7*, 343–351.

Resaland, G. K., Aadland, E., Moe, V. F., Aadland, K. N., Skrede, T., Stavnsbo, M., Suominen, L., Steene-Johannessen, J., Glosvik, Ø., Andersen, J. R., Kvalheim, O. M., Engelsrud, G., Andersen, L. B., Holme, I. M., Ommundsen, Y., Kriemler, S., van Mechelen, W., McKay, H. A., Ekelund, U., & Anderssen, S. A. (2016). Effects of physical activity on schoolchildren's academic performance: The Active Smarter Kids (ASK) cluster-randomized controlled trial. *Preventive Medicine*, *91*, 322–328. https://doi.org/10.1016/j.ypmed.2016.09.005

Rivera-Batiz, F. L. (1992). Quantitative literacy and the likelihood of employment among young adults in the United States. *The Journal of Human Resources*, *27*(2), 313–328. JSTOR. https://doi.org/10.2307/145737

Rousselle, L., & Noël, M.-P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition*, *102*(3), 361–395. https://doi.org/10.1016/j.cognition.2006.01.005

Rousselle, L., Palmers, E., & Noël, M.-P. (2004). Magnitude comparison in preschoolers: What counts? Influence of perceptual variables. *Journal of Experimental Child Psychology*, *87*(1), 57–84. https://doi.org/10.1016/j.jecp.2003.10.005

Ruiz, J. R., Ortega, F. B., Castillo, R., Martín-Matillas, M., Kwak, L., Vicente-Rodríguez, G., Noriega, J., Tercedor, P., Sjöström, M., & Moreno, L. A. (2010). Physical activity, fitness, weight status, and cognitive performance in adolescents. *The Journal of Pediatrics*, *157*(6), 917-922.e5. https://doi.org/10.1016/j.jpeds.2010.06.026

Schmidt, M., Jäger, K., Egger, F., Roebers, C. M., & Conzelmann, A. (2015). Cognitively engaging chronic physical activity, but not aerobic exercise affects executive functions in primary school children: A group-randomized controlled trial. *Journal of Sport and Exercise Psychology*, *37*(6), 575–591. https://doi.org/10.1123/jsep.2015-0069

Scudder, M. R., Federmeier, K. D., Raine, L. B., Direito, A., Boyd, J. K., & Hillman, C. H. (2014). The association between aerobic fitness and language processing in children: Implications for academic achievement. *Brain and Cognition*, *87*, 140–152.

Shephard, R. J. (1997). Curricular physical activity and academic performance. *Pediatric Exercise Science*, *9*(2), 113–126. https://doi.org/10.1123/pes.9.2.113

Shephard, R. J., Lavallee, H., Volle, M., LaBarre, R., & Beaucage, C. (1994). Academic skills and required physical education: The Trois Rivieres experience. *CAHPER Research Supplement*, *1*(1), 1–12.

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development*, *75*(2), 428–444.

Smets, K., Sasanguie, D., Szücs, D., & Reynvoet, B. (2015). The effect of different methods to construct non-symbolic stimuli in numerosity estimation and comparison. *Journal of Cognitive Psychology*, *27*(3), 310–325. https://doi.org/10.1080/20445911.2014.996568

Soltész, F., Szűcs, D., & Szűcs, L. (2010). Relationships between magnitude representation, counting and memory in 4- to 7-year-old children: A developmental study. *Behavioral and Brain Functions*, *6*(1), 13. https://doi.org/10.1186/1744-9081-6-13

Sowinski, C., LeFevre, J.-A., Skwarchuk, S.-L., Kamawar, D., Bisanz, J., & Smith-Chant, B. (2015). Refining the quantitative pathway of the Pathways to Mathematics model. *Journal of Experimental Child Psychology*, *131*, 73–93.

Suchert, V., Hanewinkel, R., & Isensee, B. (2016). Longitudinal relationships of fitness, physical activity, and weight status with academic achievement in adolescents. *Journal of School Health*, *86*(10), 734–741. https://doi.org/10.1111/josh.12424

Szucs, D., Devine, A., Soltesz, F., Nobes, A., & Gabriel, F. (2013). Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment. *Cortex*, *49*(10), 2674–2688.

Thomas, S., Reading, J., & Shephard, R. J. (1992). Revision of the physical activity readiness questionnaire (PAR-Q). *Canadian Journal of Sport Sciences*, *17*, 338–345.

Tudor-Locke, C., Craig, C. L., Beets, M. W., Belton, S., Cardon, G. M., Duncan, S., Hatano, Y., Lubans, D. R., Olds, T. S., Raustorp, A., Rowe, D. A., Spence, J. C., Tanaka, S., & Blair, S. N. (2011). How many steps/day are enough? For children and adolescents. *International Journal of Behavioral Nutrition and Physical Activity*, *8*(1), 78. https://doi.org/10.1186/1479-5868-8-78

van den Berg, V., Saliasi, E., de Groot, R. H. M., Jolles, J., Chinapaw, M. J. M., & Singh, A. S. (2016). Physical activity in the school setting: Cognitive performance is not affected by three different types of acute exercise. *Frontiers in Psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.00723

Vasold, K. L., Deere, S. J., & Pivarnik, J. M. (2019). Club and intramural sports participation and college student academic success. *Recreational Sports Journal*, *43*(1), 55–66. https://doi.org/10.1177/1558866119840085

Volpert-Esmond, H. I., Merkle, E. C., Levsen, M. P., Ito, T. A., & Bartholow, B. D. (2018). Using trial-level data and multilevel modeling to investigate within-task change in event-related potentials. *Psychophysiology*, *55*(5), e13044.

Voss, M. W., Chaddock, L., Kim, J. S., VanPatter, M., Pontifex, M. B., Raine, L. B., Cohen, N. J., Hillman, C. H., & Kramer, A. F. (2011). Aerobic fitness is associated with greater efficiency of the network underlying cognitive control in preadolescent children. *Neuroscience*, *199*, 166–176. https://doi.org/10.1016/j.neuroscience.2011.10.009

Wang, J. (Jenny), Odic, D., Halberda, J., & Feigenson, L. (2016). Changing the precision of preschoolers' approximate number system representations changes their symbolic math performance. *Journal of Experimental Child Psychology*, *147*, 82–99. https://doi.org/10.1016/j.jecp.2016.03.002

Welk, G. J., Corbin, C. B., & Dale, D. (2000). Measurement issues in the assessment of physical activity in children. *Research Quarterly for Exercise and Sport*, *71*(sup2), 59–73.

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record*, *58*(3), 475–482.

Wilkinson, K. M., Carlin, M., & Jagaroo, V. (2006). Preschoolers' speed of locating a target symbol under different color conditions. *Augmentative and Alternative Communication*, *22*(2), 123–133. https://doi.org/10.1080/07434610500483620

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*(1), B1–B11. https://doi.org/10.1016/S0010-0277(99)00066-9

Xu, F., Spelke, E. S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science*, *8*(1), 88–101.