

Research paper

Physically active learning in preschoolers: Improved self-regulation, comparable quantity estimation

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ABSTRACT

Background: Providing physical activity during the school day may mitigate increasingly sedentary lifestyles among children. Young children may be susceptible to interference during learning and consolidation when performing physical activity concurrently with academic instruction.

Methods: Preschoolers ($N = 72$, mean age 5.1 ± 0.8 years, 50% female) completed a quantity estimation task before, following, and one week after engaging in either a 20-min physically active or sedentary lesson. Physical activity intensity and volume were measured using heart rate and pedometer step counts, respectively. Off-task behavior was recorded prior to and following the lesson.

Results: Children exhibited similar learning and retention, but an added benefit of physically active lessons was a 1900% step increase and a 58% reduction in off-task behavior.

Conclusion: Providing physically active lessons instead of sitting for extended periods of time in early childhood classrooms reduces sedentary behavior and improves self-regulation while not interfering with educational outcomes.

1. Introduction

Providing opportunities to be physically active during the school day may help address children's increasingly sedentary lifestyle, which is associated with increased risk of obesity [1]. Children attend out-of-home childcare or school for a significant number of hours each day from 3 to 18 years of age, making educational contexts particularly suited for promoting health behaviors [2]. Unfortunately, children are least active during classroom lessons [3]. Single bouts of physical activity enhance attention, cognitive control, academic achievement, and classroom behavior [4]. Indeed, physically active lessons have been shown to improve on-task behavior (i.e., behavior directed towards learning activities) and reduce off-task behavior (i.e., behavior directed towards unrelated activities) in children from preschool through fifth grade [5–10]. However, full integration of physical activity with instruction presents a dual-task environment, leading to a trade-off in task prioritization. In particular, young children exhibit greater distractibility in the face of irrelevant stimuli due to underutilization of inhibitory control mechanisms and immature frontal lobes [11]. Thus, young

children are particularly vulnerable to exhibiting cognitive decrements during concurrent cognitive-motor task coordination [12]. In the context of physically active lessons, young children may allocate more cognitive resources to prioritize motor coordination over cognitive demands due to the limited resource nature of attention [13]. Consequently, preschoolers' learning and consolidation of educational outcomes could conceivably be hindered by engaging in physically active lessons. However, educationally-oriented theories (i.e., cognitive entrainment and embodied cognition) offer a contrasting hypothesis. Such theories postulate that integrating gross motor movements with academic problem-solving improves encoding of semantic information [14] even in young children [15–17]. To this end, planned physical activity purposely designed to link to mental representations of educational outcomes may provide leverage for encoding and consolidation of information. Thus, to what extent a single physically active lesson interferes with learning and consolidation of educational outcomes in young children remains an open question and the focus of this study.

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1.1. Isolating the effects of physically active lessons on precise cognitive domains

Recent reviews and meta-analyses generally point towards physically active lessons leading to large improvements in *lesson-time* physical activity and educational outcomes but small improvements in *overall* physical activity and educational outcomes [18,19]. Although extant literature points towards the beneficial effects of physically active lessons for elementary school children, a paucity of evidence exists for preschoolers [18]. However, initial evidence suggests preschoolers exhibit improved retention on assessments of literacy [20] and math [17] following interventions lasting 4 weeks to 6 months. Such gains observed over longer periods of time may be reflective of chronic training adaptations to neural structures and function [21]. Alternatively, developmental changes in cognitive control may result in improved academic achievement even if active lessons interfere with consolidation. Moreover, because these broad assessments are influenced by other higher-order cognitive operations (e.g., attention and memory), improved performance could be observed due to acute improvements or neural adaptations related to chronic training in higher-order cognitive operations even if the intervention interferes with learning. These limitations may explain equivocal findings in the literature. For instance, recent reviews revealed no changes in executive functions, fluid intelligence, immediate recall, and delayed recall following interventions [18,22]. One study even observed lower performance on delayed recall three days postintervention, suggesting the potential for dual-task interference on aspects of memory consolidation [23].

1.2. Physically active lessons present a dual-task environment

Dual-task coordination (i.e., fully integrating motor and cognitive demands) characteristic of physically active lessons may potentially interfere with learning and consolidation. As a result of coordinating cognitive control processes with motor demands, young children focus on the motor domain at the expense of cognition [12]. Consequently, encoding and consolidation of novel information presented during active lessons may be compromised. To this end, physical activity has been observed to interfere with the rate of learning during encoding, thus reducing the consolidation of novel information [24]. However, the potential negative consequences of task interference may be counteracted by acute improvements in attention following physical activity. For instance, acute bouts of physical activity improve attention [4] despite interfering with subsequent retrieval of novel information [25] and not interfering with memory recall 24-hours later [26].

1.3. Embodied cognition and cognitive load perspectives

Despite the potential negative consequences posed by dual-task frameworks of cognition, embodied cognition perspectives suggest that gross motor movements integrated with cognitive processing may facilitate the construction of higher-quality mental representations, thereby enhancing recall and memory [27]. Likewise, cognitive load theory advocates the use of movements in learning complex tasks because such automatized implicit primary knowledge (i.e., movement) requires little effort and can activate non-automatized secondary knowledge requiring explicit instruction (e.g., mathematics) [28]. However, studies observing support for embodied and cognitive load theory perspectives generally occur at light intensities of physical activity and for short durations, thus reducing the potential for dual-task interference. Whereas studies testing load theories of attention have used 16–25 minutes duration physical activity at moderate-to-vigorous intensity [4], those testing embodied cognition/cognitive load theories have used 1–15 minutes duration at light or very-light intensity [18]. Thus, the present study seeks to clarify these equivocal findings by using a physically active condition intended to encourage participation at

moderate-to-vigorous intensity for longer durations than similar prior work in this age group.

1.4. Physically active lessons in young children

Improved attention following single bouts of physical activity [4] and reduced off-task behavior following physically active lessons in school-aged children is widely supported in the literature [5]. However, preschool providers have highlighted the need for classroom strategies that address challenging behaviors, such as off-task behavior, stressing the importance of measuring this outcome in preschoolers. Although a growing body of evidence has begun to examine the effects of physically active lessons in preschool-aged children [10, 15–17,20,29], it is not possible to draw definitive conclusions due to the level of heterogeneity in intervention components and academic-related outcomes assessed in these studies. Moreover, the change in physical activity during the lesson period has been quite small, with 2–5 minutes of physical activity at moderate-to-vigorous intensity being the dose tested [15–17,29]. Measurement studies indicate that preschool children typically exhibit low levels of high intensity activity and high levels of light intensity physical activity in indoor settings. Thus, prior studies only focusing on activity at or above moderate intensity may not observe sufficient change in physical activity during the lesson period to test the effects on cognition and the changes brought about by the long-term interventions (i.e., months or years) may indeed be attributed to chronic neural adaptations or developmental changes [30,31]. Furthermore, the dose-response relationship of physical activity in preschoolers is currently underspecified. Thus, the nomothetic approach to examining the effects of moderate-to-vigorous physical activity on cognition is limited and further examination of other intensities may be preferable in studies with young children. To this end, a recent study conducted by McGowan et al. [10] observed improved on-task behavior following physically active lessons during which children accrued 13.5 minutes at or above light intensity. These findings point towards the potential benefit of physically active lessons at lower intensities for young children's cognition, especially self-regulation.

1.5. Physically active lessons and self-regulation

When entering formal schooling, children face increased expectations to regulate their behavior, focus attention for longer periods of time, work on tasks independently, transition from one activity to the next, and follow more complex rules and directions. The broad construct of self-regulation comprises children's skills in attention, working memory, and inhibitory control [32]. Acquiring strong self-regulation skills during early childhood lays the foundation for developing positive classroom behaviors—such as paying attention, remembering instructions, and staying on task in the face of distractions—supporting better overall academic achievement [33]. In preschool, self-regulation is associated with enhanced literacy, vocabulary, and math outcomes as well as gains in these educational outcomes across the school year [33]. Early self-regulatory skills predict student success well beyond elementary school, with evidence indicating that self-regulation as early as age four predicts the likelihood of obtaining a college degree [34]. Early self-regulatory skills are predictive of self-esteem, superior professional attainment, and better health in childhood and beyond [32, 35–37]. Thus, educational policies highlight the primacy of self-regulation and recognize it as one of the key areas of early child development [38]. Children low in self-regulation may miss out on important learning opportunities in the classroom, yet physically active lessons are a potent means—largely overlooked thus far—to address self-regulation development in early childhood classrooms.

1.6. Physically active lessons improve behavioral self-regulation

Recent work by McGowan et al. [10] demonstrated that children exhibited greater on-task behavior following a single physically active lesson relative to a conventional sedentary lesson. Moreover, no decrements in immediate acquisition of approximate number representations were observed in preschool-aged children. Findings suggest that the dual-task environment presented by physically active lessons does not interfere with acquisition of core academic content in young children. Although findings demonstrated short-term effectiveness of a physically active lesson on attention in preschool-aged children, the study did not assess consolidation of educational outcomes, tempering interpretation and application of the findings. Moreover, the extent to which lasting effects following participation in the physically active lesson conflate the child's participation in the sedentary lesson one-week later is unknown in the McGowan et al. [10] study or in the long-term physical activity lesson studies [see [20] for a review]. Despite counterbalancing and a one-week washout period [10], it is conceivable that if the physically active lesson resulted in better learning and consolidation, this effect may be in force when children participated in the sedentary lesson at the next visit. To address this confound, the present study builds on this previous work by using a randomized between-participants design using a serial stratification approach and assessing consolidation of quantity estimation one week later.

1.7. Assessing behavioral self-regulation in physically active lessons

Although substantial prior work has measured on-task behavior following physically active lessons [5,8,39,40], teachers have highlighted off-task behavior as a significant concern necessitating novel instructional activities to help students reduce such disruptive behavior [41]. Moreover, off-task behavior is an index of behavioral self-regulation and has been shown to be a valid and reliable method for assessing executive functioning in young children [42]. Academic perspectives are increasingly highlighting the quantification of a lack of behavioral self-regulation (i.e., off-task behavior) using event-based approaches (i.e., when the child exhibits the behavior and teacher responds) as preferable to rating scales or time-sampling snapshot methods. For example, the Behavioral Observation of Students in School system distinguishes between motor, verbal, and passive off-task behaviors [43]. This system has been widely adopted in the literature [5, 44] despite a lack of information on the discriminant and convergent validity of this system, making it difficult to judge its utility [42]. Other work has modified this coding system to use it in combination with time-sampling techniques [6,7,39,45,46], which may miss behaviors occurring over longer periods of time. Additionally, the adoption of these classification systems may conflate measurement of off-task behavior, failing to capture when off-task behavior is on-task [18,22,47] (e.g., when a child leaves their seat to ask the teacher a question related to the learning activity).

1.8. The present study

We extend the current understanding of the influence of physically active lessons on cognition in young children in multiple ways. First, we aim to replicate recent findings that the dual-task environment of physically active lessons does not interfere with immediate learning of quantity estimation and improves attentional control in young children [10]. Second, we examine the extent to which the dual-task environment of a single physically active lesson enhances or interferes with consolidation of quantity estimation one week later relative to a sedentary lesson. Third, we examine to what extent a single physically active lesson influences physical activity during the lesson period.

2. Methods

2.1. Participants

Seventy-two young children ($M = 5.1 \pm 0.8$ years, 36 females; 24% nonwhite; see Table 1) participated in this investigation. All procedures were approved by the Institutional Review Board at Michigan State University. Parents/guardians of all participants provided written informed consent and children provided verbal and written assent prior to participation in the study. Children were invited to participate from the surrounding community using university-based parent email lists, social media posts (e.g., Twitter, Facebook, Craigslist), flyers in local community centers and libraries, and handing out flyers at community events for the age group (e.g., safe walk and ride to school, teddy bear picnics, and touch-a-truck events). Additionally, local registered preschools, family-based childcare centers, and school districts were contacted and included a description of the study in their newsletters to families. Caregivers voluntarily contacted the research team to express interest in the study; following a brief phone call or email determining the child's eligibility: 1) age range between 3-5 years of age at time of testing, 2) have general good health, 3) no history of neurological problems and, 4) no significant vision difficulties, the child was enrolled in the study.

2.2. Approximate number system task

To measure acuity of the approximate number system, we used a nonsymbolic magnitude comparison paradigm [10,48]. Children were presented with two schools of spatially separated fish presented simultaneously on a grey background with button-response mappings appearing below the arrays to alleviate working memory demands (see Fig. 3) [49]. Children were instructed to respond as accurately as possible with a button press (6.4 cm wired response buttons Model: Buddy Button; AbleNet, Roseville, MN) indicating which of two schools of fish contained a greater number of fish without actually counting the fish. The number of fish in each school ranged from 2 to 20 and the magnitude of the difference between schools of fish ranged from 0.19 to 0.89 (small school / bigger school) consistent with prior work in this age group [10,50,51]. These characteristics 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).

To ensure that children engaged the approximate number system rather than responded to other stimulus presentation characteristics (e.g., surface area, individual fish size), the size of fish were equally distributed across small (39 pixels), medium (60 pixels), and large (81 pixels) fish and the surface density of the fish was counterbalanced such that all sizes of fish occurred with equal probability within arrays of

Table 1
Participant demographics (mean $\pm$ SD).

Measure	All participants	Physically active	Sedentary
N	72 (36 females)	36 (17 females)	36 (19 females)
Age (years)	5.1 $\pm$ 0.8	5.2 $\pm$ 0.8	5.0 $\pm$ 0.8
Nonwhite (%)	24	25	22
BMI-for-Age Percentile	53.9 $\pm$ 29.1	57.6 $\pm$ 26.4	50.2 $\pm$ 31.5
Months Attended Preschool	19.1 $\pm$ 13.5	23.7 $\pm$ 16.7	13.9 $\pm$ 5.3
At Least One Parent with Postsecondary Education (%)	91.7%	97%	86%

Note. BMI-for-Age Percentile calculated using Centers for Disease Control and Prevention BMI-for-Age Growth Charts in the United States for children and teens aged 2 to 20 years old [73].

greater or less quantities [10,50]. Additionally, 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 [10,52]. Children completed 12 practice trials prior to the administration of 72 experimental trials at each measurement period (grouped into three blocks of 24 trials with a short break between blocks). At each measurement period, a different randomized block of task trials was used to mitigate practice effects. Stimuli were presented on an Inspiron 5447 Dell Inc. laptop using Psychopy, 1.83.4 [53]. Reaction time was quantified using median speed of responding following the onset of the stimulus only for correct trials, ensuring a more representative measure of reaction time in pediatric populations [10]. Response accuracy was quantified as the proportion of correct responses relative to the number of experimental trials administered.

2.3. Off-task behavior

When performing a learning activity in the classroom, it is possible to distinguish between time in which students are focused on the learning task (i.e., on-task behavior) from the remaining time in which students focus on unrelated tasks (i.e., off-task behavior). For instance, a child practicing arithmetic would be considered “on-task” when asking help from the teacher regarding the pedagogical task. In contrast, the child would be considered “off-task” when doodling on a piece of paper, playing with other materials, or talking about things unrelated to the arithmetic activity. Understanding the relationship between these two inverse behaviors is important and off-task behavior is considered a significant concern for teachers [41]. Although prior work has measured on-task behavior following physically active lessons [5,8,39,40], the present study measured *off-task* behavior during performance of the computerized approximate number system task.

Off-task behavior was recorded by a trained observer using an event-based approach: whenever the experimenter (another trained research assistant) provided verbal redirection that was contingent upon the child exhibiting an easily observable off-task behavior during the pretest and posttest computer task. Off-task behavior was defined as verbal or motor behavior that was disruptive to the learning situation (i.e., pressing both buttons at the same time, diverting eye contact away from the laptop screen, talking to the experimenter) [10]. Observers and experimenters were trained research assistants blind to experimental objectives. To mitigate the potential “Hawthorne” effect of having multiple unknown observers during the study, only one trained research assistant coded off-task behavior. Although we did not have multiple observers coding off-task behavior at each time point to determine inter-rater reliability, experimenter redirection did not differ at pretest, $t(132) = 0.3$, $p = 0.8$, $d_s = 0.07$ [95% CI: -0.39 to 0.53] and intraclass correlation coefficient demonstrated moderate reliability between pretest and recall measurements of off-task behavior (ICC = 0.65), suggesting that the definition and coding system were consistently employed and the scale for off-task behavior has sufficient reliability. This approach maintained external validity with classroom practices—in which teachers frequently redirect students for exhibiting similar problem behaviors that are disruptive to learning—and reduced the burden associated with other training-intensive and time-consuming direct observation techniques. Moreover, this approach addresses the shortcomings of prior classification systems susceptible to subjective ratings of on-task behavior, is consistent with teacher concerns in the classroom providing ecological validity, is a valid assessment of young children’s executive functioning and behavioral self-regulation, and isolates disruptive off-task behavior from the types of off-task behavior that may indeed be conducive to the learning environment [10,42]. For instance, speaking to the experimenter about the task was not coded as off-task behavior as it would be helpful to the learning situation if occurring in the context of a classroom. Another strength was that a trained research assistant blind to the

experimental condition coded off-task behavior throughout the entire time the child completed the computerized task. This approach captured behavior throughout longer periods than time-sampling methods that observe behaviors in short 10-second or 30-second increments.

2.4. Physical activity measurement

During the lesson conditions (physically active, sedentary), heart rate (Model: H7; Polar Electro, Kepele, Finland) was continuously recorded as an objective physiological index of intensity, and children wore a uni-axial spring-levered pedometer (Model: Yamax Digi-Walker SW-200; Yamasa Tokei Keiki Co Ltd., Japan) on the right hip to record steps. Pedometers were reset prior to the lesson to ensure steps only taken during the lesson period were measured. At the end of the lesson, a research assistant recorded the total number of steps taken during the lesson prior to the child walking to the desk to complete the computerized quantity estimation task. To maintain consistency with the acute physical activity cognition literature, the physically active lesson was intended to encourage participation at moderate-to-vigorous intensity [4]. 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 $(HR_{\text{average}} - \text{Resting HR}/\text{Age-predicted HR}_{\text{max}} - \text{Resting HR}) \times 100$ 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 $205.8 - (0.685 \times \text{Age})$ from Robergs & Landwehr (2002) and has been shown to closely predict HR_{max} in children ages 7–17 years old [54]. Resting heart rate was quantified as the lowest 1-minute period during non-task related or instructional periods.

2.5. Procedure

Using a randomized between-participants repeated-measures design (see Fig. 1A), participants visited the laboratory on two separate days (mean days apart 7.1 ± 1.3 ; mean time of day difference 28.9 ± 196.3 min). During the first visit following the pretest assessment of approximate number system acuity, children were randomly assigned to either a conventional sedentary instruction or physically active instruction experimental condition using a randomized serial stratification approach accounting for pretest performance, age, and biological sex. Following cessation of the 20-min experimental condition, children completed a posttest assessment of approximate number system acuity. Children returned to the lab one week later to complete a recall assessment to understand how lessons differentially influenced retention of quantity estimation.

2.5.1. Sedentary lesson

Sedentary instruction replicated externally-valid activities previously used to strengthen the acquisition of quantity estimation in preschoolers [10] and aligned with Michigan early learning standards for numeracy [55]. During the sedentary lesson (see Fig. 4), children 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.

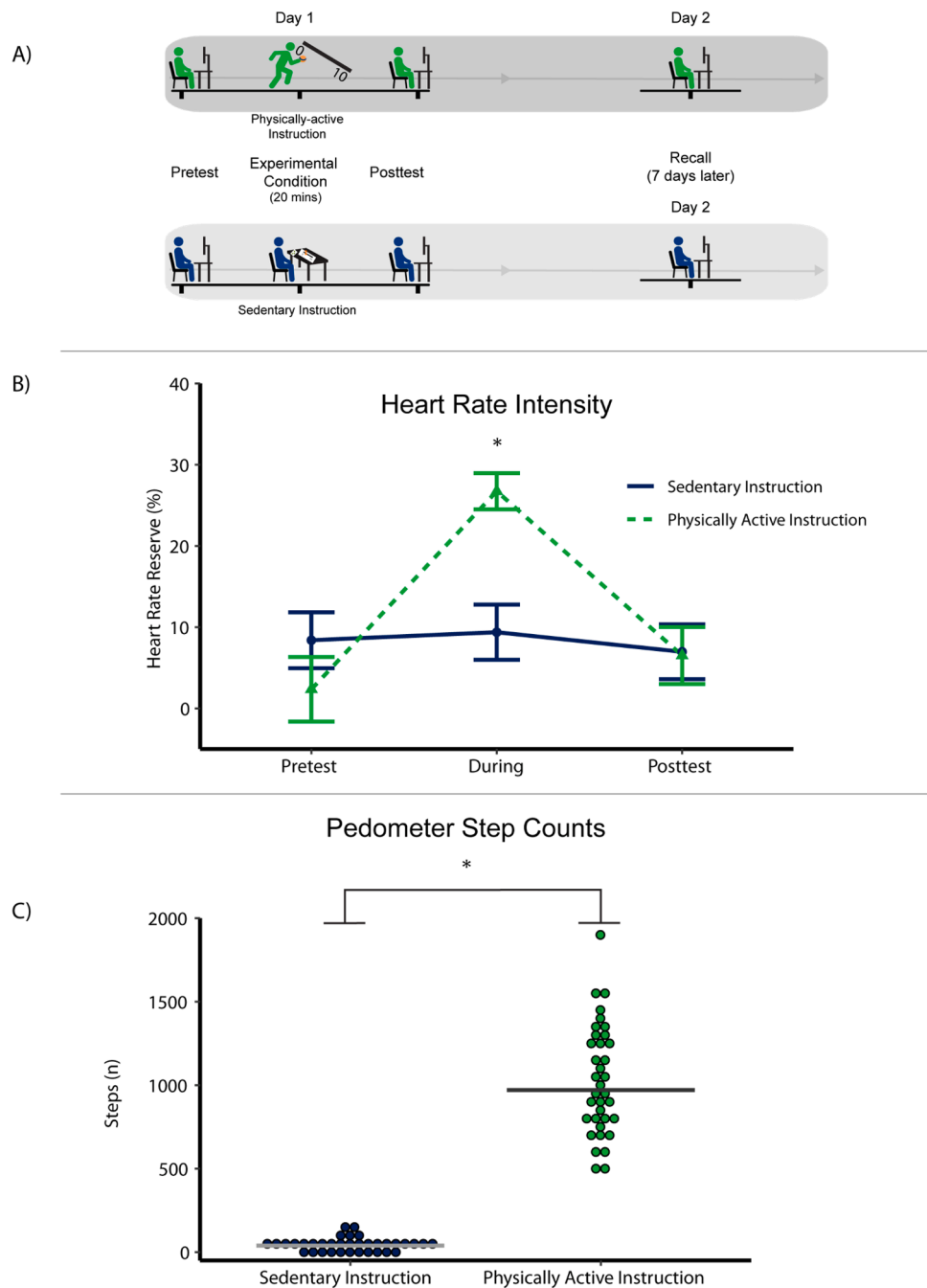


Fig. 1. Illustration of (A) randomized between-subjects design with recall testing 7 days following the first testing session (B) heart rate intensity and (C) pedometer step counts during each experimental condition. Mean step counts for each condition is noted with a grey line for the sedentary instruction and black line for the physically active instruction. * denotes $p < .05$.

2.5.2. Physically active lesson

The physically active lesson used the same activities with the incorporation of physically active components and included Michigan early learning standards of developing body control and gross motor skills (see Fig. 4). 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 bounced and two-hand caught 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.

2.6. Statistical analyses

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 quantity estimation learning was differentially impacted by physically active instruction relative to sedentary instruction, analysis of performance on the approximate number system task was conducted separately for median reaction time, response accuracy, and off-task behavior. Multi-level models for reaction time and response

accuracy tested the fixed effects of *mode* (sedentary instruction, physically active instruction), *time* (pretest, posttest, recall), and *ratio* (very easy, easy, hard). Frequency of experimenter redirection as an index of off-task behavior was analyzed using multilevel models testing the fixed effects of *mode* (sedentary instruction, physically active instruction) and *time* (pretest, posttest, recall). All models included a random intercept for *participant*. All analyses were performed using the lme4 [56], lmerTest [57], and emmeans [58] packages in R version 3.6 [59] 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). Given a sample size of 72 participants and a beta of 0.20 (i.e., 80% power), the present research design theoretically had sufficient sensitivity to detect differences between groups exceeding $d_s = 0.66$ and differences within groups exceeding $d_{rm} = 0.43$ (with a two-sided alpha).

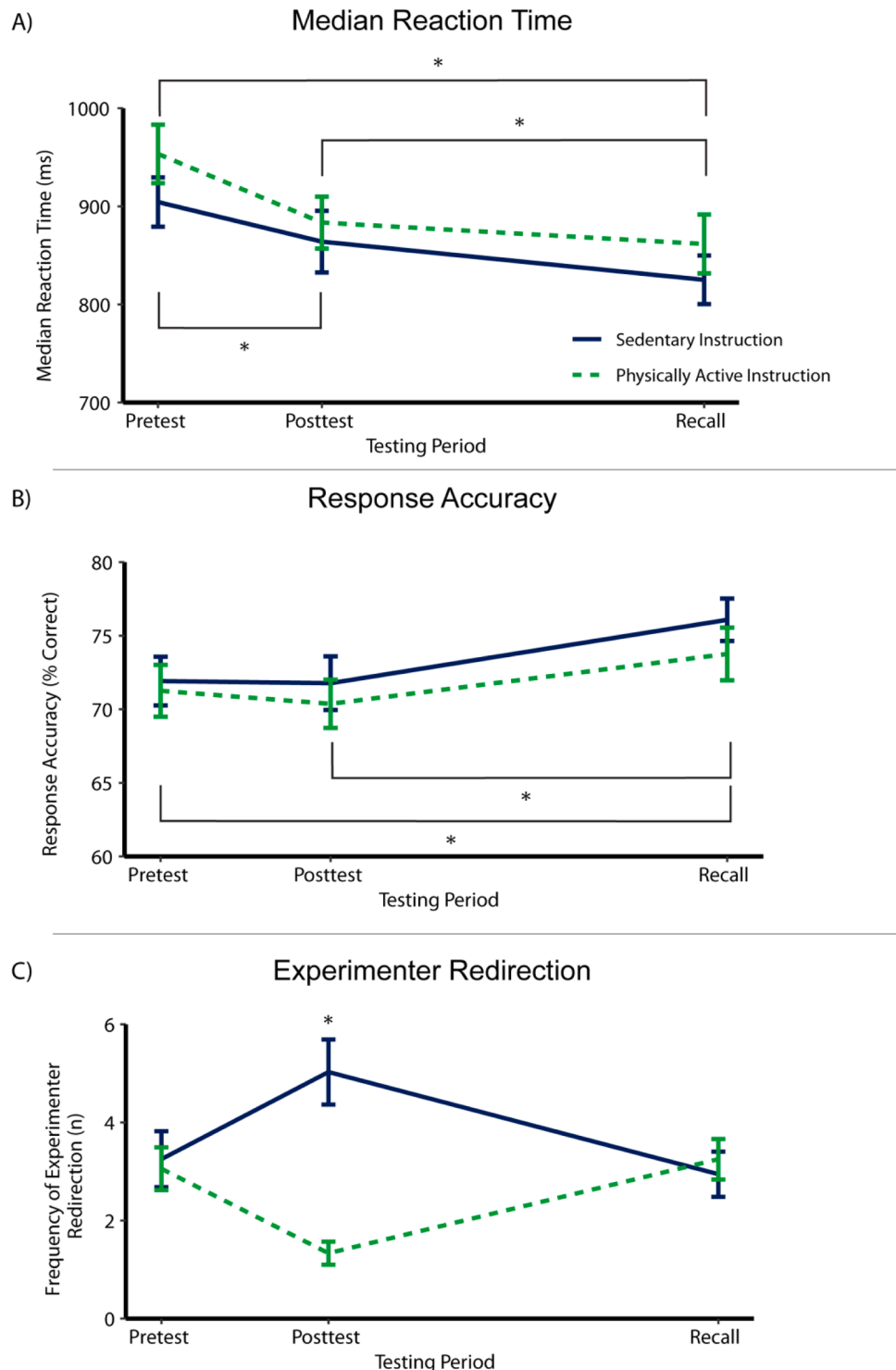


Fig. 2. Illustration of the effects of mode and time for (A) median reaction time, (B) response accuracy, and (C) experimenter redirection. * denotes $p < .05$.

3. Results

3.1. Approximate number system task performance

3.1.1. Reaction time

Similar learning and retention as indexed by shorter median reaction time occurred following both physically active and sedentary instruction, $t's(560) \geq 2.5$, $p's \leq 0.013$, $d_{rm}'s \geq 0.25$ [95% CI: 0.05 to 0.91], see Fig. 2A and Table 3. Further, median reaction time slowed with increased task difficulty, $t's(560) \geq 5.0$, $p's < 0.001$, $d_{rm}'s \geq 0.23$ [95% CI: 0.14 to 1.17]. However, there were no significant differences between conditions, $F's(2,70) \leq 1.5$, $p's \geq 0.22$, $f^2's \leq 0.03$ [95% CI: 0 to 0.11].

3.1.2. Response accuracy

Similar learning and retention as indexed by greater accuracy were observed following both physically active and sedentary instruction, $t's(560) \geq 4.0$, $p's < 0.001$, $d_{rm}'s \geq 0.39$ [95% CI: -0.09 to 0.62], see Fig. 2B and Table 2. Further, response accuracy decreased with increased task difficulty, $t's(560) \geq 36$, $p's < 0.001$, $d_{rm}'s \geq 3.87$ [95% CI: 3.56 to

4.37]. A Time $\times$ Ratio interaction, $F(4, 560) = 2.4$, $p = 0.048$, $f^2 = 0.01$ [95% CI: 0.00 to 0.06] was observed such that immediate deterioration in performance on very easy comparisons was observed, $t(142) = 2.4$, $p = 0.016$, $d_{rm} = 0.19$ [95% CI: 0.03 to 0.34] and gains in retention on easy and hard comparisons were observed one week later, $t's(142) \geq 3.2$, $p's \leq 0.002$, $d_{rm}'s \geq 0.33$ [95% CI: 0.12 to 0.91]. However, no such gains were observed for easy comparisons, $t(142) = 1.7$, $p = 0.1$, $d_{rm} = 0.13$ [95% CI: -0.02 to 0.29] and there were no significant differences between conditions in immediate learning or retention at one week later, $t's(2,70) \leq 2.4$, $p's \geq 0.095$, $f^2's < 0.01$ [95% CI: 0 to 0.04].

3.2. Off-task behavior

Children exhibited reduced off-task behavior immediately following physically active instruction relative to sedentary instruction, $t(132) = 5.4$, $p < 0.001$, $d_s = 1.28$ [95% CI: 0.79 to 1.76] and increased off-task behavior following sedentary instruction, $t's(70) \geq 3.3$, $p's < 0.001$, $d_{rm}'s \geq 0.45$ [95% CI: 0.17 to 1.15], see Fig. 2C and Table 3. Within each mode, a main effect of time was observed such that following physically active instruction, off-task behavior was reduced from pretest (3.1 ± 2.6) to posttest (1.3 ± 1.4) whereas off-task behavior increased following sedentary instruction from pretest (3.2 ± 3.4) to posttest (5.0 ± 4.0), $t's(69) \geq 3.3$, $p's = 0.001$, $d_{rm}'s \geq 0.45$ [95% CI: 0.17 to 1.15]. However, there were no significant differences in off-task behavior between conditions at pretest or one week later, $t's(132) \leq 0.4$, $p's \geq 0.7$, $d_s's \leq 0.11$ [95% CI: -0.36 to 0.57].

3.3. Physical activity

During sedentary instruction ($M = 20.1 \pm 0.4$ min), participants accumulated 2.8 minutes [95% CI: -0.6 to 6.1] of activity at or above a light intensity (at or above 30% of heart rate reserve); mean heart rate = 108.9 bpm [95% CI: 104.4 to 113.4], heart rate reserve = 9.4 % [95% CI: 2.5 to 16.3], see Fig. 1. During physically active instruction ($M = 20.1 \pm 0.5$ min), participants accumulated 9.3 minutes [95% CI: 7.2 to 11.4] minutes of activity at or above a light intensity (at or above 30% of heart rate reserve); mean heart rate = 128.3 bpm [95% CI: 124.3 to 132.3], heart rate reserve = 26.7 % [95% CI: 22.2 to 31.3]. Participants took more steps during physically active instruction (1032.7 ± 327.1) than during sedentary instruction (48.7 ± 37.7), $t = 17.9$, $p < 0.001$, $d_s = 4.2$ [3.4 to 5.1], see Table 2.

4. Discussion

We measured quantity estimation using behavioral performance (i.e., reaction time, response accuracy) on an approximate number system task in addition to off-task behavior before and after children participated in either a physically active lesson or sedentary lesson and at one week later. Children demonstrated similar quantity estimation (as indexed by shorter reaction time and greater accuracy) immediately following both physically active and sedentary lessons but improved attentional control following the physically active lesson—replicating recent findings by McGowan et al. [10] and adding to the dearth of literature in this area for young children [18]. Novel to this study, we showed that following a single physically active lesson, children exhibit similar consolidation of quantity estimation one week later relative to a sedentary lesson (as evidenced by shortened reaction time and greater accuracy). Further, we demonstrate a single physically active lesson reduced sedentary time relative to a seated lesson in young children. During a 20-min physically active lesson, children accrued 984 ± 10.2 additional steps relative to sedentary instruction (see Fig. 1B) and 9 minutes of physical activity at low-to-moderate intensity.

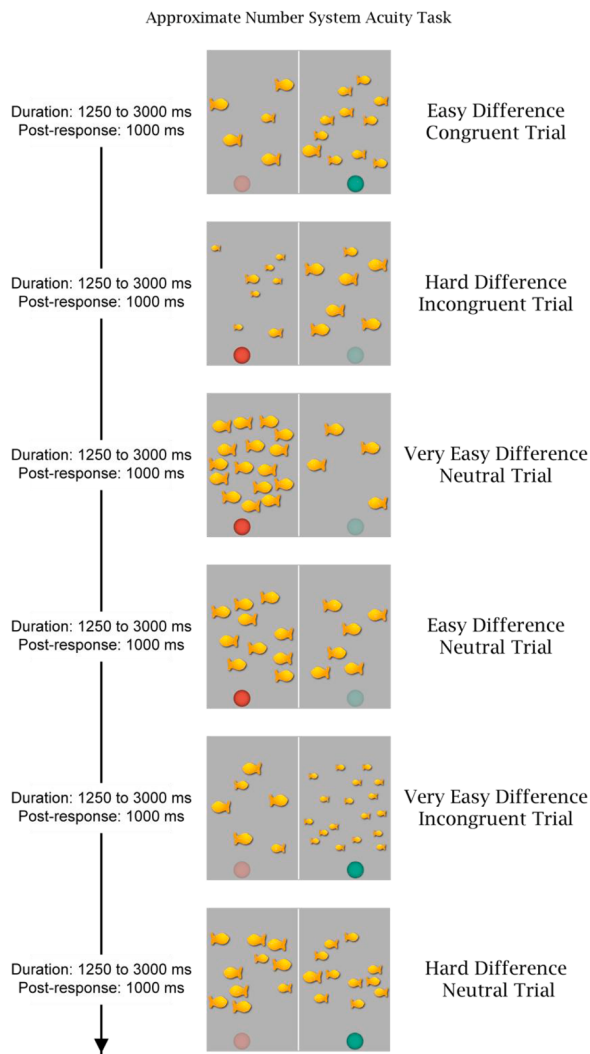


Fig. 3. Illustration of the computerized approximate number system task. For reference, the correct response to each stimulus is depicted. Comparisons were equally distributed across very easy difference ratios (≤ 0.30), easy difference ratios (0.33–0.5), and hard difference ratios (≥ 0.67) where the ratio represents smaller quantity/larger quantity and across congruent (greater surface density for the greater quantity), incongruent (greater surface density for the smaller quantity), and neutral (matching surface density between quantities) trials.

Sedentary Lesson



Number Line Estimation



Less Than/Greater Than



Counting

Physically Active Lesson

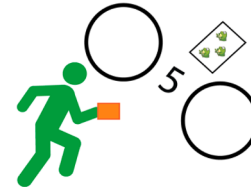
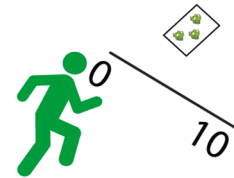


Fig. 4. Illustration of the activities included in the sedentary and physically active lesson. The number line estimation activity required children place a quantity on a number line from 1 to 10. The less than/greater than activity required children indicate whether a quantity was less than or greater than five. The counting activity required children count the number of items in a presented quantity.

4.1. Benefits of physically active lessons over time

Children demonstrated an immediate deterioration in performance on very easy comparisons in the approximate number system task and retention of learning one week later for only more difficult task conditions (i.e., easy and hard), which may appear initially surprising. However, theories of physical exertion and embodied cognition may offer explanations for these findings. Physical exertion theories suggest that integrating physical activity with learning results in greater attentional requirements and physiological exertion, depleting attentional resources and leading to physiological fatigue, thus leading to deterioration in cognitive performance [13]. In addition to learning quantity estimation and early numeracy skills, some children were also learning gross motor skills for the first time, such as bouncing a ball or tossing a bean bag. The load theory of attention [13,60] can be extended to suggest that when cognitive and energetic demands are too low, students may appear to be more distractible given the greater perceptual stimuli available in this context and the involuntary nature of perception. Thus, children likely exhibited decrements in performance on the easiest task condition perhaps due to a combination of physiological fatigue and insufficient load for attention to be engaged optimally.

Further, embodied cognition theory supports the retention of the difficult task conditions one week later. The use of bodily movements during the learning process helps to transform abstract information into concrete tangible concepts, creating a richer trace in long-term memory whereby the process of retrieval is improved, resulting in better recall one week later [27,61]. In this way, children learned quantity estimation and ordinality concepts encoded with the movements, and the motor image created was linked to underlying mental approximate number representations, resulting in better consolidation following the physically active lesson and retention one week later. These findings provide support for using physically active lessons in the preschool classroom to support the development of early numeracy skills.

4.2. Physically active lessons reduce off-task behavior

Novel to the present study, children exhibited a reduction in off-task behavior immediately following participation in a single physically active lesson. Despite using a similar intervention and task, McGowan et al. [10] did not observe such a finding following false discovery rate control, which may be partially explained by the difference in study design used (within-subject repeated measures vs. between-subject repeated measures). How long the after-effects of a single bout of physical activity on cognition last remains an open question, and it may be that the lasting effects following participation in a single physically active lesson may be in force when young children participate in within-participant designs testing a second experimental condition one week later. Furthermore, the dose-response of physical activity on cognition, especially in preschoolers, remains unknown. Thus, future work assessing the effects of educational interventions may opt to use between-participant designs or use within-participant designs with a longer washout period (e.g., 2 weeks) for young children to mitigate this potential confound.

4.3. Physically active lessons counteract dual-task interference

Children demonstrated immediate learning and retention one week later, counteracting the concerns of dual-task interference raised by Schaefer et al. [12]. These findings are in contrast to load theories of attention suggesting young children allocate more resources to motor demands, leading to cognitive decrements [13,60]. This evidence also diverges from the notion that young children are more vulnerable to cognitive task interference due to less developed cognitive control operations [11,12]. However, the low intensity of the lesson period may have reduced the potential for cognitive task interference. Alternatively, lesson duration (9.3 minutes at or above light intensity) exceeded the dose in other studies in this population [15–17,29,62] and aligns with the optimal dose suggested to improve attention and inhibitory control in older populations [4,63]. Thus, the facilitative effects of the lesson on attention and inhibitory control may have counteracted the potential

Table 2

Mean ($\pm$ SD) values for experimental session characteristics.

Measure	Physically active	Sedentary	<i>t</i>	<i>p</i>	<i>d_s</i> [95% CI]
Pretest assessment					
Heart rate (bpm)	104.3 $\pm$ 15.9	106.3 $\pm$ 17.5	0.5	0.6	0.1 [-0.4 to 0.6]
Heart rate reserve (%)	2.4 $\pm$ 23.9	8.4 $\pm$ 20.4	1.1	0.3	0.3 [-0.2 to 0.7]
Time preceding experimental condition (min)	10.4 $\pm$ 4.3	11.8 $\pm$ 12.0	0.4	0.5	0.2 [-0.3 to 0.6]
Experimental condition					
Heart rate (bpm)	128.3 $\pm$ 11.7	108.9 $\pm$ 13.0	6.6	0.001*	1.6 [1.0 to 2.1]
Heart rate reserve (%)	26.7 $\pm$ 13.4	9.4 $\pm$ 20.1	4.3	0.001*	1.0 [0.5 to 1.5]
Percent of heart rate max	63.4 $\pm$ 5.8	53.8 $\pm$ 6.4	6.6	0.001*	1.6 [1.0 to 2.1]
Steps (n)	1032.7 $\pm$ 327.1	48.7 $\pm$ 37.7	17.9	0.001*	4.2 [3.4 to 5.1]
Session Duration (min)	20.1 $\pm$ 0.5	20.1 $\pm$ 0.4	0.5	0.6	0.1 [-0.4 to 0.6]
Days Between Posttest and Recall	7.1 $\pm$ 1.4	7.1 $\pm$ 1.1	0.0	1	0.0 [-0.5 to 0.5]
Post-test assessment					
Heart rate (bpm)	108.9 $\pm$ 13.2	105.6 $\pm$ 15.1			
1.0	0.3	0.2 [-0.2 to 0.7]			
Heart rate reserve (%)	6.5 $\pm$ 20.8	7.0 $\pm$ 20.0	0.1	0.9	0.02 [-0.5 to 0.5]
Time following experimental condition (min)	2.7 $\pm$ 2.7	2.5 $\pm$ 2.4	0.3	0.8	0.1 [-0.4 to 0.5]

Note. The *t*-tests reflect the differences between physically active and sedentary instruction 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 $205.8 - (0.685 \times \text{Age})$ from Robergs & Landwehr (2002). [74] Heart rate and pedometer step counts were unreported for $n = 1$ sedentary instruction participant for refusal to wear the devices.

negative effects of the dual-task environment [12]. If the dual-task environment interfered with learning and retention of numeracy, we would expect children to have demonstrated immediate deterioration in performance following the lesson period and further deterioration one week later. Because the optimal dose of physical activity to induce cognitive benefits remains unknown, we cannot rule out that the duration and intensity of physical activity in the present study was insufficient to accrue cognitive benefits.

Although physically active lessons did not increase acquisition and retention of quantity estimation beyond sedentary lessons, the effects observed in the present study are still noteworthy. That is, moderate effect sizes of d 's ≥ 0.5 were observed following physically active instruction. However, based on educational intervention standards, which observe average effect sizes following education interventions of $d = 0.27$ [64], the effect of physically active lessons was quite large [64]. In contrast to the extant evidence that young children are particularly susceptible to cognitive decrements while concurrently performing motor tasks [12] and single bouts of physical activity may hinder subsequent retrieval of novel information [25], findings from the present study suggest that physically active lessons do not interfere with encoding and consolidation of educational outcomes. This finding aligns with a burgeoning body of literature demonstrating enhancements in attention following acute physical activity [4]. These findings also suggest that academic achievement gains observed following long-term implementation of physically active lessons may occur due to transient changes in attentional control following the lesson or neural adaptations related to chronic training or development.

Table 3

Statistical summary of post-hoc comparisons at each time point for each mode.

	Physically active	Sedentary	<i>t</i>	<i>p</i>	<i>d_m</i> [95% CI]
Median reaction time (ms)					
Pretest	983.7 $\pm$ 208.6	938.0 $\pm$ 204.1	1.2	0.2	0.3 [-0.2 to 0.7]
Posttest	906.0 $\pm$ 199.0	896.8 $\pm$ 230.7	0.2	0.8	0.1 [-0.4 to 0.5]
Recall	894.4 $\pm$ 246.4	842.5 $\pm$ 165.2	1.3	0.2	0.3 [-0.2 to 0.8]
Response accuracy (% correct)					
Pretest	71.3 $\pm$ 19.0	71.9 $\pm$ 20.0	0.3	0.8	0.1 [-0.4 to 0.5]
Posttest	70.4 $\pm$ 19.2	71.8 $\pm$ 19.6	0.6	0.6	0.1 [-0.3 to 0.6]
Recall	73.7 $\pm$ 18.1	76.1 $\pm$ 16.9	1.0	0.3	0.2 [-0.2 to 0.7]
Experimenter redirection (n)					
Pretest	3.1 $\pm$ 2.6	3.2 $\pm$ 3.4	0.3	0.8	0.1 [-0.4 to 0.5]
Posttest	1.3 $\pm$ 1.4	5.0 $\pm$ 4.0	5.4	0.001*	1.3 [0.8 to 1.8]
Recall	3.2 $\pm$ 2.5	2.9 $\pm$ 2.8	0.4	0.7	0.1 [-0.4 to 0.6]

Note. The *t*-tests reflect the differences between experimental conditions for each dependent variable at each time point. * denotes the *t*-test was significant at $p < 0.05$.

4.4. Physically active lessons improve self-regulation

Physically active lessons were observed to offer potential benefits for classroom behavior: children exhibited reduced off-task behavior immediately following physically active lessons whereas greater off-task behavior was observed following sedentary lessons. Therefore, physically active lessons may be a viable strategy for addressing challenging behaviors in preschoolers. The present findings provide preliminary evidence to suggest that implementing physically active lessons has the potential to support young children's self-regulation, thereby promoting children to focus on learning opportunities as well as reducing frustration and escalation to more severe challenging behaviors during learning. Preschool providers could offer physically active lessons throughout the day as a way to promote engagement and to reduce the need for teachers to redirect disruptive behavior, thus, reducing job-related stress [65]. Particularly, physically active lessons may help those children with low self-regulation reduce challenging behaviors (e.g., aggression, noncompliance, tantrums). Thus, such approaches have the potential to positively influence both teachers' and students' mental health and wellbeing and retain children in early learning programming.

The present study offers support for using ecologically-valid approaches to quantifying behavioral self-regulation. We classified off-task behavior in young children using an easily observable and strictly-defined approach that determines the frequency with which children go off-task—directly engaging with other materials or people not related to the present learning task. This approach demonstrated sufficient reliability (ICC = 0.65), suggesting the definition and coding system were consistently employed and the approach has acceptable reliability. Furthermore, this approach addresses the shortcomings of prior classification systems (e.g., lack of support for validity/reliability, susceptible to subjectivity, and conflation of on-task/off-task behavior), is consistent with teacher concerns in the classroom [10,42], and is less time-intensive than other methods.

4.5. Active learning reduces sedentary behavior

These results support that a brief physically active lesson substantively increased steps relative to sedentary instruction consistent with similar active math lessons in school-aged children, which observed increases of about 700 steps [66] and 1800 steps [67] over 30-90 min lessons. These additional steps account for approximately 10% of the daily recommended step count [68] and represent a 1900% step increase relative to sedentary lessons. Preschoolers spent almost 50% of the lesson at or above light intensity physical activity; thus, the brief physically active lesson resulted in more steps and a greater proportion of the lesson spent at a higher intensity of physical activity relative to similar studies in preschoolers [15–17]. In the context of the World Health Organization's guidelines on physical activity for children under age 5 [69], the physically active lesson contributed to children meeting 15% of the daily recommended 60 minutes of moderate-to-vigorous physical activity in a short 20-minute lesson period. Recent work has demonstrated that meeting this recommendation is associated with desirable health indicators in preschool-aged children, including decreased risk of being overweight or obese [70], improved bone and skeletal health [71], and superior gross motor skill development [72]. Thus, integrating physical activity with educational content can reduce sedentary behavior during classroom lessons and support positive physical health outcomes.

4.6. Limitations and future directions

The strengths of this study included the randomized between-participants design controlling for performance level, the use of low-equipment lessons that align with early learning standards, and the use of an externally valid control group and easily observable off-task behavior coding approach. These features make this laboratory-based study easily translatable to a school-based environment in future research. The study used an objective index of approximate number system acuity to isolate the influence of the lessons on quantity estimation, unlike other studies using teacher-designed or standardized achievement tests that are influenced by other cognitive processes. Objective assessment of physical activity dose and intensity were estimated using pedometer step counts and heart rate; given the paucity of such measures in preschoolers, these data provide preliminary estimates for determining intensity in future studies. The limitations of the study were the use of a single coder for off-task behavior, rendering the inter-rater reliability of behavior ratings indeterminable, and the lack of monitoring habitual physical activity outside the lesson period to determine whether the lessons contributed to significant change in daily physical activity behaviors. Future studies should address these limitations and investigate the influence of physically active lessons on changes in more severe disruptive behaviors across longer periods of time and developmental trajectories of academic success, especially for children at greater risk of expulsion (i.e., male children of color and children from low-income backgrounds).

5. Conclusion

Findings indicate that the dual-task environment presented by a single physically active lesson at low-to-moderate intensity immediately reduces disruptive behavior, does not interfere with encoding or consolidation of quantity estimation up to one week later, and reduces sedentary behavior. This innovative study contributes to the dearth of research examining the impact of physical activity on cognition during early childhood. Implementing physically active instruction in early childcare settings may address the growing trend of sedentary behavior by contributing to attainment of daily physical activity recommendations while enhancing self-regulation—serving as a viable strategy to prevent children from missing out on learning opportunities offered in early childhood classrooms.

5.1. Practical implications

- Physically active lessons do not interfere with encoding or consolidation of quantity estimation.
- Additional movement during 20-min physically active lessons provides a useful contribution to daily physical activity recommendations.
- Physically active lessons reduce off-task behaviors, having the potential to improve young children's self-regulation and reduce challenging behaviors.

Ethical approval

The study described herein was conducted with prior approval of the Institutional Review Board at Michigan State University. All participants and/or their legal guardians signed an Informed Assent/Consent form prior to participation in the study and their rights were protected.

CRediT authorship contribution statement

Amanda L. McGowan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Hope K. Gerde:** Funding acquisition, Writing – review & editing, Supervision. **Karin A. Pfeiffer:** Writing – review & editing, Supervision. **Matthew B. Pontifex:** Methodology, Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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