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Cross-lagged analysis of physical fitness and cognitive control in Chinese early adolescents

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This study aims to explore the relationship between physical fitness levels and cognitive control in Chinese early adolescents, focusing on longitudinal analysis to understand how these variables interact over time. Additionally, the study investigates the moderating effect of gender on this relationship. The study included 160 junior high students (aged 12–14) with gender-balanced participation (64 boys, 79 girls retained after attrition). Utilizing a two-wave longitudinal design, baseline assessments (T1: March–April 2023) evaluated physical fitness through six indicators: body composition (BMI), cardiorespiratory endurance (gender-specific distance runs), vital capacity, speed (50 m sprint), muscular strength (gender-specific tests), and flexibility (sit-and-reach). Cognitive control was measured via: (1) Stroop Color-Word Task (interference inhibition), (2) Go/No-Go Task (impulse control), and (3) Task-Cueing paradigm (cognitive flexibility). Eight-month follow-up (T2: November–December 2023) retained 143 participants (mean age: 12.7 ± 0.52). Cross-lagged path modeling in Mplus 8.0 examined bidirectional causation relationships between fitness domains and cognitive functions, supplemented by SPSS 26.0-based correlational analyses. Descriptive statistics revealed that girls outperformed boys in several physical fitness and cognitive control measures. At T1, girls had significantly higher physical fitness levels (M = 82.51, SD = 8.09) compared to boys (M = 72.19, SD = 10.44, $P < 0.001$) and performed better in interference inhibition ($P < 0.001$) and impulse control ($P < 0.01$). At T2, girls maintained higher physical fitness levels ($P < 0.001$), but boys demonstrated better cognitive flexibility (M = 802.54, SD = 318.08 vs. M = 983.10, SD = 239.49, $P < 0.001$). Correlation analysis showed significant associations between physical fitness and cognitive control, including negative correlations with interference inhibition ($r = -0.582$, $P < 0.01$, indicating that higher fitness levels correspond to lower interference suppression IES scores reflecting better inhibitory control) and cognitive flexibility ($r = -0.548$, $P < 0.01$, indicating that higher fitness levels correspond to lower cognitive flexibility IES scores reflecting better cognitive flexibility), and a positive correlation with impulse control ($r = 0.282$, $P < 0.01$). Cross-lagged analysis indicated that physical fitness at T1 significantly predicted interference inhibition ($\beta = -0.234$, $P < 0.05$), impulse control ($\beta = 0.148$, $P < 0.05$), and cognitive flexibility ($\beta = -0.499$, $P < 0.01$) at T2. Gender differences analysis revealed that the relationship between physical fitness and cognitive flexibility was significant for boys ($P = 0.036$, < 0.05) but not for girls. These findings highlight the importance of physical fitness in enhancing cognitive control capabilities during adolescence. The results provide a theoretical foundation for policymakers and educational institutions to prioritize comprehensive physical education programs to foster healthy youth development.

Keywords Physical fitness, Cognitive control, Interference Inhibition, Impulse control, Cognitive flexibility, Gender differences

In 2023, the Ministry of Education and the National Health Commission of the People's Republic of China, in conjunction with other relevant departments, jointly released the "Special Action Plan for Comprehensively Strengthening and Improving Student Mental Health Work in the New Era (2023–2025)"[1], emphasizing China's commitment to improving student mental health. This initiative targets key psychological challenges among adolescents, particularly aggression, anxiety, and interpersonal difficulties. One critical pathway to achieving these goals is enhancing adolescents' cognitive control—the capacity to regulate thoughts, emotions, and

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behaviors in complex and changing environments to achieve specific objectives[2]. Cognitive control encompasses interference inhibition, impulse control, and cognitive flexibility[2]. Empirical evidence consistently links deficiencies in cognitive control to heightened aggression, increased anxiety, depressive symptoms, and social conflicts[3]. All of which are central concerns outlined in the national policy. Thus, improving cognitive control is a crucial strategy for alleviating adolescent mental health problems and fulfilling the goals of China's national initiative.

Given the importance of cognitive control in promoting mental well-being, increasing attention has been paid to potential behavioral strategies that may enhance it, among which physical activity plays a crucial role. According to the World Health Organization, over 80% of adolescents worldwide fail to meet recommended physical activity guidelines[4]. National surveys reveal that China reflects similar trends, with declining physical fitness levels reported among Chinese school-aged youth over the past two decades[5]. Addressing physical inactivity and its associated cognitive and psychological consequences is thus not only a national priority but also aligns with global public health efforts.

Building on the recognized role of physical activity, physical fitness—an important indicator of physical health—has become a key focus in understanding its cognitive benefits. Physical fitness is a crucial indicator of overall health, encompassing various elements such as physical structure, function, and psychological well-being. It includes body composition, endurance, strength, and flexibility, all of which contribute to an individual's well-being and ability to maintain an active lifestyle[6]. Research indicates that youth physical fitness levels are closely associated with sleep quality[7] and academic performance[8]. In recent years, growing interest has been in exploring the relationship between youth physical fitness levels and cognitive control due to increased problem behaviors among adolescents. A growing body of research indicates that higher levels of physical fitness are associated with enhanced cognitive control functions, such as interference inhibition, impulse control, and cognitive flexibility[9,10]. For instance, Wang et al. (2019) found that individuals with better physical fitness demonstrated stronger interference inhibition ability[11]. Hogan et al. (2013) found that adolescents with lower aerobic fitness demonstrated higher error rates in tasks requiring inhibitory control[12]. Westfall et al. (2013) found that higher fitness was associated with shorter reaction time and higher accuracy in the flanker task[13]. However, findings across studies are inconsistent. Stroth et al. (2009), for instance, reported no significant relationship between physical fitness and cognitive performance in certain cognitive domains[14]. These mixed results suggest that the relationship between physical fitness and cognitive control is complex and may vary depending on the specific cognitive function examined.

Despite growing interest in the relationship between physical fitness and cognitive control, most existing studies have focused on unidirectional effects—typically how physical fitness influences cognition. However, cognitive-behavioral theories propose that this relationship may be reciprocal, whereby cognitive control capacities such as interference inhibition, impulse control, and cognitive flexibility also influence individuals' ability to initiate, maintain, and adapt physical activity behaviors[15–17]. For instance, adolescents with stronger executive functioning may be more capable of setting goals, resisting distractions, and sustaining engagement in exercise routines[2,18]. ultimately benefiting their physical fitness. Recent reviews (e.g., Lubans et al., 2021) have emphasized the need for research utilizing bidirectional frameworks to better capture the dynamic interplay between physical and cognitive development[19]. Empirically, however, such investigations remain limited, especially those employing cross-lagged panel models that can evaluate temporal precedence and reciprocal influences over time[20]. Given the developmental shifts during early adolescence, a longitudinal design spanning at least six months is critical for detecting meaningful changes and clarifying causal directions in the fitness–cognition relationship[21,22]. This extended period will facilitate the observation of temporal changes and provide a robust theoretical basis for exploring the causal interactions between these variables over time.

Furthermore, gender differences are an important consideration in adolescent development. Biological factors, such as hormonal variations (e.g., estrogen and testosterone levels) and differences in neurodevelopmental timing, may result in gender-specific patterns in both physical fitness and cognitive control[23]. Sociocultural influences, including differential expectations regarding physical activity and socialization practices, may further modulate these developmental trajectories. Prior studies have found that boys generally exhibit higher physical fitness levels during adolescence, while girls may display advantages in specific cognitive control, particularly early in adolescence[24–26]. Therefore, examining gender differences in the bidirectional relationship between physical fitness and cognitive control may yield critical insights into adolescent health and development.

Given these considerations, the present study aims to establish a bidirectional relationship model between physical fitness and cognitive control among early adolescents, investigating their causal links over time and examining potential gender differences. Notably, although different components of physical fitness (e.g., cardiorespiratory endurance, muscular strength, flexibility) may exhibit distinct associations with specific aspects of cognitive control, the present study employed a composite physical fitness score as a global indicator of adolescents' physical fitness. This approach enables a more parsimonious modeling strategy within the cross-lagged framework and reduces the risk of overfitting given the available sample size. Specifically, this study addresses the following research questions:

1. Does physical fitness predict changes in cognitive control over time?
2. Does cognitive control predict changes in physical fitness over time?
3. Are there gender differences in the relationship between physical fitness and cognitive control?

Cross-lagged analysis methods will be employed to explore the causal dynamics between these variables and the moderating effects of gender, providing valuable insights for enhancing adolescent health interventions and promoting cognitive and physical development.

Research methodology
Participants

Regarding the sample size calculation for the cross-lagged model, this study initially employed G*Power software for estimation. However, since the cross-lagged model is based on structural equation modeling (SEM), G*Power does not directly support such analyses. Therefore, we simplified the model to a linear regression framework in G*Power, with the significance level ($\alpha = 0.05$), power ($1 - \beta = 0.95$), and effect size ($f^2 = 0.15$) set as parameters to estimate the required sample size. The effect size value of $f^2 = 0.15$ was chosen based on Cohen's (1988)[27] guidelines, where $f^2 = 0.02$, 0.15, and 0.35 represent small, medium, and large effects, respectively. Given the exploratory nature of this study and the moderate associations typically reported in previous research on physical fitness and cognitive control in children[28], a medium effect size was deemed both theoretically and empirically justified. Moreover, a meta-analysis by Alvarez-Bueno et al. (2017)[29] reported average effect sizes in the small-to-moderate range for similar cognitive outcomes, further supporting the appropriateness of using $f^2 = 0.15$ in our power analysis. This analysis yielded a required sample size of $N = 107$. In consideration of the analytical characteristics of the cross-lagged SEM employed in this study, the adequacy of the sample size was further evaluated based on the empirical rule proposed by Bentler and Chou (1987)[30], which recommends a minimum of 10 participants per estimated free parameter. The final model included 10 free parameters (including autoregressive paths, cross-lagged paths, covariances, and residual variances), indicating a minimum required sample size of 100. The final effective sample size was $N = 143$, exceeding both the regression-based estimate and the SEM-based guideline. Meanwhile, according to Kline (2015)[31], a sample size between 100 and 200 is generally recommended for SEM, further supporting the appropriateness of our sample. This study recruited 160 adolescents (aged 12–14) from Guangzhou, Guangdong Province, China, all of whom participated in the first wave of testing. The study was conducted in two phases. The first phase, a cross-sectional baseline assessment, was conducted from March to April 2023 to evaluate participants' physical fitness and cognitive control. The second phase, a follow-up assessment, took place from November to December 2023. Due to school absences, illness, school transfers, and voluntary withdrawal, 10 participants did not participate in the second wave. After data screening and the exclusion of 7 cases with invalid data, a total of 143 participants (64 males and 79 females) were included in the final analysis (Fig. 1). The participants' average age was $M = 12.71$, $SD = 0.52$. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee for Scientific Research of Guangzhou College of Commerce (No. GCC2023-003). All methods were performed in accordance with the relevant guidelines and regulations, and informed consent was obtained from each participant's legal guardian. To address potential attrition bias due to the exclusion of 17 participants, we compared the baseline characteristics of retained ($n = 143$) and excluded ($n = 17$) participants. Independent samples t-tests showed no significant differences in age, physical fitness scores between the two groups (all $p > 0.05$). These results suggest that attrition was random rather than systematic, minimizing the risk of bias in the final sample.

Research instruments
Physical fitness level assessment

Physical Fitness Scores were derived based on the National Physical Fitness Standards for Students (NPFSS)[32], with six key fitness components assessed according to the participants' age. These components included body composition (height and weight), cardiorespiratory endurance (1,000-meter run for males and 800-meter run for females), vital capacity, speed (50-meter sprint), muscular strength (pull-ups for males and one-minute sit-ups for females), and flexibility (sit-and-reach test). To ensure reliable results, males and females were tested separately. The assessment of muscular strength was demonstrated by the instructor before participants performed the exercises, with correct repetitions carefully recorded. The components were weighted as follows: body composition (BMI) and vital capacity (15% each), cardiorespiratory endurance and speed/agility (20% each), and muscular strength and flexibility (10% each). During the process of scoring the above-mentioned test
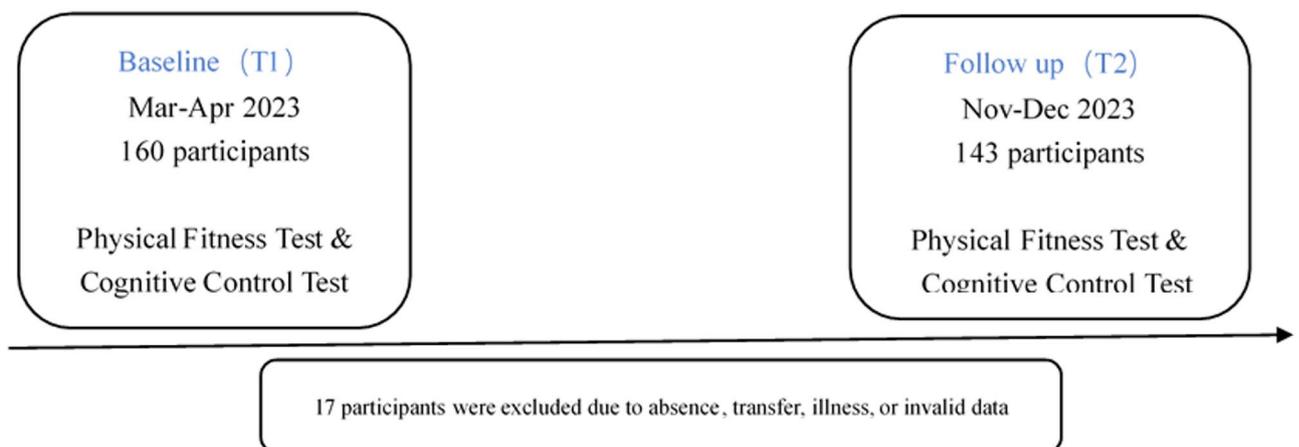

Fig. 1. Test schedule chart.

items, we adopted different scoring standards based on gender differences. For instance, when conducting the push-up test, boys used the scoring standard specific to boys, while girls employed the sit-up scoring standard applicable to girls. These scoring standards referred to the existing gender-specific physical fitness assessment standards and strictly followed their respective scoring norms. According to NPFSS, a total score of 90 points or above is considered excellent, 80 to 89.9 points is good, 60 to 79.9 points is a pass, and 59.9 points or below is a fail.

Interference inhibition

Interference inhibition was measured using the Stroop Color-Word task[33], in which participants determined whether the meaning of a word matched its font color by pressing the "f" key for congruent pairs and the "j" key for incongruent pairs. After entering their numbers in the E-prime3.0 program, the participants first watched the instructions. The instructions were presented in the center of the screen. After reading them, they proceeded to the practice experiment. First, a fixation point appeared on the screen for 500ms, and then the fixation point disappeared while a color-word picture (such as the consistent and inconsistent pictures randomly appeared as shown in Fig. 2) appeared randomly in the center of the computer screen for 1000ms. The participants needed to complete the cognitive judgment within the time when the stimulus materials appeared. During the practice stage, three kinds of text feedback (judgment error, judgment correct, no key press response) would be given according to the participants' key press responses. After the practice was completed, if the correct rate did not reach 70% or higher, the participants would continue to practice; otherwise, they would enter the formal experiment. This paradigm adopted key press responses: press "f" if the font and the filling color are consistent, press "j" if they are not consistent. After completing the cognitive judgment, a blank screen of 1000 ms would appear. During the experiment, the experimenter did not give any hints, feedback, or intrusive behaviors that would interfere with the participants. This task included one practice block and one formal block. Each participant in the practice block completed 25 trials, and the formal block included 288 trials. The stimulus materials appeared randomly and lasted approximately 14 min. Reaction times for error trials, as well as for trials immediately following errors, were excluded. Additionally, reaction times below 100 ms and those deviating more than 3.32 median absolute deviations from the median were removed[34]. The performance evaluation was quantified using the Inverse Efficiency Score (IES)[35], which combines reaction time and accuracy into a single measure to account for individual differences in the speed–accuracy trade-off. A higher IES indicates poorer inhibitory control, reflecting either increased error rates and/or slower reaction times. Although IES is not yet widely used in physical fitness research, it has been increasingly adopted in cognitive psychology to provide a more comprehensive measure of cognitive control. We opted to use IES in the present study as it allows us to capture both speed and accuracy simultaneously, which is particularly valuable when evaluating interference inhibition in tasks that demand both fast and correct responses. This approach enables a more nuanced assessment of cognitive control compared to using either accuracy or reaction time alone.

Impulse control

Impulse control was assessed with the Go/No-Go task[36], in which participants responded to "Go" stimuli (upward arrows) by pressing the "f" key and refrained from responding to "No-Go" stimuli (downward arrows). After entering their own numbers in the E-prime3.0 program, the participants first watched the instructions. The instructions were presented in the center of the screen. After reading them, they proceeded to the practice experiment (Fig. 3). First, a black " +" fixation point appeared on the screen for 500ms, and then a random stimulus material (such as an upward or downward arrow) appeared randomly in the center of the computer screen for 1000ms. After making a judgment, they entered a 500ms blank screen. During the practice stage, two types of text feedback (judgment error, judgment correct) would be given according to the participants' key responses. After the practice was completed, if the correct rate did not reach 70% or higher, the participants would continue to practice; otherwise, they would enter the formal experiment. In this experiment, the participants were required to respond with keys to the GO stimuli, and no response was required for the No Go stimuli. In the first part, the upward arrow was the GO stimulus, and the downward arrow was the No Go stimulus. At this time, the participants needed to press the "f" key for the upward arrow and inhibit the response for the downward arrow. In the second part, the inhibition of the upward arrow response was required. At this time, the participants needed to inhibit the response for the upward arrow and press the "f" key for the downward arrow. During the experiment, the experimenter did not give any hints, feedback, or intrusive behaviors to the participants. This task included 2 practice blocks and 2 formal blocks. Each participant completed 20 trials in
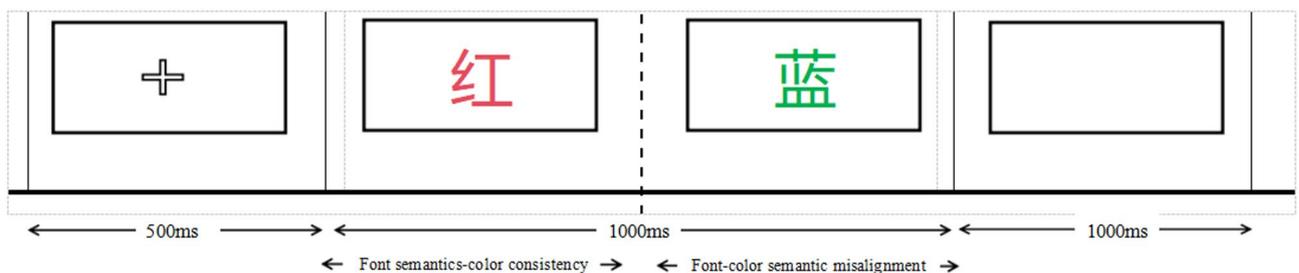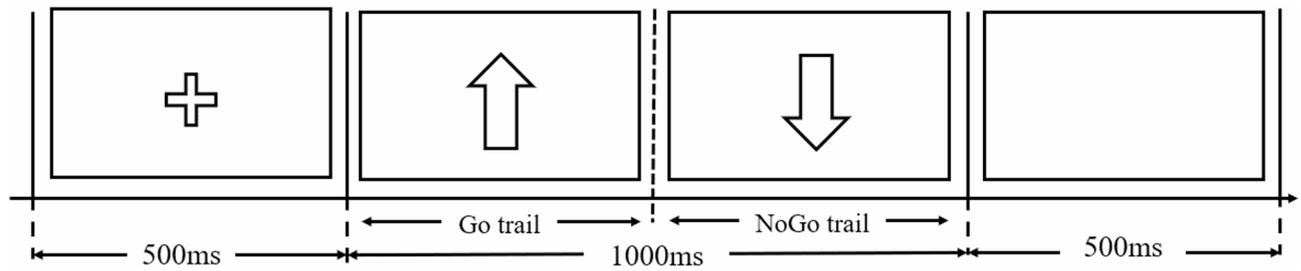

Fig. 2. Stroop color-word task flow chart.

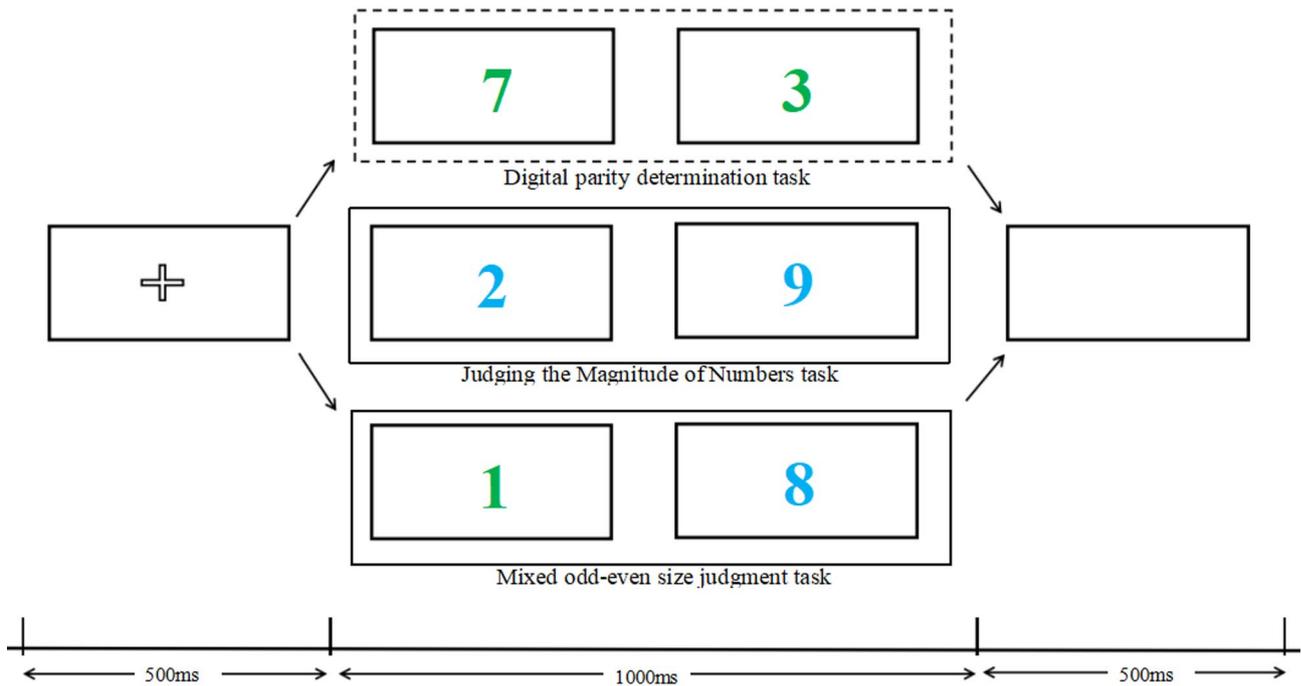**Fig. 3**. Go/no go task flow chart.

Fig. 4. Task-cueing paradigm task flow chart.

the practice block, and the formal block contained 400 trials. The stimulus materials appeared randomly and were expected to last for 16 min. Data analysis focused on the accuracy of No-Go trials. The accuracy rate of teenagers usually falls between 70% and 90%, which reflects the performance of individuals in completing such tasks under normal circumstances. The higher the value of the No-Go trials' accuracy is, the better the impulse control ability is.

Cognitive flexibility

Cognitive flexibility was measured using the Task-Cueing paradigm[37], which involved tasks for odd/even and magnitude judgments in both repeat and switch sequences. Participants responded to green-colored numbers based on parity (even or odd) and blue-colored numbers based on magnitude (greater or less than 5). After entering their numbers in the E-prime3.0 program, the participants first watched the instructions. The instructions were presented in the center of the screen. After reading them, they proceeded to the practice experiment (Fig. 4). First, a black "+" fixation point appeared on the screen for 500 ms, and then a random stimulus material (such as a single blue number, a single green number, or a mixed blue and green number) appeared randomly in the center of the computer screen for 1000 ms. After making a judgment, they entered a 500ms blank screen. During the practice stage, three types of text feedback (judgment error, judgment correct, and no key press response) would be given according to the participants' key press responses. After the practice was completed, if the correct rate did not reach 70% or higher, the participants would continue to practice; otherwise, they would enter the formal experiment. In this experiment, the participants were required to press keys to respond to the stimuli. The experimental task included 3 practice blocks and 3 formal experiment blocks. Each practice block contained 36 trials, and the formal experiment repeated the sequence of 200 trials, with 200 trials for the switching sequence. The experiment lasted approximately 20 min. The experimenter did not give any hints, feedback, or intrusive behaviors to the participants during the experiment. Reaction times for error trials, as well as for trials immediately following errors, were excluded. Additionally, reaction times below 100

ms and those deviating more than 3.32 median absolute deviations from the median were removed[34]. Cognitive flexibility is evaluated by the Inverse Efficiency Score (IES) of the sequence switching. Higher IES values indicate lower cognitive flexibility, reflecting either higher error rates and/or slower reaction times.

Testing procedure

The physical fitness assessments were conducted with two staff members independently recording the results to ensure data reliability. If the two recorded values differed by more than a pre-defined threshold (5% deviation), a re-test was conducted immediately under the supervision of the evaluators. Otherwise, the final score for each participant was calculated as the average of the two recorded values. This protocol ensured both accuracy and consistency in physical fitness measurement. Cognitive control assessments were conducted over three weeks, with each task being measured once per week at the same location and time to ensure consistency and that participants were in a calm and stable state. Four graduate students supervised the administration of the cognitive control tests, and no cognitive tests were administered on the same day as the physical tests.

Data collection

Data collection involved both physical fitness and cognitive control measurements. For physical fitness assessments, scores for each test were recorded, with time-based tasks measured to the second, and count-based tasks only recording correct repetitions. The final scores were averaged from the results of two independent observers and converted into a percentage-based score according to national physical fitness standards. Cognitive control data were collected using E-Prime 3.0 software, with the E-Data Aid function used to extract data. Any corrupted files were recovered using E-Recovery3. The data were labeled "ID + name + paradigm + test date" for easy identification and tracking.

Data analysis

The collected data were subjected to normality testing using SPSS 26.0, and the results indicated that the data followed a normal distribution. Descriptive statistics, including mean ± standard deviation (X ± SD), were used to report the total physical fitness score and three cognitive control variables (inhibition of interference, impulse control, and cognitive flexibility) at baseline (T1) and follow-up (T2) time points, providing a comprehensive view of the central tendency and variability of the data. Additionally, correlation analyses were conducted at both time points to explore the relationship between physical fitness and cognitive control, assessing the strength and direction of their associations over time. To address potential multicollinearity among predictor variables, we examined the Variance Inflation Factors (VIFs) and tolerance values before estimating the cross-lagged model. VIF values below 5 and tolerance values above 0.2 were considered indicative of acceptable levels of multicollinearity[38]. Multicollinearity diagnostics indicated that all VIF values were below 2.3, and all tolerance values were above 0.43, suggesting no significant multicollinearity issues among the predictors. Therefore, the stability of parameter estimates in the cross-lagged model was deemed acceptable. To examine the dynamic temporal relationship between physical fitness and cognitive control, a cross-lagged analysis using Structural Equation Modeling (SEM) was conducted to analyze the changes between baseline (T1) and follow-up (T2). In this study, Mplus 8 was used for the cross-lagged model analysis to test the bidirectional effects between physical fitness and cognitive control, thereby providing a comprehensive understanding of their changes over time. Mplus 8 offers advanced features for handling complex models and missing data, providing greater flexibility in modeling situations where other software might not fully recognize the model. By using Mplus 8, the robustness and reliability of the results were ensured. All three cross-lagged models were saturated (i.e., degrees of freedom = 0), meaning that the number of estimated parameters equaled the number of observed variances and covariances. Consequently, standard fit indices such as CFI and RMSEA were not available. Although saturated models can offer a full representation of the data, they may also risk overfitting. To address this, we additionally tested more constrained models by fixing non-significant paths to zero, and found that the main patterns of significant associations remained consistent. This supports the robustness and replicability of the key findings. Finally, to test potential moderation effects, we employed chi-square difference tests to compare constrained and unconstrained cross-lagged panel models. Although multi-group SEM is considered the gold standard for testing moderation, it was not adopted in the present study due to the relatively small sample size within each subgroup (e.g., 64 boys vs. 79 girls). Therefore, the chi-square difference test served as a more parsimonious and statistically valid alternative to evaluate whether constraining paths across groups significantly reduced model fit, with gender as the grouping variable (male = 1, female = 2). The level of statistical significance was set at $p < 0.05$. Measurement invariance across gender was tested before model comparison using a stepwise procedure, including configural, metric, and scalar invariance. The results supported at least metric invariance, indicating that path coefficients could be meaningfully compared across groups[39].

Results
Descriptive results

Table 1 summarizes the descriptive statistics of physical fitness and cognitive control abilities among Chinese early adolescents, stratified by gender. No significant age difference was found between boys and girls ($P = 0.297$). However, girls consistently outperformed boys in several aspects of both physical fitness and cognitive control. At T1, girls showed significantly higher physical fitness levels (M = 82.51, SD = 8.09) compared to boys (M = 72.19, SD = 10.44, $P < 0.001$). In terms of interference inhibition, girls had lower scores, indicating better performance (M = 596.55, SD = 183.3 vs. M = 752.2, SD = 244.94, $P < 0.001$). Similarly, girls exhibited higher impulse control (M = 0.89, SD = 0.11 vs. M = 0.84, SD = 0.10, $P < 0.01$). There was no significant gender difference in cognitive flexibility ($P = 0.63$). At T2, the trend persisted, with girls maintaining significantly higher physical fitness

	Boys (*n* = 64)		Girls (*n* = 79)		
Variable	M	SD	M	SD	P-value
Age	12.66	0.51	12.75	0.52	0.297
Physical fitness scores (T1)	72.19	10.44	82.51	8.09	**< 0.001**
Interference inhibition (T1)	752.2	244.94	596.55	183.3	**< 0.001**
Impulse control (T1)	0.84	0.1	0.89	0.11	**< 0.01**
Cognitive flexibility (T1)	883.75	329.73	908.88	281.58	0.63
Physical fitness scores (T2)	73.11	11.8	79.51*	8.98	**< 0.001**
Interference inhibition (T2)	636.87*	232.71	589.89	163.53	0.159
Impulse control (T2)	0.8*	0.14	0.89	0.12	**< 0.001**
Cognitive flexibility (T2)	802.54*	318.08	983.1*	239.49	**< 0.001**

Table 1. Descriptive statistics of physical fitness and cognitive control in Chinese early adolescents. *Statistically significant difference from T1 to T2 within gender group, *p* < 0.05 (paired-sample t-test). Significant values are in bold.

	Variable	1	2	3	4	5	6	7	8
1	Physical fitness scores (T1)	1							
2	Interference inhibition (T1)	− 0.582**	1						
3	Impulse control (T1)	0.282**	− 0.333**	1					
4	Cognitive flexibility (T1)	− 0.548**	0.394**	− 0.182*	1				
5	Physical fitness scores (T2)	0.618**	− 0.492**	0.289**	− 0.317**	1			
6	Interference inhibition (T2)	− 0.342**	0.322**	− 0.239**	0.307**	− 0.379**	1		
7	Impulse control (T2)	0.301**	− 0.348**	0.587**	− 0.138	0.307**	− 0.27**	1	
8	Cognitive flexibility (T2)	− 0.516**	0.396**	− 0.218**	0.306**	− 0.8**	0.443**	− 0.297**	1

Table 2. Correlation matrix between physical fitness and cognitive control in Chinese early adolescents. **P < 0.01, *P < 0.05.

levels ($P < 0.001$). However, no significant gender difference was observed in interference inhibition ($P = 0.159$). Girls continued to outperform boys in impulse control (M = 0.89, SD = 0.12 vs. M = 0.80, SD = 0.14, $P < 0.001$). In cognitive flexibility, boys showed superior performance at T2, with significantly lower scores (M = 802.54, SD = 318.08 vs. M = 983.10, SD = 239.49, $P < 0.001$). These results highlight significant gender differences in physical fitness and cognitive control, with girls demonstrating advantages in most measures across both time points, while boys excelled in cognitive flexibility at T2.

In addition to examining gender differences at each time point, we conducted paired-sample t-tests within each gender group to evaluate changes from T1 to T2. As indicated in Table 1, boys showed significant improvements in interference inhibition, impulse control, and cognitive flexibility. Girls exhibited significant improvements in physical fitness scores and cognitive flexibility over time. These results highlight developmental changes during early adolescence and underscore the importance of examining within-gender trajectories.
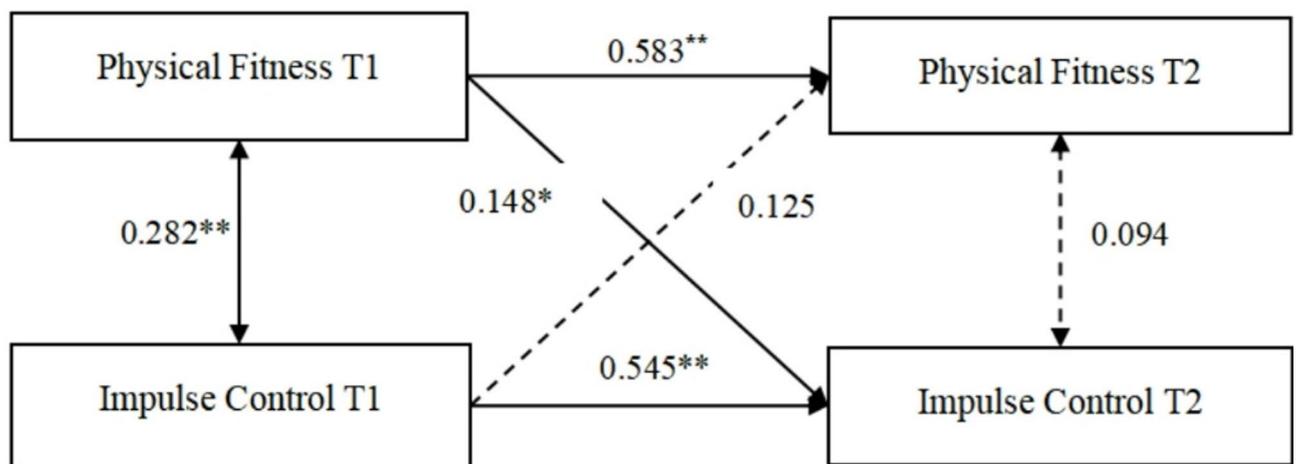
Correlation analysis

Table 2 presents the correlation matrix between physical fitness levels and cognitive control among Chinese early adolescents. The results show significant associations across various variables. At T1, total physical fitness scores were negatively correlated with interference inhibition ($r = − 0.582$, $P < 0.01$) and cognitive flexibility ($r = − 0.548$, $P < 0.01$), but positively correlated with impulse control ($r = 0.282$, $P < 0.01$). Similarly, at T2, physical fitness scores exhibited significant negative correlations with interference inhibition ($r = − 0.492$, $P < 0.01$) and cognitive flexibility ($r = − 0.8$, $P < 0.01$), and a positive correlation with impulse control ($r = 0.289$, $P < 0.01$). These findings indicate that higher levels of physical fitness are generally associated with enhanced cognitive control, as evidenced by superior interference inhibition, impulse control, and cognitive flexibility.

Cross-lagged analysis between physical fitness levels and interference inhibition

The cross-lagged analysis between physical fitness levels and interference inhibition (Fig. 5) demonstrated significant bidirectional effects. Specifically, physical fitness levels at T1 significantly predicted interference inhibition at T2 ($\beta = -0.234$, $P < 0.05$), and interference inhibition at T1 significantly predicted physical fitness levels at T2 ($\beta = -0.2$, $P < 0.05$). Based on Eisma's (2019) criteria for causal inference, which require that the correlation between Variable A at T1 and Variable B at T2 be stronger than the reverse and that the stability of Variable A across time be greater than that of Variable B[40], the results suggest a causal relationship. Physical fitness levels are likely the primary driving factor influencing changes in interference inhibition.
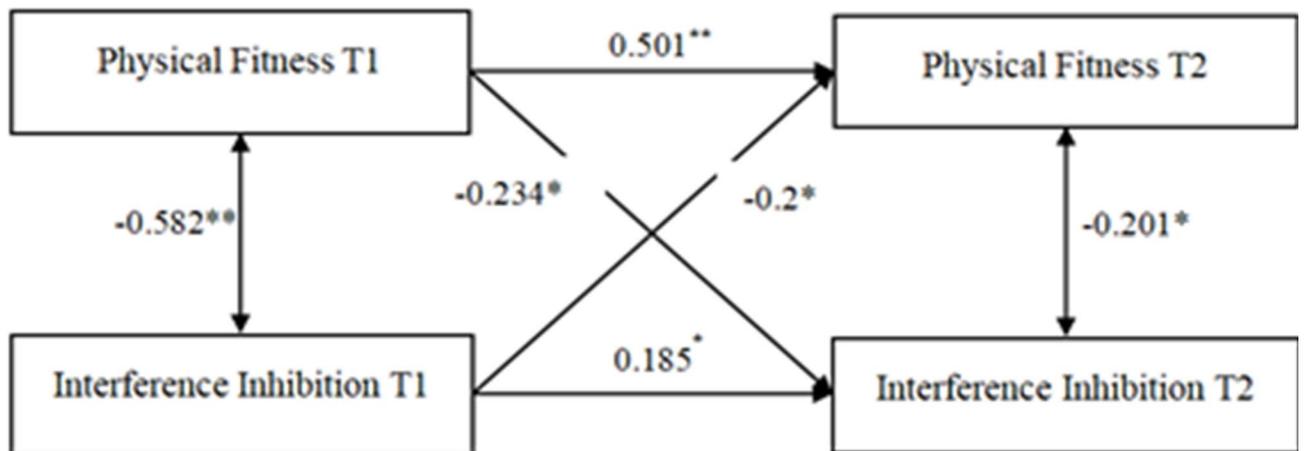
Fig. 5. Cross-lagged relationship model between physical fitness and interference inhibition in Chinese early adolescents.
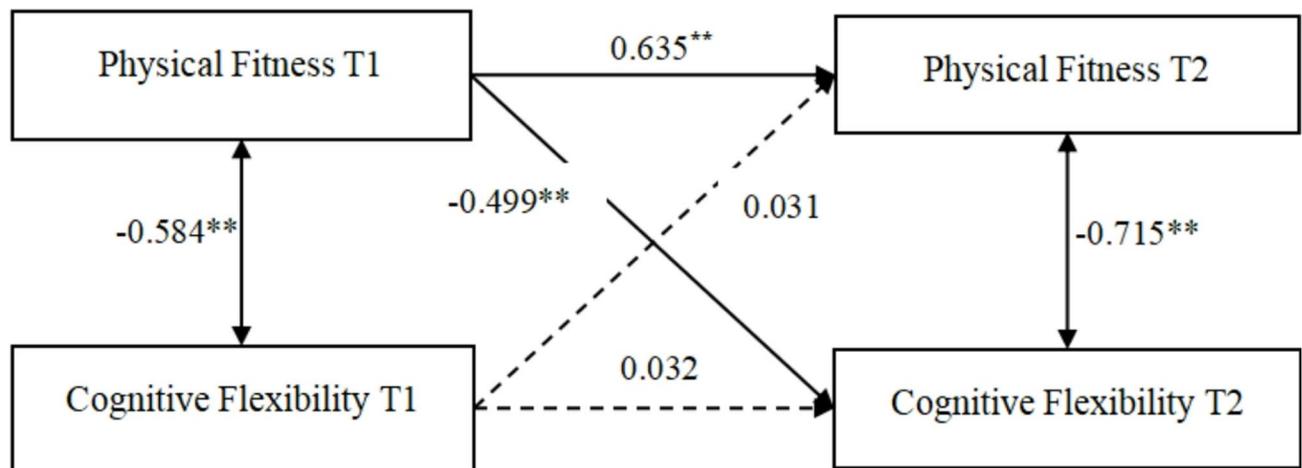

Fig. 6. Cross-lagged relationship model between physical fitness and impulse control in Chinese early adolescents.

Cross-lagged analysis between physical fitness levels and impulse control

The cross-lagged analysis between physical fitness levels and impulse control (Fig. 6) revealed that physical fitness levels at T1 significantly predicted impulse control at T2 ($\beta = 0.148$, $P < 0.05$), indicating that higher baseline physical fitness contributes to improvements in impulse control over time. However, impulse control at T1 did not significantly predict physical fitness levels at T2 ($\beta = 0.125$, $P > 0.05$), suggesting a weaker reciprocal relationship. Based on the theoretical framework, these findings suggest that physical fitness levels are likely the primary causal factor driving changes in impulse control. This underscores the critical role of physical fitness in enhancing cognitive control, particularly in improving impulse control.

Cross-lagged analysis between physical fitness levels and cognitive flexibility

The cross-lagged analysis between physical fitness levels and cognitive flexibility (Fig. 7) showed that physical fitness levels at T1 significantly predicted cognitive flexibility at T2 ($\beta = -0.499$, $P < 0.01$), suggesting that higher baseline physical fitness contributes to improvements in cognitive flexibility over time (with lower scores indicating better performance). Conversely, cognitive flexibility at T1 did not significantly predict physical fitness levels at T2 ($\beta = 0.031$, $P > 0.05$), indicating no reciprocal effect. Drawing from prior research and theoretical perspectives, these results suggest that physical fitness levels are likely the primary causal factor driving changes in cognitive flexibility. This underscores the essential role of physical fitness in enhancing higher-order cognitive processes such as cognitive flexibility.

Fig. 7. Cross-lagged relationship model between physical fitness and cognitive flexibility in Chinese early adolescents.

Gender differences in cross-lagged analysis between physical fitness levels and cognitive control

The results showed no significant gender differences in the cross-lagged relationships for interference inhibition and Impulse control. However, a significant gender difference was observed for cognitive flexibility ($\chi^2 = 2.566$, $P = 0.0362$). These findings suggest that gender differentially influences the relationship between physical fitness levels and cognitive flexibility. Specifically, among boys, higher physical fitness levels at baseline were associated with significantly better cognitive flexibility eight months later, whereas no significant relationship was found between physical fitness levels and cognitive flexibility development among girls. This underscores the moderating effect of gender on the impact of physical fitness levels on cognitive flexibility, indicating that the developmental trajectory of cognitive flexibility may differ between boys and girls.

Discussion

This study explores the relationship between physical fitness and cognitive control in Chinese early adolescents, with a particular focus on gender differences and changes over time. The findings reveal a significant bidirectional relationship between physical fitness and cognitive control, moderated by gender in certain aspects. Additionally, the impact of physical fitness on cognitive control is time-dependent, with distinct developmental trajectories emerging for boys and girls.

Gender differences in physical fitness and cognitive control among Chinese early adolescents

The study found that girls outperformed boys in all fitness indicators at both the T1 and T2 stages. This finding aligns with existing research, such as the National Student Physical Fitness Standards, which show that girls typically have a higher fitness pass rate than boys[41]. Similar results were reported by Qin Guoyang et al. (2023) in Jinan and Zhang Liqiang et al. (2023) in Tibet, where girls consistently scored higher than boys[42,43]. Physiologically, girls tend to mature faster than boys during puberty, which may contribute to their superior physical fitness and endurance[44]. Since the main focus of this study was to investigate the longitudinal relationship between overall physical fitness and cognitive control in adolescents, gender comparisons were conducted at the composite fitness level rather than for specific physical components such as cardiorespiratory endurance, muscular strength, or flexibility.

Regarding cognitive control, the study found gender differences across several aspects. Girls excelled in impulse control, a finding consistent with existing literature[45]. This may be due to earlier prefrontal cortex development in girls[46] and socialization processes that encourage greater self-discipline and behavioral control[47]. However, for interference inhibition, girls had a significant advantage at T1, but this difference disappeared by T2, likely due to the varying neurodevelopmental timelines between genders; as boys' cognitive abilities mature, they catch up with girls' abilities[46]. In terms of cognitive flexibility, no gender differences were observed at T1, but boys outperformed girls at T2. One possible explanation is that boys may engage more frequently in dynamic sports, such as basketball and football, which require rapid decision-making and adaptability. These types of physical activities might contribute to the development of cognitive flexibility. However, this interpretation is speculative and was not directly assessed in the present study. Future research should explore this possibility empirically. In addition, alternative mechanisms such as differences in hormonal maturation (e.g., testosterone-related neurodevelopment) or sex-specific trajectories of neural plasticity may also contribute to gender differences in cognitive flexibility[48,49]. These factors warrant further investigation to better understand the developmental dynamics underlying cognitive flexibility in adolescence.

The significant improvements observed in boys' interference inhibition, impulse control, and cognitive flexibility, as well as the improvements in girls' physical fitness scores and cognitive flexibility, highlight important developmental differences between the genders during early adolescence (ages 10–14). These findings

underscore that early adolescence is a period of significant growth, with distinct developmental pathways for boys and girls in both physical and cognitive domains[50]. The results highlight the necessity for gender-specific interventions that address these developmental differences and promote balanced growth across both domains.

Causal relationship between Chinese early adolescents' physical fitness and cognitive control

The results indicate a significant relationship between physical fitness and cognitive control, with physical fitness partially predicting changes in cognitive control. Specifically, the study revealed a bidirectional relationship between physical fitness and interference inhibition. Higher physical fitness at T1 significantly predicted better interference inhibition performance at T2 ($\beta = -0.234$, $P < 0.05$), as reflected by lower IES scores. Conversely, better interference inhibition at T1 also predicted improvements in physical fitness at T2 ($\beta = -0.2$, $P < 0.05$). Previous research has shown that higher levels of physical activity and better physical fitness can predict improvements in cognitive control, particularly interference inhibition[51]. These findings suggest a reciprocal and reinforcing relationship between physical fitness and cognitive control, which may be particularly relevant during early adolescence, a developmental stage characterized by heightened vulnerability to distraction and impulsivity. Early adolescents, in particular, are especially vulnerable to external distractions, such as mobile phone use or peer interactions, which can disrupt their exercise routines[52]. Adolescents with weaker interference inhibition may struggle to resist such distractions and maintain regular physical activity, whereas stronger inhibition may support self-regulation and exercise adherence. This perspective is supported by previous research suggesting that cognitive control, including interference inhibition, plays a critical role in goal-directed behaviors and health-related habit formation[2,16]. Therefore, the observed bidirectional relationship between physical fitness and interference inhibition may reflect a dynamic interplay in which neurocognitive development both influences and is influenced by physical activity engagement.

The study highlighted a unidirectional relationship between physical fitness and impulse control. Specifically, higher physical fitness at T1 significantly predicted better impulse control performance at T2 ($\beta = 0.148$, $p < 0.05$), suggesting that adolescents with greater physical fitness demonstrated enhanced ability to regulate impulsive behaviors over time. Conversely, impulse control at T1 did not show a significant predictive relationship with physical fitness at T2. This underscores the idea that improvements in physical fitness are a key factor in enhancing impulse control, while the reverse effect is less evident. These findings align with previous research emphasizing that physical fitness, particularly aerobic fitness, is associated with improved self-regulation and impulse control[16,53,54]. Although our study did not include neurophysiological data, previous research has suggested that improvements in impulse control through physical activity may be mediated by enhanced functioning of the prefrontal cortex, a brain region associated with inhibitory control[55]. Physical activity has also been linked to increased cerebral blood flow and changes in neurotransmitter levels (e.g., dopamine, serotonin), which may support neuroplasticity and cognitive regulation[55]. These potential mechanisms warrant further investigation in future studies employing neuroimaging or neurochemical assessments. In addition, activities like tennis or swimming that demand continuous self-monitoring and decision-making may further foster impulse control across various scenarios. The weaker predictive effect of impulse control on physical fitness may be related to the relative stability of physical fitness levels over short periods, in contrast to the greater plasticity observed in cognitive functions. Future research could investigate whether long-term gains in impulse control can meaningfully impact physical fitness by boosting motivation and encouraging sustained participation in physical activities.

Regarding cognitive flexibility, the study found that adolescents with higher physical fitness at T1 demonstrated significantly better performance in cognitive flexibility at T2 ($\beta = -0.499$, $P < 0.01$), as indicated by lower IES scores. This suggests a positive impact of physical fitness on the development of cognitive flexibility. In contrast, cognitive flexibility at T1 did not significantly predict physical fitness at T2, suggesting that improvements in cognitive flexibility had limited effects on physical fitness during the study period. Cognitive flexibility is the capacity to adapt thinking and behavior in dynamic situations and is essential for cognitive control and problem-solving. These findings are consistent with previous research suggesting that physical activity may enhance neural efficiency[56,57], which plays important roles in attention switching and cognitive flexibility. However, our study did not directly measure neural activity, so this interpretation remains speculative. Behaviorally, engaging in dynamic, decision-heavy physical activities may directly enhance cognitive flexibility; for instance, sports like basketball and soccer require players to quickly analyze and alter strategies in reaction to opponents' actions, paralleling real-world cognitive flexibility demands. Future research should investigate how different types, intensities, and durations of physical activity moderate the relationship between physical fitness and cognitive flexibility.

The moderating role of gender in the relationship between Chinese early adolescents' physical fitness and cognitive control

This study further explored the moderating role of gender in the relationship between physical fitness and cognitive control. The results revealed a significant gender difference in the relationship between physical fitness and cognitive flexibility. Specifically, physical fitness at T1 significantly predicted cognitive flexibility at T2 in boys ($\chi^2 = 2.566$, $P = 0.0362 < 0.05$), while no such relationship was found in girls. This suggests that gender significantly influences how physical fitness impacts cognitive flexibility. Specifically, for boys, a greater level of physical fitness at the first time point (T1) significantly predicted enhancements in cognitive flexibility at the second time point (T2). In contrast, this relationship was not found for girls, indicating a potential difference in how physical fitness affects cognitive abilities based on gender. One possible explanation relates to the differing patterns of sport participation[58]: boys are more likely to engage in physically intense and cognitively demanding sports (e.g., basketball, football) that promote decision-making and adaptability[59], whereas girls may participate more in structured or less dynamic activities, such as skipping or dance. In addition to behavioral differences,

neurodevelopmental factors may also contribute to this divergence. Prior research has demonstrated sex-specific trajectories in brain maturation during adolescence, including differences in prefrontal cortex development, white matter integrity, and functional connectivity—all closely related to executive functions such as cognitive flexibility[48,60]. Moreover, hormonal changes during puberty, particularly fluctuations in testosterone and estrogen, may further shape these neurocognitive pathways. These biological and experiential factors may interact with physical fitness to produce gender-differentiated cognitive outcomes. Future research should consider incorporating neurobiological assessments to clarify these mechanisms.

Practical implications and applications

The findings of this study have important practical implications for promoting physical fitness and cognitive control in early adolescents. First, the identified relationship between physical fitness and cognitive control suggests that increasing physical activity, particularly activities aimed at improving fitness, can enhance cognitive functions. Schools and families can support holistic child development by providing more opportunities for physical activities, especially those promoting physical fitness and cognitive flexibility, such as basketball and football. Second, the observed gender differences highlight the importance of designing gender-sensitive physical education programs. Tailored interventions may help maximize the cognitive benefits of physical activity. For boys, physical education curricula might prioritize dynamic, fast-paced activities that require rapid information processing and decision-making, such as soccer, basketball, or table tennis, to strengthen cognitive flexibility. For girls, incorporating structured yet cognitively engaging activities such as rhythmic gymnastics, martial arts, or dance-based coordination training may support improvements in impulse control and overall self-regulation. These differentiated approaches could foster equitable cognitive development and optimize the impact of physical fitness programs in school and community settings.

Research limitations and future research directions

This study has certain limitations. First, the diversity of the sample could be further enhanced. This study exclusively recruited adolescents from Guangzhou, which restricts the external validity of the findings. Future research should consider including participants from multiple cities to increase sample diversity, thereby enhancing the generalizability of the results. Second, the duration of the longitudinal study could be extended. Initially, this study aimed to track a cohort of adolescents for 12 months; however, due to scheduling constraints at the participating schools, the tracking period was limited to 8 months. A longer tracking period in future studies would provide a more comprehensive understanding of the evolving relationship between physical fitness and cognitive control over time. Finally, the number of testing phases could be increased. In this study, two testing phases were conducted over the 8 months. To further substantiate causal relationships, future research could incorporate three testing phases over 12 months. This extended approach would allow for a more detailed exploration of the temporal dynamics between physical fitness and cognitive control.

Conclusion

This study sheds new light on the bidirectional relationship between physical fitness and cognitive control in early adolescents within a non-Western context. While girls demonstrated consistently higher physical fitness scores and impulse control, boys exhibited greater gains in cognitive flexibility over time. The findings underscore the predictive role of physical fitness—especially in enhancing cognitive flexibility—and highlight that interference inhibition can, in turn, support the maintenance of physical fitness. These results contribute to a growing body of literature emphasizing the dynamic interplay between physical and cognitive development during early adolescence. Importantly, the observed gender-specific pathways suggest that a one-size-fits-all approach to promoting youth development may be suboptimal. These insights hold practical implications for designing culturally and developmentally appropriate physical education curricula and public health interventions. Programs that integrate physical activity with cognitive stimulation—especially those tailored by gender—can be strategically implemented in schools to support both physical and mental development during this critical life stage.

Data availability

The data of this study can be obtained upon reasonable request to the corresponding author.

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Author contributions

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee for Scientific Research of Guangzhou College of Commerce (No. GCC2023-003). All methods were performed in accordance with the relevant guidelines and regulations, and informed consent was obtained from each participant's legal guardian.

Additional information

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