



# Brief Pre-Class Physical Exercise Selectively Enhances Mathematics-Specific Inhibitory Control: A Cluster-Randomized Trial in Authentic Classrooms

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## Abstract

Brief pre-class physical exercise may enhance executive function (EF) processes proximal to mathematics learning. However, the effect is likely dependent on the alignment between the physical exercise and subsequent instructional demands. We tested a dual-process framework in authentic classrooms, predicting selective gains in mathematics-specific inhibitory control rather than broad executive function. Using a cluster-randomized trial, four Grade-5 classes ( $N=182$  students) were assigned to mentally passive sedentary behavior (e.g., video watching), mentally active sedentary behavior (e.g., numeracy practice), 5-minute physical exercise, or 10-minute physical exercise. EF outcomes were assessed at baseline, immediately post-intervention, and after the mathematics instruction using a domain-general flanker task and a mathematics-specific negative priming task. Both physical exercise groups outperformed mentally passive sedentary behavior on the inverse efficiency score of the negative priming task at post-instruction, with no differences between 5- and 10-minute physical exercise, and no consistent advantages on the flanker interference performance. These results support a task–context alignment mechanism in which brief physical exercise may prime motivational/alerting states that translate into improved inhibition when followed by domain-relevant instruction. Short, pre-class physical exercise routines can be integrated without displacing teaching time and may enhance readiness for mathematics learning by selectively improving mathematics-specific inhibitory control. We discuss implementation parameters for classroom use and implications for theory on how physical exercise influences psychological processes central to learning.

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**Keywords** Domain-specific executive function · Physical activity · Classroom-based intervention · School children · Classroom learning · Arousal

## Introduction

The early development and improvement of mathematics skills is foundational to promoting future academic achievement and occupational success (OECD, 2010; Silver & Libertus, 2022; Watts et al., 2014). Despite the acknowledged importance of early mathematics proficiency, sizable inter-individual variability persists in students' learning efficiency and academic performance in real-world settings (Gjicali & Lipnevich, 2021). Recent research attributed a substantial portion of this inter-individual variability to differences in students' development of executive function (EF)—a set of higher-order cognitive processes including the core components of inhibitory control, working memory, and cognitive flexibility (Cragg et al., 2017; Diamond, 2013). In particular, inhibitory control—a multifaceted function that encompasses the deliberate suppression of task-irrelevant thoughts, distracting information, or inappropriate behaviors—plays an especially critical role in mathematics learning (Diamond, 2013). Indeed, effective engagement in mathematical tasks frequently requires students to not only inhibit interference from irrelevant numerical or misleading problem-solving strategies (e.g., heuristics) but also resist intrusion from non-mathematical distractions (e.g., classroom noise) that may compete for cognitive resources (De Keersmaecker et al., 2023; Jiang et al., 2020). Consequently, strengthening inhibitory control has become a key target for interventions aiming to enhance academic learning.

Accumulating evidence supports the positive effects of physical activity, including planned and structured forms referred to as physical exercise<sup>1</sup> (Caspersen et al., 1985), on cognitive performance (including EF), and that such benefits are observed following single bouts (Chang et al., 2025; Garrett et al., 2024; Ishihara et al., 2021; Kao et al., 2022) and after long-term training (Hillman et al., 2019; Mavilidi et al., 2025; Singh et al., 2019). The transient effects of single bouts of exercise (i.e., acute physical exercise) may be especially relevant for the school context physically wherein PA have the potential to facilitate the learning of academic subjects by supporting EF efficiency and effectiveness. Indeed, a recent meta-analysis synthesizing 383 interventional studies ( $N=18,347$ ) indicated that acute physical exercise significantly improved EF ( $SMD=0.36$ ), with benefits observed across age groups and different exercise types (Chang et al., 2025). However, it still remains inconsistent in children, with some studies suggesting transient academic benefits in domains such as mathematics and language (Muntaner-Mas et al., 2024; Yangüez et al., 2024), whereas others report null or mixed findings (Dixon et al., 2025). Notably, the equivocal findings in the area might relate to the heterogeneity of study designs including the nature of

<sup>1</sup> While the classical definition of exercise by Caspersen et al. (1985) emphasizes improvements in physical fitness, more recent conceptual work (Herold et al., 2021) has expanded the term to include planned and structured activity purposive to maintain or improve outcomes in other domains, such as cognition (see also (Anzeneder et al., 2023)).

the cognitive assessment (e.g., types of the inhibitory control task that typically refers to domain-general and domain-specific measures), control condition (e.g., sedentary behavior type), and quantitative characteristics of the single-bout exercise intervention (e.g., time and intensity).

The majority of work examining the impact of PA on EF have been also conducted in controlled laboratory settings (Pontifex et al., 2019). Against this background, researchers have recently started conducting exercise-cognition studies in simulated classroom environments (Feter et al., 2024). For example, Yu et al. (2024) demonstrated that in university students, a 15-minute moderate- or vigorous-intensity PA break during prolonged sitting acutely improved EF (i.e., inhibitory control) and enhanced frontal cortical activation in a simulated classroom schedule. Thus, when purposefully integrated into the school day, brief physical exercise may serve to enhance students' on-task behavior and promote learning efficiency. It is, however, important to recognize that within the limited time available between lessons, the implementation of in-class physical exercise breaks may entail transitional and logistical challenges (e.g., organizing students efficiently, accommodating other break-time needs) that may constrain their feasibility in everyday school practice (Herold et al., 2025; Muntaner-Mas et al., 2024; Zhang et al., 2025). In response to these limitations, "exercise priming" - wherein a brief bout of physical exercise is scheduled immediately before formal classroom instruction - has emerged as a promising alternative (Sivaramakrishnan et al., 2022). This approach, sometimes referred to as "zero-hour physical exercise," aims to leverage the priming effects of acute physical exercise to optimize cognitive function for learning, while minimizing interference with instructional time (Marashian & Khorami, 2012; Phillips, 2017). Building on robust evidence that acute physical exercise can facilitate subsequent cognitive performance for a transient duration (Pontifex et al., 2019), strategically placing physical exercise immediately before instructional time may improve learning efficiency during subsequent in-class time (Zhu et al., 2025). In line with this notion, a systematic review has shown that classroom-based physical exercise interventions consistently improve students' on-task behavior and highlight their potential to create more favorable conditions for learning (Ruhland & Lange, 2021). That said, empirical evidence remains limited regarding whether acute pre-class physical exercise effectively enhances cognitive (i.e., inhibitory control) and academic performance (e.g., classroom mathematics performance), and how long such benefits may last in authentic classroom contexts from primary to higher education (Castelli & Ward, 2012; Ruhland & Lange, 2021; Zhu et al., 2025).

In many school systems, the time immediately before formal instruction is devoted to sitting activities such as morning reading or mathematics practice (often being referred to sedentary behaviors) (Tremblay et al., 2017) and may themselves serve to cognitively prime students for subsequent learning. Notably, such sitting activities are not homogeneous; their cognitive and neural consequences depend strongly on the type of activity performed (Hallgren et al., 2020; Wang et al., 2025; Zhang et al., 2025). In particular, mentally passive sedentary behaviors (e.g., television viewing) have been associated with poorer cognitive outcomes, whereas mentally active sedentary behaviors (e.g., reading or doing mathematics practice) have been linked to more favorable psychological and neural profiles (Zhang et al., 2025; Zou et al.,

2024). Indeed, recent neuroimaging evidence indicates mentally active sedentary behaviors are associated with increased EF network activity and connectivity compared to their passive sedentary behavior counterparts (Zhang et al., 2025; Zou et al., 2024). This suggests that engaging in mentally active sedentary behaviors, such as pre-class reading or mathematics practice, may prime students for learning. Accordingly, mentally active and passive sedentary behaviors can provide a meaningful and ecologically valid comparison for evaluating the added value of pre-class physical exercise priming in enhancing inhibitory control and mathematics performance (Zhu et al., 2025; Zou et al., 2024).

In this regard, a critical nuance that has often been overlooked is that domain-general and domain-specific EF (the latter one refers to cognitive processes closely tailored to the content and cognitive demands of specific academic subjects such as mathematics-specific inhibitory control), contribute differently to classroom learning (Zhang et al., 2025). Specifically, domain-general EF tasks may not fully predict specific academic performance, whereas domain-specific tasks better capture subject-aligned cognitive demands (Zhang et al., 2025). Previous studies have mainly assessed the effects of physical exercise using domain-general EF tasks (e.g., classic Stroop or Flanker paradigms) that measure inhibitory control processes in a context-independent manner (de Greeff et al., 2018; Miyake et al., 2000). Although these paradigms are scientifically robust, they often appear disconnected from the everyday experiences of teachers and students, making it difficult to translate observed improvements into classroom-relevant outcomes. By contrast, domain-specific EF (Zhang et al., 2025) may provide complementary insights into the cognitive benefits associated with physical exercise interventions leveraged in educational settings (Cragg & Gilmore, 2014; Jiang et al., 2020).

In a recent theoretical review, we proposed a dual-process framework asserting that physical exercise interventions may simultaneously enhance both domain-general and domain-specific EF via parallel yet interdependent cognitive pathways (Zhang et al., 2025). According to this framework, domain-general EF are proposed to enhance classroom learning through generalized improvements in inhibitory control, and domain-specific EF benefits cognitive processes more directly related to the academic content (Zhang et al., 2025). Importantly, investigating the immediate effects of single bouts of physical exercise provide a useful opportunity to examine candidate mechanisms that can explain the benefits of exercise on cognition, although caution is needed for generalization to those as drivers of long-term benefits (Hillman et al., 2011; Pontifex et al., 2019). By measuring both domain-general and domain-specific EF, one can directly test whether physical exercise produces broader, and/or narrower benefits for specific cognitive skills relevant for classroom learning. Thus, this distinction is essential for understanding potential mechanisms for physical exercise-associated cognitive and academic improvements, and for developing educational practices that are effective and efficient (Wilkey, 2023).

The present study adopted a cluster-randomized controlled trial to systematically compare the immediate and delayed effects of different acute pre-class activities on both domain-general and domain-specific (i.e., mathematics) inhibitory control in primary school students, including two experimental conditions (i.e., 5-minute and 10-minute physical exercise) and two forms of sedentary behavior (i.e., math prac-

tice as a mentally active sitting versus watching video as a mentally passive sitting). The use of 5-minute versus 10-minute physical exercise provided a basis to probe a potential dose–response effects of pre-class acute exercise on EF (i.e., sufficient arousal with minimal fatigue), while ensuring that the intervention remains feasible for school settings. To ensure ecological validity, the interventions were delivered in the school setting before regular morning instruction (i.e., mathematics lesson). More specifically, the primary aim of this study was to investigate whether these pre-class activities differentially influenced domain-general and domain-specific EF, assessed both immediately after the intervention and following the subsequent mathematics lesson. We hypothesized that acute ‘exercise priming’ would outperform both conditions with sedentary behavior, particularly mentally passive sitting concerning both EF outcomes, and would elicit a larger magnitude benefit to mentally active sitting concerning the mathematics-specific EF outcome. These results have the potential to inform the design of evidence-based pre-class programs that not only optimize cognitive engagement but also align directly with academic demands and contribute to the development of more effective and contextually relevant educational interventions.

## Methods

### Participants

The research team collaborated with an elementary school in Shenzhen, China. Four of twelve fifth-grade classes were randomly assigned to the four experimental conditions using a computer-generated randomization procedure in Microsoft Excel 2019 (Microsoft Corporation, Redmond, Washington, USA). Randomization was conducted at the class level to preserve natural classroom structures. Allocation was concealed from teachers until three days prior to intervention delivery to minimize preparatory differences between classes. Because all classes were drawn from the same grade level within a single school, no further stratification was performed. The process of participant screening, eligibility determination, and inclusion in the study is illustrated in Fig. 1. Nine students were excluded from the study because they were absent when the cardiorespiratory fitness assessments were conducted. The experiment was conducted between May 9, 2025 and June 5, 2025, and the Ethics Committee of the School of Shenzhen University (SZU\_PSY\_2024\_171) approved the study protocol, which complied with the ethical principles of the latest version of the Declaration of Helsinki.

Prior to beginning the experiment, the research team explained the purpose of the experiment, as well as the possible dangers and the safety measures needed during the experiment to the math teachers of the four participating classes. This information, including the potential benefits and risks, was also provided to the students and their parents. The participation was voluntary, and the legal guardian of every participating child was required to sign a written informed consent before their child was included in this study.

Based on physical examinations and self-reports, all participants had no history of cardiovascular, metabolic, gastrointestinal, neurological, or psychiatric disorders

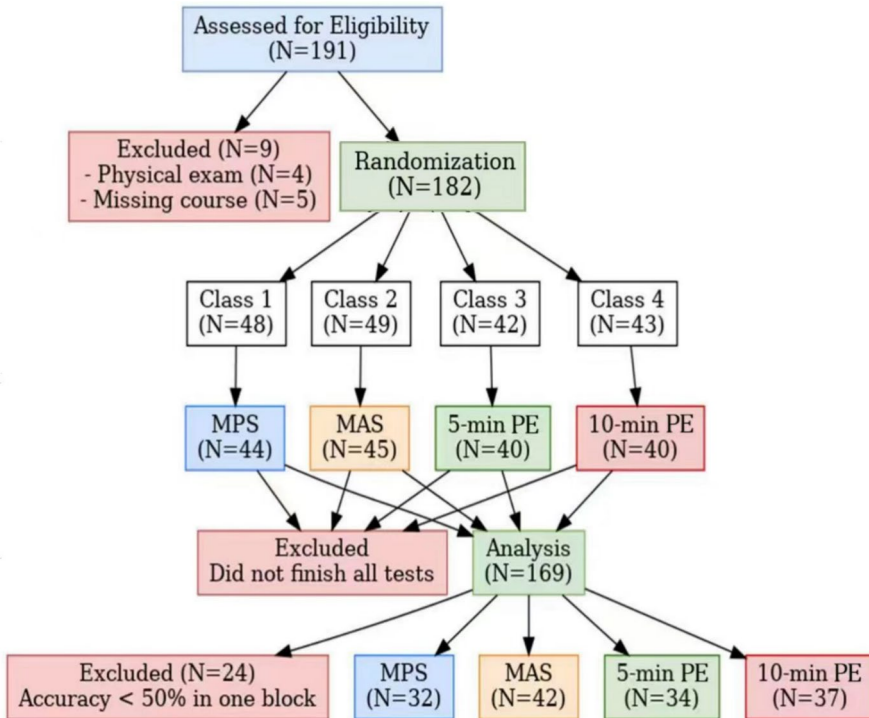


**Fig. 1** Flow of Participants. MPS=Mentally Passive Sitting, MAS=Mentally Active Sitting, PE=Physical Exercise

or conditions requiring medical attention. Participating students were right-handed, had normal or corrected-to-normal visual acuity, and normal color vision. The school administrator had shared basic information of participating students on physical fitness tests, and we selected students who had previously completed cardiorespiratory fitness tests to ensure that they could successfully perform an acute 5- or 10-minute pre-class physical exercise bout.

## Cognitive Paradigms

### Flanker Task: Domain-General Inhibition

The task was adapted from Simmering et al. (2022) and presented in PsychoPy (v2021.1; Peirce, 2007, 2009; Peirce et al., 2019). Each trial began with a central fixation cross (500 ms). Subsequently, a target stimulus (i.e., left- or rightward facing picture of a fish) was presented at the fixation location and on congruent trials the target was flanked by four fish (two on each side) that faced the same (i.e., congruent trial) or opposite (i.e., incongruent trial) direction as the target stimulus. On neutral trials, the central target fish was presented without surrounding flankers. The target and flanking stimuli subtended  $\sim 1.9^\circ$  of visual angle with  $\sim 0.25^\circ$  spacing. Participants indicated the target's direction using a keyboard and pressed "F" and "J" for

left- and right-facing target stimuli, respectively. Each session of flanker task performance included six practice trials with feedback, followed by 36 experimental trials that were equally distributed across congruent, incongruent, and neutral conditions (12 per condition). Figure 2 displays the visual stimuli and target sequence for the flanker task.

Across all tasks, accuracy (ACC, %) and mean reaction time (RT, ms) associated with a correct response were recorded. To obtain a composite measure that accounted for response speed and accuracy, we calculated the Inverse Efficiency Score (IES), with lower values indicating better cognitive performance. IES was computed using the following formula (Bruyer & Brysbaert, 2011):

$$IES = \frac{RT}{ACC}$$

### Negative Priming Task: Domain-Specific Inhibition

The negative priming (NP) task was adapted from the fraction comparison task (Jiang et al., 2020). In this task, participants were presented with two fractions and asked to judge which fraction was numerically larger. If the fraction on the left was larger, participants pressed the “F” key; if the fraction on the right was larger, they pressed the “J” key. The NP paradigm usually consists of two types of trials with each trial including a prime and a probe item. In the control trial, participants were instructed to respond to a non-numerical cue: pressing “F” if an underscore (“\_”) appeared beneath the left stimuli or pressing “J” if it appeared beneath the right stimulus. Following this prime, the probe required participants to compare two fractions with the same denominator, making the comparison straightforward (e.g., 8/9 vs. 7/9) (Ni & Zhou, 2005). For test trials, the prime presented two fractions with the same numerator (e.g., 7/8 vs. 7/9), creating conflict because people have a natural bias to apply

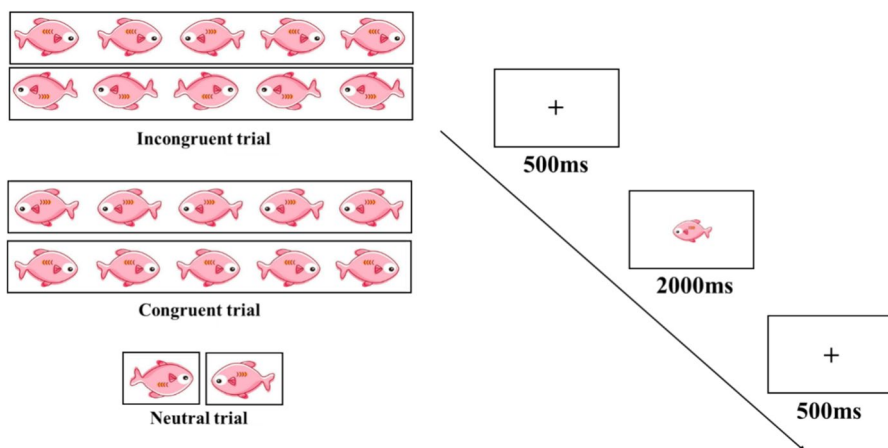


**Fig. 2** The Flanker Task. Participants Responded to the Direction of the Central Fish While Ignoring the Flanking Fish. Three Trial Types Were Included: Incongruent, Congruent, and Neutral

whole number rules and make the judgment that 8 is smaller than 9, against the correct response (Ni & Zhou, 2005). The test probe is the same as control probe where whole number rules align with the accurate fraction comparison. The logic of the NP paradigm is that neutral trials (underscore cue) did not require numerical comparison, and the control probe was served as a baseline condition. In the test prime, inhibitory control is required because participants must suppress their automatic but misleading denominator-based strategy in inconsistent trials. The negative priming effect emerges when the test probe trial shows a slower and/or less accurate response as compared to control probe trials, indicating the inhibition of a specific numerical strategy (i.e., whole number rules) would impair the subsequent activation of such a numerical strategy when it is feasible. Accordingly, the NP task provided a measure of interference control within a numerical reasoning context.

Prior to completing experimental trials, participants completed a practice block composed of six trials (i.e., two probe trials, two detect-prime trials, and two control-prime trials). In the formal experiment, each participant completed 48 trials: 12 detect-prime trials, 12 control-prime trials, and 24 probe trials. Each trial followed a fixed sequence. A fixation cross appeared for 500 ms, followed by the priming display (2500 ms). After a second fixation cross (500 ms), the probe display was presented (2500 ms) and after which a masking stimulus was shown for 500 ms during which no response was required. The full trial sequence is illustrated in Fig. 3. Performance in the NP task was assessed using the same measures as in the Flanker task, including reaction time (RT), accuracy (ACC), and inverse efficiency score (IES).

## Study Process

Following informed consent, participants' basic information, including body mass index (BMI) and cardiorespiratory fitness (CRF), was assessed. BMI was calculated as body weight in kilograms divided by height in meters squared, with height and

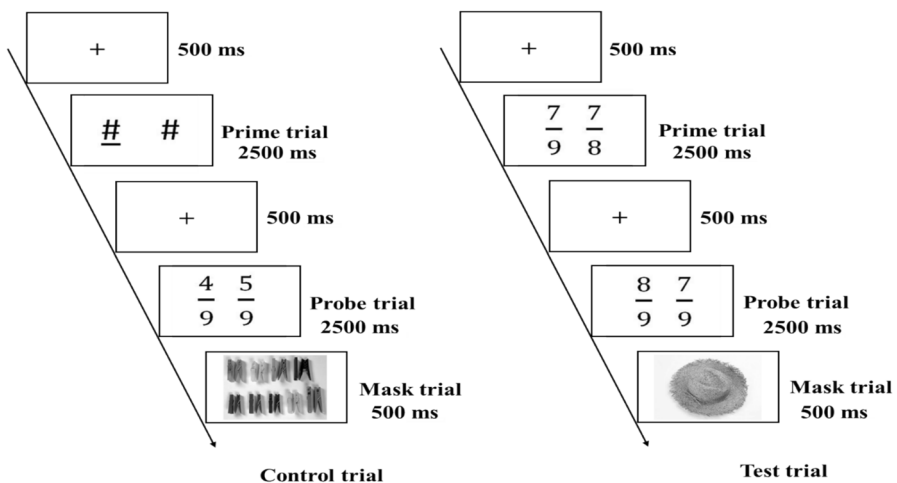


**Fig. 3** Trial Sequence of the Negative Priming Task

weight measured using an automatic portable stadiometer (BSM370, Seoul 135–960, Korea). As done in a previous study Hu et al. (2022), CRF was assessed using the standardized 50 m  $\times$  8 shuttle run test, in which students were required to run back and forth over a 50-m distance eight times (total distance = 400 m) as quickly as possible. Completion time was recorded and used as an indicator of cardiorespiratory fitness (Hu et al., 2022). This study employed a cluster-randomized controlled trial design. In the participating grade level, a total of 12 classes were available. Four classes were randomly selected using a computer-generated random number sequence. These four intact classes were then randomly assigned in a 1:1:1:1 ratio to one of the four intervention conditions: (1) mentally passive sedentary behavior (i.e., watching a video), (2) mentally active sedentary behavior (i.e., doing arithmetic work), (3) 5-minute physical exercise, and (4) 10-minute physical exercise. Each group completed cognitive assessments at three time points: (1) pre-intervention, (2) post-intervention (i.e., just before class), and (3) after an instruction (i.e., a mathematics lesson), allowing for a within- and between-participant comparison of intervention effects on two types of executive function.

All participants were instructed to arrive at the classroom at 08:00 a.m. The session began at 08:10 a.m. with a 6-minute cognitive test administered by a trained teacher using a standardized script, which served as the pre-intervention assessment. Between 08:20 a.m. and 08:30 a.m., participants engaged in the assigned intervention activity. In the sitting conditions (i.e., mentally passive and mentally active sedentary behaviors), participants remained seated for 10 minutes without any interruption. Those in the mentally passive sitting condition watched an emotionally neutral video about pandas, unrelated to academic content, whereas those in the mentally active sitting condition completed basic numeracy practice (i.e., simple numerical manipulation not related to fraction comparison). They were instructed to stay quietly at their desks and refrain from talking or engaging in any other activities under supervision by the experimenters. In the physical exercise condition, participants engaged in an instructor-guided, video-based group physical exercise routine (i.e., running in place, knee lifts, and deep squats) designed to elicit light-to-moderate intensity, which was deemed appropriate for the classroom setting. Those in the 5-minute condition began physical exercise at 08:25 a.m., whereas the 10-minute group started at 08:20 a.m. Exercise intensity was monitored using the Borg Category-Ratio scale (CR10; Borg, 1998; Borg, 1982), ranging from 0 (“nothing at all”) to 10 (“extremely strong”). Participants reported their perceived exertion immediately before and after the sitting or physical exercise intervention to assess exercise intensity and confirm a sufficient physiological response.

Following the intervention, participants immediately completed the cognitive assessments. At 08:40 a.m., all participants attended a standardized 40-minute mathematics lesson delivered by the original teachers using identical instructional slides and materials. The lesson focused on graphical mathematics concepts unrelated to fraction comparison and thereby reduced overlap with the domain-specific EF assessment. At 09:20 a.m., immediately after the 40-minute mathematics lesson, participants completed the final cognitive test. The entire schedule was carefully structured to align with standard classroom procedures, ensuring that the academic routine remained undisturbed (see Fig. 4 for experimental timeline).

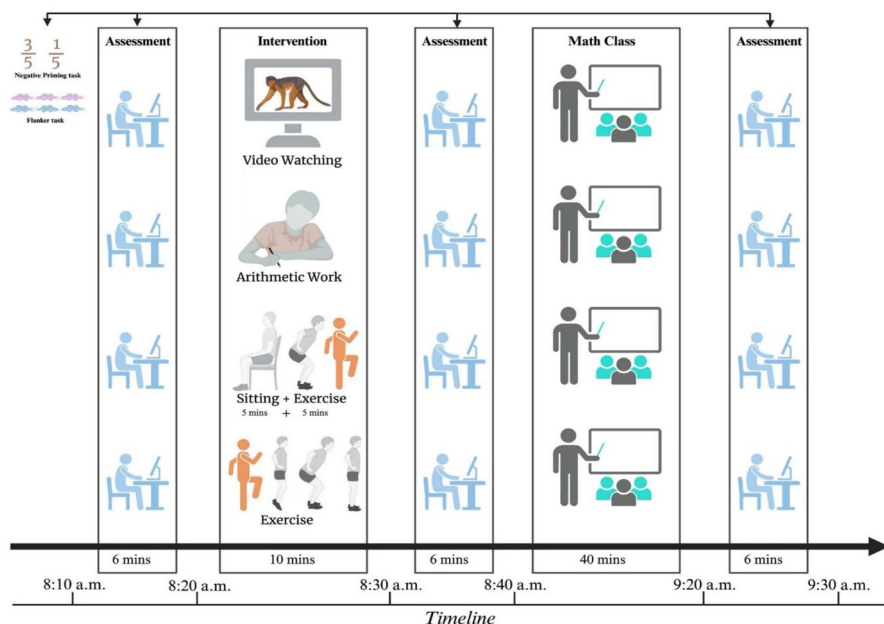


Fig. 4 Experimental Process

## Statistical Analyses

Randomization occurred at the class level ( $k=4$  clusters; one class per experimental condition). Given that the number of clusters was fixed, an a priori power analysis was not feasible (Junqueira et al., 2023). We therefore prespecified the primary endpoint as the IES in the Negative Priming task after instruction, representing mathematics-specific inhibitory control (Cameron & Miller, 2015; Killip et al., 2004). Following the CONSORT recommendations for cluster-randomized trials (Junqueira et al., 2023), we estimated the class-level intraclass correlation coefficient (ICC) for this primary endpoint to quantify the proportion of variance attributable to class-level clustering. The statistical analysis was conducted using R (version 4.4.0; The R Foundation, Vienna, Austria).

To confirm the interventions differed in intensity, we conducted 4 (experimental group: mentally passive sedentary behavior, mentally active sedentary behavior, 5-minute physical exercise, and 10-minute physical exercise)  $\times$  2 (time of assessment: pre- and post-intervention) repeated-measures ANOVA on RPE.

Interference effects in the Flanker task were calculated in three ways: (1) ACC interference, defined as congruent accuracy minus incongruent accuracy, with lower scores indicating less interference and better performance; (2) RT interference, defined as incongruent mean RT minus congruent mean RT, with smaller scores reflecting less interference and thus better performance; and (3) IES interference, defined as incongruent IES minus congruent IES, with smaller scores indicating less interference and better inhibitory control. Comparable effects were calculated for the

Negative Priming task: RT and IES interference were defined as detect minus control, whereas ACC interference was defined as control minus detect. Finally, as an additional check, Appendix 4 reports an alternative measure of interference based on the difference between incongruent and neutral trials.

In the main analysis, we considered interference effects for the Flanker task and the NP task as the primary outcomes. We ran linear mixed-effects models (LMMs) with fixed effects of group (mentally passive sedentary behavior, mentally active sedentary behavior, 5-minute physical exercise, and 10-minute physical exercise), time (pre-intervention, post-intervention, and post-instruction), and group  $\times$  time interaction, adjusting for sex, BMI, CRF, and the participant-specific baseline value of the outcome. Random intercepts were included for participants. LMMs are particularly suitable in this context given that randomization was implemented at the class level; that is, students were nested within classes. This approach appropriately accounts for the hierarchical data structures while estimating both fixed and random effects (Barr et al., 2013). LMMs were applied to the NP task to investigate behavioral outcomes (i.e., RT, ER, and IES) across the four experimental groups, three assessment time points, and two task conditions (control versus detect). Last, LMMs were used for the Flanker task to evaluate behavioral outcomes (i.e., RT, ACC, and IES) across the four experimental groups, three assessment time points, and two task conditions (neutral versus incongruent). The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) balanced model fit and complexity. Both criteria reward goodness of fit but penalize model complexity, thereby favoring parsimonious models that explain the data without overfitting (Burnham & Anderson, 2004). Maximum likelihood estimation was used for fixed and random effect parameter estimation. Corresponding analyses were conducted using “lme4” packages (Bates et al., 2003) of R software. A two-tailed  $p$ -value less than 0.05 was considered statistically significant.

## Results

### Cluster Design and Participants' Characteristics

To quantify class-level dependency, we first calculated the intraclass correlation coefficient (ICC) for the primary outcome, IES in the Negative Priming (NP) task after instruction. The ICC was 0.026, indicating that 2.6% of the total variance in post-instruction NP IES scores was attributable to between-class differences.

Participants' demographics stratified by class are reported in Appendix 1. Of the 169 recruited participants, 46 were excluded: Nine due to missing physical examination or class participation, 13 because they did not complete the entire study procedure, and 24 because their cognitive task performance was below 50% accuracy in each block (a threshold indicating possible misunderstanding of instructions or guessing; see Fig. 1). In the final analysis, 145 participants (70 girls, age:  $10.86 \pm 0.35$  years; BMI:  $17.91 \pm 3.16$  kg/m<sup>2</sup>; CRF:  $58.83 \pm 11.67$  s) were included.

## Manipulation Check for Intervention

The ANOVA for RPE revealed a significant group  $\times$  time interaction,  $F(3, 270) = 8.872$ ,  $p < 0.001$ , indicating that the change in RPE over time varied significantly across the four groups. Specifically, no significant change (from baseline to post-intervention) in RPE was observed in the mentally passive sedentary behavior group ( $\Delta = 0.18$ ,  $p = 0.15$ ) or the mentally active sedentary behavior group ( $\Delta = 0.10$ ,  $p = 0.58$ ). In contrast, RPE significantly increased following both the 5-minute physical exercise ( $\Delta = 2.71$ ,  $p < 0.001$ ) and 10-minute physical exercise ( $\Delta = 3.29$ ,  $p < 0.001$ ) interventions. The RPE scores for the 5-minute and 10-minute physical exercise groups were 3.71 and 4.51, respectively, and thus indicate a mild to moderate intensity (Garber et al., 2011). Furthermore, a 2 (group: 5-minute physical exercise versus 10-minute physical exercise)  $\times$  2 (time: pre-intervention versus post-intervention) repeated-measures ANOVA was conducted to examine whether exercise duration influenced perceived intensity. The analysis revealed no significant group  $\times$  time interaction,  $F(1, 67) = 1.94$ ,  $p = 0.17$ . In addition, there was no significant difference in RPE between the two physical exercise groups at baseline.

## Linear Mixed Models in the Flanker Task

Analyses were conducted for the incongruent-congruent contrasts of the Flanker task. For accuracy, no significant main effects for group and time were observed and the group  $\times$  time interaction did not attain a statistically significant level (all  $|t| \leq 1.28$ , all  $p \geq 0.20$ ). For RT, a significant main effect for group was observed. Compared with the mentally passive sitting group, participants in the 5-minute physical exercise group exhibited overall higher interference scores across assessment times ( $\beta = 0.538$ ,  $SE = 0.246$ ,  $df = 413$ ,  $t = 2.18$ ,  $p = 0.03$ , 95% CI [0.05, 1.02]). No other group contrasts were significant (all  $p \geq 0.18$ ) and neither the main effect for assessment time nor the group  $\times$  time interactions reached a statistically significant level (all  $|t| \leq 1.73$ , all  $p \geq 0.08$ ). For IES, main effects for group and assessment time, as well as the group  $\times$  time interaction, did not reach a statistically significant level (all  $|t| \leq 1.01$ , all  $p \geq 0.31$ ). Results from the Flanker task are presented in Fig. 5.

In supplementary analyses of the Flanker task, using the incongruent-neutral contrasts as the dependent measure, a significant group  $\times$  time interaction was observed. Specifically, 5-minute physical exercise ( $\beta = -0.930$ ,  $p = 0.01$ ) and 10-minute physical exercise groups ( $\beta = -0.713$ ,  $p = 0.03$ ) showed significant RT reductions from pre-intervention to post-intervention. Significant group effects emerged for two parameters (RT and IES). For RT, participants in 5-minute physical exercise group ( $\beta = 0.802$ ,  $p = 0.001$ ) and 10-minute physical exercise group ( $\beta = 0.473$ ,  $p = 0.046$ ) responded significantly worse than those in the mentally passive sitting group. For IES, participants in mentally active sitting group ( $\beta = 0.462$ ,  $p = 0.05$ ) and 10-minute physical exercise group ( $\beta = 0.500$ ,  $p = 0.04$ ) responded significantly worse than mentally passive sitting group. No significant effects were found for accuracy (all  $p \geq 0.19$ ). Full LMM results are reported in Appendix 3.

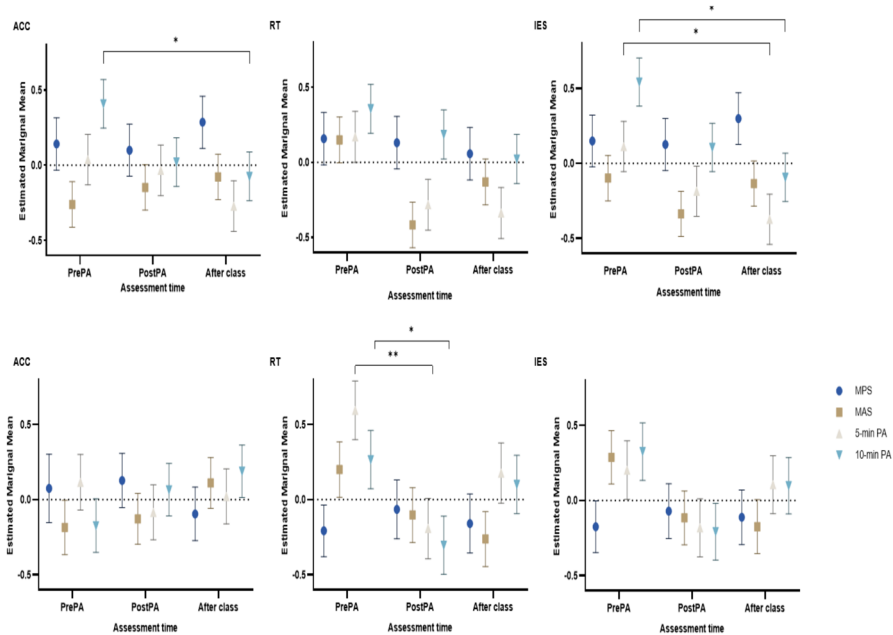


**Fig. 5** Significant results for the Flanker task (neutral level) and Negative Priming Task

### Linear Mixed Models in the Negative Priming Task

For accuracy, a significant group  $\times$  time interaction was detected, whereas the main effects of group and assessment time were non-significant. The interaction effect indicated that participants in the 10-minute exercise group showed greater accuracy gains from pre-intervention to post-instruction ( $\beta=0.646$ ,  $SE=0.317$ ,  $df=282$ ,  $t=2.04$ ,  $p=0.04$ , 95%  $CI$  [0.03, 1.26]) compared to mentally passive sedentary behavior. For RT, no significant main effects or interactions were observed for all levels (all  $|t| \leq 1.89$ , all  $p \geq 0.06$ ).

For IES, a significant group  $\times$  time interaction was observed. Relative to mentally passive sedentary behavior, 5-minute ( $\beta=-0.635$ ,  $SE=0.315$ ,  $df=282$ ,  $t=-2.01$ ,  $p=0.045$ , 95%  $CI$  [-1.25, -0.01]) and 10-minute ( $\beta=-0.785$ ,  $SE=0.309$ ,  $df=282$ ,  $t=-2.54$ ,  $p=0.01$ , 95%  $CI$  [-1.39, -0.18]) exercise groups exhibited larger reductions in interference scores from pre-intervention to post-instruction. No significant effects were observed for the 5-minute or 10-minute groups immediately after the intervention (all  $p \geq 0.18$ ).

### Discussion

In an authentic classroom setting, we compared brief pre-class physical exercise with mentally active and passive sedentary behaviors on both domain-general and mathematics-specific inhibition, assessed at baseline, immediately post-intervention, and after the regular instruction (i.e., mathematics lesson). Results indicated that a

brief bout of physical exercise did not improve domain-general inhibitory control (as measured by the Flanker task, especially the incongruent-congruent contrasts) immediately after the intervention or following the classroom instruction. In turn, we observed a significant enhancement in mathematics-specific inhibitory control (as assessed by the negative priming effect in the fraction comparison task) after students participated in the subsequent mathematics lesson, compared to baseline performance. Our findings add importantly to the exercise-cognition literature as they suggest real-class context, pre-class physical exercise differentially influences domain-general and domain-specific EF. Results will be interpreted in more detail below.

### **Lack of Effects of Acute Physical Exercise on Domain-General Inhibitory Control**

Brief pre-class physical exercise did not lead to improvements in domain-general inhibitory control (i.e., the Flanker task-related parameters including RT, accuracy, and IES) – a finding independent of whether the assessment was completed immediately post-exercise or following the classroom instruction. This finding stands in contrast to a substantial body of literature in children and adolescents (de Greeff et al., 2018; Shi et al., 2022) reporting that a single bout of aerobic exercise enhances each core component of EF. It is, however, important to recognize that our findings support a very recent meta-analysis asserting the absence of acute physical exercise-induced EF benefit in preadolescent children, with a high heterogeneity across studies (Dixon et al., 2025). Further, a previous meta-analytical review in youth reported small, immediate EF benefits after  $\geq 20$ –30 minutes of exercise on the Flanker/Stroop/Go-No-Go (Hedges  $g \approx 0.2$ –0.3) (Liu et al., 2020). As such, our null findings concerning an effect on domain-general EF can be attributed to (i) the short exercise duration (5-minute versus 10-minute) may not provide a sufficient dose–response to elicit measurable improvements in domain-general EF, and (ii) the use of interference scores rather than absolute incongruent RTs (Ligeza et al., 2024) or incongruent-neutral contrast, which are more sensitive to broad alerting effects of acute physical exercise.

More specifically, the dose is, among other factors, a key factor for the effectiveness of an intervention (Herold et al., 2019). As identified in a systematic review (Shi et al., 2022), the majority of studies (12 of 13) reporting the positive effects of acute physical exercise on EF in children and adolescents employed interventions lasting 30 to 50 minutes. In contrast, Cooper et al. (2016) reported significant improvements in inhibitory control (via the Stroop task) following a 10-minute high-intensity sprint exercise in 44 adolescents (aged  $12.6 \pm 0.6$  years), suggesting that higher physiological demand may compensate for shorter duration. In turn, the present study used light-to-moderate physical exercise as a priming activity. This difference in both duration (Shi et al., 2022) and intensity (Cooper et al., 2016) likely limited the overall arousal–dose threshold needed to elicit broad domain-general EF effects. However, a light to moderate-intensity and less than 15 minutes protocol was intentionally chosen as a realistic pre-class priming activity that could be feasibly implemented within typical school schedules and physical spaces (Daly-Smith et al., 2018). Importantly, the broader cognitive indices examined in our supplementary analyses revealed that,

under this ecologically valid implementation, the physical exercise groups exhibited significant improvements in the incongruent-neutral contrasts (i.e., RT and IES). In line with the arousal theory of physical exercise (McMorris, 2015; Yerkes & Dodson, 1908), light-to-moderate physical exercise intensity may increase general alertness sufficient to affect broad cognitive processes such as response speed, but fall short of the optimal arousal required to selectively enhance complex inhibitory control.

Another potential moderator relates to ecological context. Most evidence for acute physical exercise benefits stems from controlled laboratory studies, whereas our intervention was conducted under authentic classroom conditions. Although the environment used is educationally relevant, it also allows for a lower level of standardization of experimental conditions, potentially introducing greater variability (e.g., classroom management demands, peer-related distractions) that may reduce the resolution to detect physical exercise-based changes in domain-general and domain-specific EF (Donnelly & Lambourne, 2011). Our findings suggest that, within the constraints of typical school schedules, traditional cognitive paradigms may not fully capture the breadth of cognitive changes induced by brief bouts of physical exercise. Incorporating assessment tools that are more closely aligned with educational goals may therefore provide a more comprehensive understanding of how school-based interventions support student learning.

### **Delayed Effects of Acute Physical Exercise on Mathematics-Specific Inhibitory Control**

Our results showed that both 5- and 10-minute acute pre-class physical exercise interventions produced a reduction in negative priming IES scores, suggesting a post-instruction improvement in mathematics-specific inhibitory control. This delayed effect aligns with meta-analytic evidence that the benefits of acute physical exercise on EF in children may manifest contextually after cognitive engagement (Song et al., 2023).

Notably, although previous research has consistently reported immediate post-exercise enhancements in domain-general EF tasks (e.g., the flanker or the Stroop tasks) following exercise interventions (de Greeff et al., 2018), our results showed that a benefit of domain-specific EF did not emerge immediately post-exercise, but was observed only after participants engaged in a mathematics lesson. This suggests that acute physical exercise may prime cognitive systems, but the expression of these gains in domain-specific EF is contingent upon subsequent academic experiences that actively recruit these skills (Roig-Hierro et al., 2024). This interpretation aligns with the predictions of the guided plasticity facilitation framework (Fissler et al., 2013; Herold et al., 2018), which proposes that exercise-induced facilitation of neuroplasticity requires subsequent cognitive engagement to stabilize and consolidate functional benefits. Viewed in the context of the dual-process account (Zhang et al., 2025), these findings may suggest traditional domain-general tasks may be sensitive to immediate physiological and neurocognitive changes induced by acute physical exercise, whereas domain-specific measures are more likely to capture the educationally meaningful impact of physical exercise as it interacts with classroom learning. Accordingly, while prior research has consistently demonstrated immediate benefits

of acute physical exercise on domain-general EF (Shi et al., 2022), our findings suggest that domain-specific EF gains may additionally be closely linked to the subsequent learning context, manifesting after students engage with academic material that actively recruits these skills.

As noted above, the 5- and 10-minute acute pre-class physical exercise interventions elicited improved IES to a similar extent, suggesting that even exercise bouts with a shorter duration can be a valuable means to boost domain-specific EF in the classroom setting. In contrast, the broader literature and evidence on dose-response-relationships among children and adolescents suggests exercise interventions shorter than 15 minutes (Shi et al., 2022) do not reliably improve domain-general inhibition. This discrepancy between domain-general and domain-specific measures may highlight a potential advantage of incorporating domain-specific assessments, as they may be more sensitive to capturing the subtle yet educationally meaningful effects of brief bouts of physical exercise in the ecological school contexts. Further research is needed to confirm these patterns and clarify the optimal characteristics of such interventions to effectively prime academic performance. Taken together, our findings suggest brief physical exercise is best conceptualized as a primer whose cognitive benefits are realized when instruction immediately recruits similar inhibitory demands.

In contrast to prior research, we found that mentally active sedentary behavior (e.g., completing basic numeracy practice) did not produce a significant improvement in mathematics-specific inhibitory control compared to mentally passive sitting. Previous studies have shown that cognitive engagement can enhance executive functions; however, effects are typically confined to the specific tasks or cognitive domains that are directly practiced - a phenomenon known as near transfer (Karchach & Verhaeghen, 2014; Sala & Gobet, 2020). For example, Zhao et al. (2020) used a task-switching training paradigm and found that students improved not only on the trained task but also on a structurally similar untrained switching task, demonstrating near transfer. However, no cognitive benefits were found in far transfer tasks involving working memory, inhibitory control, and/or fluid intelligence, highlighting the domain-specificity of cognitive training effects (Zhao et al., 2020). This represents an important consideration because in real-world educational settings, it is often impractical to ensure that pre-class cognitive activities are directly aligned with the cognitive demands associated with the upcoming assessment and/or learning period. Thus, the diversity of subject matter and instructional content means that direct transfer from practice to broader cognitive outcomes is rarely achievable. The findings highlight a potential limitation of using cognitive engagement as a classroom ‘warm-up’ strategy because its benefits may be highly specific and unlikely to generalize across different domains or tasks (Kassai et al., 2019).

### Implications for Classroom Practice

Five key points should be highlighted for practical implication. Firstly, strategically implementing 5–10 minutes of physical exercise immediately before a mathematics lesson can help maximize alignment with task demands observed in class (when

to schedule). Secondly, light-to-moderate, space-efficient routines (e.g., running in place, knee lifts, squats) are sufficient; avoid complex dual-task choreography that could raise extraneous cognitive load before instruction (Zou et al., 2025) (what to do). Thirdly, effects of short acute physical exercise with light to moderate intensity may be selective—improved mathematics-specific inhibitory control rather than broad EF changes—and may emerge after regular instruction, not immediately post-exercise (what to expect). Fourth, no equipment is required, for example, routines can be teacher-led with a simple video prompt that is suitable for typical classrooms and schedules (feasibility/equity). Fifth, when feasible, it is necessary to monitor on-task behavior and mathematics-aligned inhibition (e.g., IES of NP task) for evaluating implementation quality and impact.

### Limitations and Future Directions

Several limitations of the present study should be acknowledged. First, the sample was restricted to primary school students from a single educational context, which constrains the generalizability of the findings to other age groups and educational systems. Second, the intervention focused on brief, light-to-moderate-intensity aerobic exercise. This format is highly feasible in school settings, particularly before lessons, and represents a practical strength of the study design. At the same time, it remains unclear whether pre-class physical exercise bouts with slightly longer exercise duration (e.g., 15–20 minutes, which may still be feasible before academic instruction) or with a higher exercise intensity would yield stronger (or broader) benefits. Third, the study relied on well-established but logic-separate paradigms to assess domain-general and domain-specific inhibitory control. Although this approach facilitates comparison with prior literature, it does not capture potential overlaps between the two domains; integrating general and subject-specific elements into a single paradigm could provide more ecologically valid insights in future work. Moreover, the modified version of the Flanker task employed in the current study was different from those commonly used in the field (e.g., inclusion of a fixation cross, fewer trials), which may have reduced the reliability of individual mean values due to limited trial numbers. Fourth, the study focused only on immediate and short-term delayed assessments (i.e., after the subsequent instruction). The persistence of benefits beyond a single lesson was not examined, leaving the duration of potential effects for educational practice unclear. Last, classroom-level factors such as differences in instructional content, teaching style, or student engagement during mathematics lessons were not systematically controlled and may have contributed to the observed effects. Additionally, future studies are encouraged to incorporate portable neurophysiology (e.g., functional near-infrared spectroscopy) alongside cognitive performance measures to elucidate mechanisms underlying the exercise-related behavioral effects in classroom settings.

Despite the above-mentioned limitations, the study has several notable strengths. First, by embedding the acute physical exercise intervention within classroom routines, the study provides enhanced ecological validity relative to previous lab-based assessments as well as offered the opportunity to study how acute physical exercise

priming can interact with real instructional processes. Second, the design simultaneously assessed domain-general and mathematics-specific inhibitory control to provide a differentiated EF perspective that moves beyond the predominant reliance on context-independent measures (Zhang et al., 2025). Considering both domain-general and mathematics-specific inhibitory control performance allowed us to elucidate whether the cognitive benefits of short bouts of pre-class acute physical exercise may only manifest when aligned with subsequent academic demands, offering novel theoretical and practical implications. Third, the inclusion of mentally passive and active sedentary behaviors as control conditions, alongside two exercise conditions with different duration, provided a novel, and ecologically valid approach to estimate the unique value of acute physical exercise beyond mentally passive and active sedentary behaviors in the classroom. This design not only strengthened internal validity but also generated insights into the relative value of different pre-class intervention strategies to ‘prime’ specific cognitive processes, a matter of high practical relevance for improving educational practice.

## Conclusion

Our findings suggest that a brief bout of pre-class physical exercise, regardless of their duration, did not produce measurable improvements in domain-general inhibitory control, but selectively enhanced mathematics-specific inhibitory control after subsequent mathematics instruction. The pattern supports a theory of task–context alignment and guided plasticity, whereby brief physical exercise elevates motivational readiness that translates into improved mathematics-specific inhibition only when followed by domain-relevant instruction. The study further underscores the importance of employing domain-specific measures to capture the physical exercise-related effects. From a practical perspective, integrating brief, acute physical exercise routines before class may represent a feasible and viable strategy to support cognitive function for learning, while consuming a minimum amount of instructional time. For practice, 5–10 minutes, light-to-moderate exercise primers are feasible within typical schedules and may enhance readiness for mathematics without displacing teaching time. Future research should determine optimal exercise characteristics, by investigating the efficacy of alternative modalities such as cognitively enriched physical exercise, and examining delayed or cumulative effects across diverse age groups and educational contexts, thereby advancing the development of evidence-based pre-class interventions.

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## Declarations

**Ethical Approval** This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of the School of Psychology, Shenzhen University (SZU\_PSY\_2024\_171).

**Competing Interests** The authors have no competing interests to declare that are relevant to the content of this article.

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