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Association between physical activity and executive function of Chinese adolescents aged 13–18

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Objective: This study aimed to investigate the relationship between physical activity (PA) and executive function (EF) among adolescents in China.

Methods: Using a stratified cluster random sampling, we recruited 4,991 adolescents from 11 Chinese cities, including Urumqi, Lhasa, and Naqu etc. Participants completed execution function test and PA questionnaire survey. Data were analyzed using one-way ANOVA, *Pearson* correlation analysis, and 30-minute isotemporal substitution models (ISM) to assess the association between PA and EF.

Results: Daily moderate-to-vigorous physical activity (MVPA) time in both boys and girls was negatively correlated with inhibitory control RTs ($r = -0.279$, -0.173 , $P < 0.01$), 2back-RTs ($r = -0.367$, -0.268 , $P < 0.01$), and cognitive flexibility RTs ($r = -0.283$, -0.305 , $P < 0.01$). Replacing 30 min of sedentary behaviour (SB) with MVPA was significantly shorter RTs in inhibitory control ($P < 0.05$), 2back tasks ($P < 0.01$), and cognitive flexibility ($P < 0.01$). Similarly, substituting 30-min of light physical activity (LPA) with MVPA led to reduced RTs in all three EF domains ($P < 0.05$ for inhibitory control; $P < 0.01$ for others). After adjusting for covariates, a U-shaped dose-response relationship emerged between MVPA duration and EF performance. Adolescents with 59.02–60.88 min/day of MVPA (the relatively high-level group) demonstrated the lowest RTs in inhibitory control, working memory, and cognitive flexibility ($P < 0.05$).

Conclusions: After controlling for confounders, MVPA exhibited an inverted U-shaped relationship with inhibitory control, working memory, and cognitive flexibility. Optimal EF improvement was observed at 59.02–60.88 min/day of MVPA, suggesting this range may be most beneficial for adolescents' executive function.

KEYWORDS

inhibitory control, working memory, cognitive flexibility, physical activity, executive function, adolescents

1 Introduction

Executive function (EF) has become an important area of research in various academic fields including psychology, education, and physical education. With the increase of interdisciplinary research, more scholars have focused on the relationship between physical activity (PA) and EF of adolescents. Previous studies

have indicated that PA is most closely associated with the sub-functions of EF (inhibitory control, working memory, and cognitive flexibility). (1). However, research on the correlation between PA and EF in adolescents remains inconclusive. Some studies have found a significant association between PA and EF among adolescents (2, 3) and long-term regular PA has been shown to benefit the improvement of EF of adolescents (1, 4). In addition, numerous studies suggest that regularly increasing PA in adolescents enhances both EF and learning ability (5, 6), while a lack of long-term PA has negative effects on EF (7).

However, others studies have found no significant difference between PA and EF in adolescents (8–10). These discrepancies may be due to factors such as differences in sample sizes and selection of subjects, variations in methods for assessing PA and EF, and the control of independent variables. Additionally, research on the relationship between different levels of sedentary behavior (SB), PA (including LPA, low physical activity; MVPA, moderate-to-vigorous physical activity; TPA, total physical activity.) and the sub-functions of EF among adolescents remains limited and lacks depth.

Building on previous studies, PA is recognized as an important, controllable, and easily modifiable factor affecting the EF of adolescents. Therefore, this study aims to investigate the relationship between PA and EF in adolescents, with a particular focus on the optimal amount of daily PA required to achieve the greatest improvement in EF. The findings of the study will help identify effective strategies to promote the healthy development of EF among adolescents.

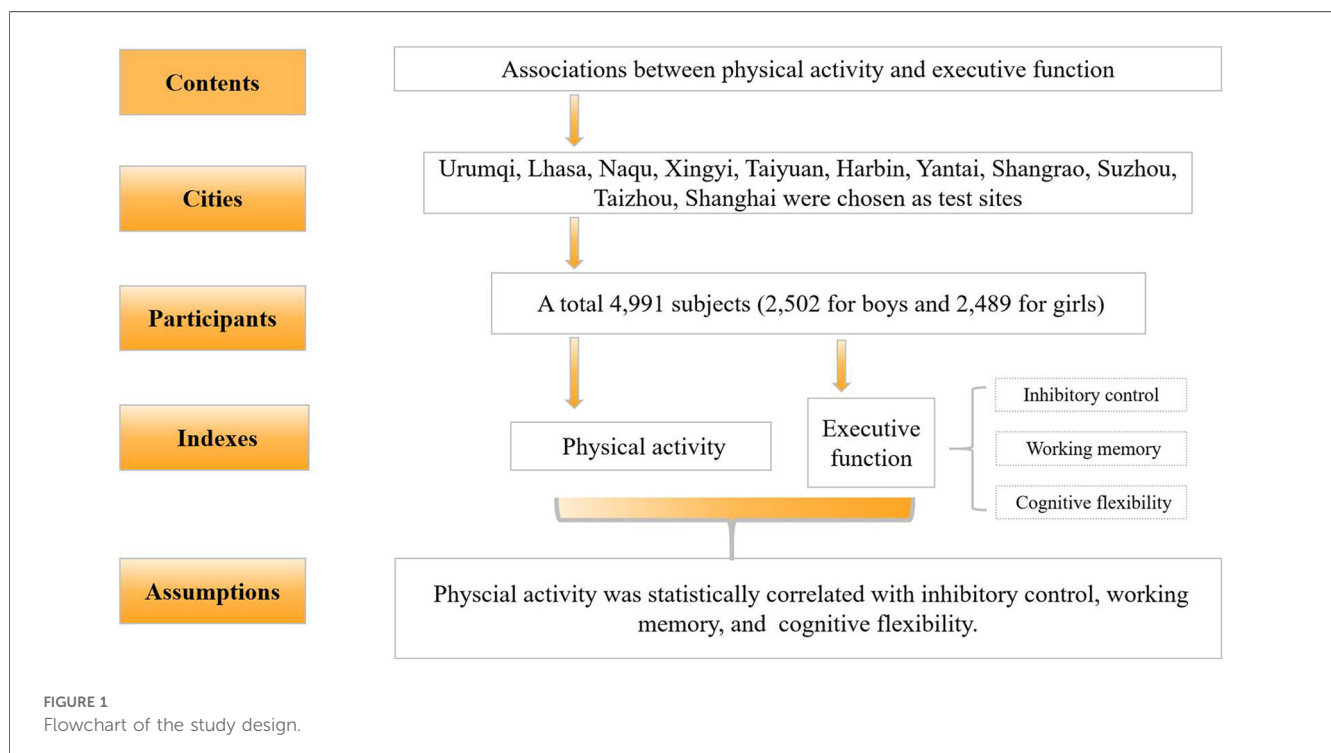
2 Methods

2.1 Data sources and participants recruitment

A stratified random cluster sampling method was adopted to select test sites based on surveys of the physical health of Chinese students. Eleven cities —Urumqi, Lhasa, Naqu, Xingyi, Taiyuan, Harbin, Yantai, Shangrao, Suzhou, Taizhou, Shanghai —were included as test sites in this study. To minimize confounding factors, the participants with locomotor deficits or neurodevelopmental disorders that could potentially affect executive function (EF) were excluded prior to EF testing. Additionally, after conducting the EF test, only data from participants who achieved an accuracy rate exceeding 80% in each task were retained as valid. The inclusion criteria for participants were as follows: (1) aged 13–18 years, (2) no color blindness, and (3) no serious physical or mental illness. Following the exclusion of invalid data and outliers, and ensuring a gender ratio of approximately 1:1, a total of 4,991 participants (2,502 boys, 50.95%; 2,489 girls, 49.05%) were included in the final analysis. Data collection spanned from August 2023 to December 2024 across China (Figure 1).

2.2 Physical activity

To assess physical activity (PA) levels, we adopted the Health Industry Standard of the People's Republic of China (Physical



Activity Level Evaluation for Children and Adolescents Aged 7–18 Years) as the reference framework (11). The questionnaire demonstrated good internal consistency (Cronbach's $\alpha = 0.717$, $P < 0.01$) and high structural validity (12). Additionally, its test-retest reliability ($r = 0.69$) exceeded the minimum threshold of 0.60 (13), further supporting its robustness. Exercise intensity, as a critical dimension of physical activity, was quantified in Metabolic Equivalent of Task (MET) units (14). The World Health Organization (WHO) defines it as “the rate of work performed or the magnitude of force exerted during a given exercise or physical activity” (15). In accordance with the Ainsworth et al. (16) classification system for physical activity intensity, MET-based thresholds delineate three distinct categories:

Sedentary behavior (SB): <1.5 METs;

Low-intensity physical activity (LPA): ≥ 1.5 METs but <3 METs;

Moderate-intensity physical activity (MPA): ≥ 3 METs but ≤ 6 METs;

Vigorous-intensity physical activity (VPA): >6 METs.

2.3 Executive function and related assessments

The EF task-cuing paradigm was developed by Aiguo et al. (17) and includes tests for inhibition (Eriksen flanker task) (18), working memory test by (N-back task) (19), and cognitive flexibility (more-odd shifting task) (20). Reaction time (RT) served as the primary outcome measure for all tasks, with shorter RTs indicating superior performance. The difference in RT between incongruent and congruent trials was used to estimate inhibition. The 1-back and 2-back tests were used to assess working memory. The difference in RT between heterogeneous and homogeneous trials was used to estimate cognitive flexibility. The EF tests were conducted using a program created by the E-prime 1.1 software system (Psychology Software Tools Inc., Pittsburgh, USA).

2.4 Isotemporal substitution models

The 30-min ISM was employed to evaluate the relationship between the mutual substitution of SB, LPA, and MVPA and sub-function of EF. Prior to model execution, all activity durations (SB, light LPA, and MVPA) were normalized by dividing by 30-minute time units, consistent with physical activity guideline recommendations (21). Here, an increase of 1 unit represents an additional 30 min per day. Constructing the isotemporal substitution model involves three steps: building single-factor models, developing the partition model, and performing isotemporal substitution. The single-factor model examines the relationship between each activity behavior and the dependent variable, adjusted for confounders but without accounting for other activity types or considering substitution effects. Taking SB as an example—the single-factor model is: dependent variable = (β_1) SB + (β_5) covariates. The partition

model is: dependent variable = (β_1) SB + (β_2) LPA + (β_3) MVPA + (β_5) covariates, where the coefficients of activity behaviors indicate the improvement of time changes while keeping other activities constant. The isotemporal substitution model represents the improvement of replacing one activity type with another while keeping the total wear time constant. For example, replacing SB with LPA or MVPA, the isotemporal substitution model is: dependent variable = (β_2) LPA + (β_3) MVPA + (β_4) total activity time + (β_5) covariates.

2.5 Covariates

The study covariates included age (22), gender (23), site location (24), socioeconomic status (25), body mass index (26), waist circumference (27), breakfast frequency per week (28), and sugar-sweetened beverage (29) consumption. Data on age, gender, site location, breakfast frequency, and SSB consumption were collected using questionnaires derived from the Chinese National Survey on Students' Constitution and Health (CNSSCH) (30). Information on breakfast intake was obtained by separate questionnaires with four questions in the past 7 days. Respectively are “How many times did you have breakfast? (≤ 2 , 3–4, 5–7)”, “What is the frequency of eating milk? (≤ 2 , 3–4, 5–7)”, “How many times did you drink sugar-sweetened beverage (SSB)? (≤ 2 , 3–4, 5–7)”, and “What is the frequency of eating soybean product consumption in the past 7 days? (≤ 2 , 3–4, 5–7)”. Physical health, height, weight, and WC of the participants were taken according to the implementation rules of the 2014 national survey (31). BMI was calculated as weight (kg) divided by height (m) square.

2.6 Statistical analyses

Firstly, the normality test was performed on the data. If the data followed a normal distribution, mean \pm standard deviation (SD) was used to describe the data. For data that did not follow a normal distribution, quartiles ($<P_{25}$, $P_{25}-P_{50}$, $P_{50}-P_{75}$, and $>P_{75}$) were used to describe the data (32). According to MVPA, the cut-off points were based on P_{25} , P_{50} , and P_{75} percentiles for each age and gender (33, 34) categorizing participants into the following MVPA groups: lowest MVPA group ($MVPA < P_{25}$), lower MVPA group ($P_{25} \leq MVPA < P_{50}$), higher MVPA group ($P_{50} \leq MVPA \leq P_{75}$), and highest MVPA group ($MVPA > P_{75}$). The correlation between PA and RT of EF was assessed by Pearson correlation. A linear regression model was applied to diagnose multicollinearity, aiming to minimize distortion caused by high correlations between independent variables. After addressing multicollinearity of the independent variables, a linear regression model was applied to explore the effects of SB, LPA, MVPA and TPA on the EF of adolescents. Corresponding data analysis was conducted using SPSS 26.0 software, with $\alpha = 0.05$ set as the two-tailed

test level. Image processing was performed using Origin Pro9.1 software.

3 Results

3.1 Descriptive characteristics for various variables

The study included 2,950 participants (59.11%) from urban areas and 2041 (40.89%) from rural areas (Table 1). Socioeconomic status (SES), distribution was as follows: high SES ($n = 968$, 19.40%), middle SES ($n = 2,071$, 41.49%), and low SES ($n = 1,952$, 39.11%), with the middle SES group representing the largest proportion. Participant characteristics stratified by sedentary behavior (SB), light physical activity (LPA), moderate-to-vigorous physical activity (MVPA), and total physical activity (TPA) levels are detailed in Table 1.

3.2 Pearson correlation of SB, LPA, MVPA, and TPA in different EF RTs groups

Figure 2 presents the Pearson correlation coefficients between SB, LPA, MVPA, and TPA with RTs across different executive function domains, stratified by gender. Positive correlations are denoted in orange, while negative correlations are indicated in green, with color intensity reflecting the strength of association. There was no significant correlation between daily SB and inhibitory function RTs in the youth cohort. However, daily MVPA time exhibited a significant negative correlation with inhibitory function RTs ($P < 0.05$). Daily SB time showed a positive correlation with working memory RTs in both males and females ($r = 0.142, 0.183, P < 0.01$). Conversely, daily LPA and MVPA time were negatively correlated with working memory RTs in both genders ($P < 0.05$). A positive correlation was observed between daily SB time and cognitive flexibility RTs, whereas daily MVPA time demonstrated a negative correlation ($P < 0.01$).

3.3 Isotemporal substitution model of SB, LPA, MVPA in different EF RTs groups

After adjusting for total time, isotemporal substitution analysis revealed significant associations between physical activity exchanges and executive function performance (Table 2). Isotemporal replacement of SB by MVPA for 30 min was associated with shorter inhibitory function RTs ($B = -0.062$, 95% CI: -0.081 to -0.005 , $P < 0.05$), working memory RTs ($B = -0.787$, 95%CI: -1.199 to -0.228 , $P < 0.01$), and cognitive flexibility RTs ($B = -0.359$, 95%CI: -0.471 ~ -0.9082 , $P < 0.01$). Isotemporal substitution model of LPA by MVPA for 30 min was associated with shorter inhibition RTs ($B = -0.023$, 95%CI: -0.041 to -0.009 , $P < 0.05$), working memory RTs ($B = -0.811$, 95%CI: -1.411 to -0.298 , $P < 0.01$), and cognitive flexibility RTs ($B = -0.377$, 95%CI: -0.528 to -0.094 , $P < 0.01$).

TABLE 1 Characteristics of the participants.

Characteristics	Overall (N = 4,991)
Age [y [mean (SD)]]	15.4 (1.7)
Sex [n (%)]	
Boys	2,502 (50.95)
Girls	2,409 (49.05)
Residential district, n (%)	
Urban	2,950 (59.11)
Rural	2,041 (40.89)
SES, n(%)	
Low SES	968 (19.39)
Middle SES	2,071 (41.49)
High SES	1,952 (39.12)
The frequency of eating breakfast, n (%)	
5–7 times/week	2,470 (49.49)
3–4 times/week	1,389 (27.83)
≤2 times/week	1,132 (22.68)
The frequency of eating milk, n (%)	
5–7 times/week	2,194 (43.96)
3–4 times/week	1,118 (22.40)
≤2 times/week	1,679 (33.64)
The frequency of eating SSB, n (%)	
5–7 times/week	908 (18.19)
3–4 times/week	1,191 (23.86)
≤2 times/week	2,892 (57.95)
The frequency of eating soybean product consumption, n (%)	
5–7 times/week	1,405 (28.15)
3–4 times/week	1,322 (26.49)
≤2 times/week	2,264 (45.36)
BMI, n (%)	
Underweight	384 (7.69)
Normal	3,516 (70.45)
Overweight	687 (13.76)
Obesity	404 (8.10)
WC (Mean, SD)	70.96 (10.01)
CRF (Mean, SD)	49.08 (9.33)
Inhibitory control RTs (Mean, SD)	8.44 (9.47)
Working memory RTs (Mean, SD)	1,060.72 (302.58)
Cognitive flexibility RTs (Mean, SD)	305.62 (171.64)
SB (Mean, SD)	671.93 (174.88)
LPA (Mean, SD)	33.68 (19.70)
MVPA (Mean, SD)	43.42 (26.53)
TPA (Mean, SD)	77.02 (22.17)

SES, social economic status; SSB, sugar-sweetened beverage; BMI, body mass index; WC, waist circumference; CRF, cardiorespiratory fitness; RT, reaction time; SB, sedentary behavior; LPA, low physical activity; MVPA, moderate-to-vigorous physical activity; TPA, total physical activity.

As shown in Table 3, the participants were divided into four groups according to the overall percentile of MVPA time. The linear regression analysis of MVPA on each sub-function of executive function RTs revealed that: In the Q3 ($59.02 \text{ min/day} \leq \text{MVPA} \leq 60.88 \text{ min/day}$) group, the absolute value of β coefficients of the influence of MVPA on inhibitory function RTs, working memory RTs, and cognitive flexibility RTs was higher than that in Q1 ($\text{MVPA} < 48.21 \text{ min/day}$), Q2 ($48.21 \text{ min/day} \leq \text{MVPA} < 59.02 \text{ min/day}$) and Q4 ($\text{MVPA} > 60.88 \text{ min/day}$) groups. The β coefficients were -0.102 ,

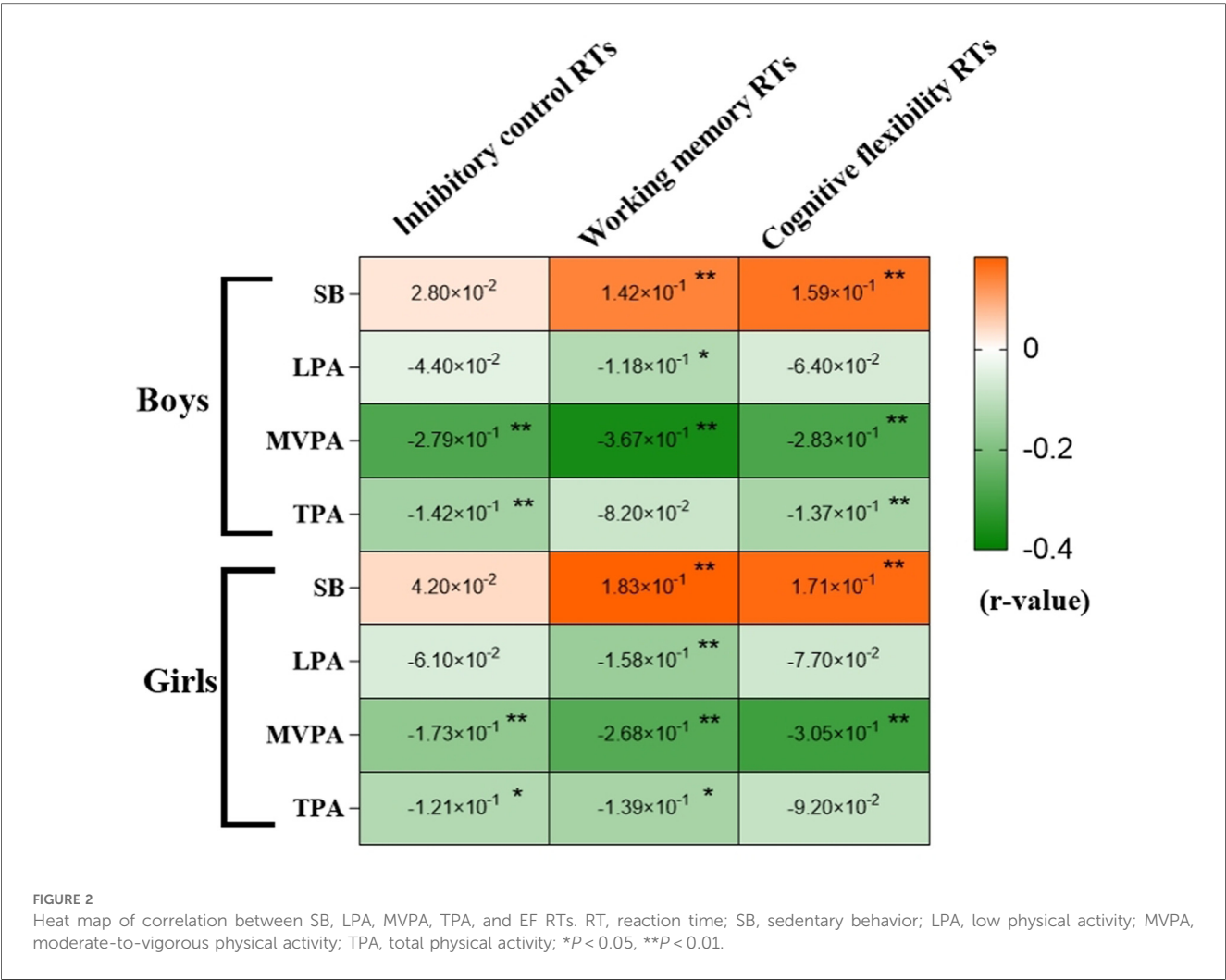


TABLE 2 The isotemporal substitution model of SB, LPA, MVPA on EF RTs.

Subgroups	30 min SB			30 min LPA		
	B	95% CI	B	95% CI	B	95% CI
Inhibitory control RTs						
Substitution- SB	–	–	–0.008	–0.024 to 0.002	–0.062*	–0.081 to –0.005
Substitution- LPA	0.008	–0.002 to 0.024	–	–	–0.023*	–0.041 to –0.009
Substitution- MVPA	0.062*	0.005~ 0.081	0.023*	0.009 to 0.041	–	–
Working memory RTs						
Substitution- SB	–	–	–0.079*	–0.301 to 0.127	–0.787*	–1.199 to –0.228
Substitution- LPA	0.079*	–0.127 to 0.301	–	–	–0.811**	–1.411 to –0.298
Substitution- MVPA	0.787**	0.228 to 1.199	0.811**	0.298~ 1.411	–	–
Cognitive flexibility RTs						
Substitution- SB	–	–	–0.051*	–0.153 to 0.078	–0.359**	–0.471 to –0.082
Substitution- LPA	0.051*	–0.078 to 0.153	–	–	–0.377**	–0.528 to –0.094
Substitution- MVPA	0.359**	0.082 to 0.471	0.377**	0.094 to 0.528	–	–

RT, reaction time; SB, sedentary behavior; LPA, low physical activity; MVPA, moderate-to-vigorous physical activity; *P < 0.05, **P < 0.01.

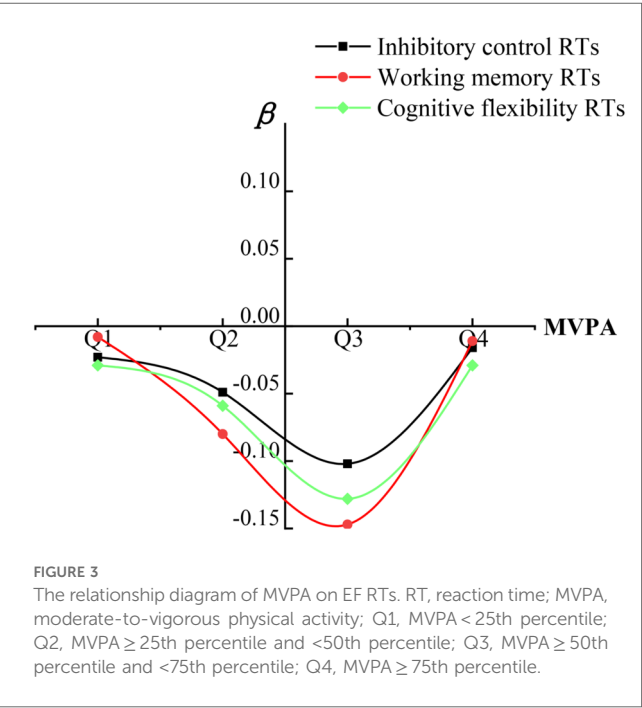
–0.147, and –0.128, respectively, and the differences were statistically significant ($P < 0.01$). The MVPA time of 59.02 min/day–60.88 min/day was beneficial to the improvement of the inhibitory control RTs, working memory RTs, and cognitive flexibility RTs.

In **Figure 3**, according to the overall percentile of MVPA time, participants were divided into four groups. The trend analysis confirmed a U-shaped relationship (**Figure 3**) between MVPA duration and: inhibitory control RTs, working memory RTs, and

TABLE 3 The association of MVPA on EF RTs among adolescents.

Subgroups	Q1 (95% CL)	Q2 (95% CL)	Q3 (95% CL)	Q4 (95% CL)
Inhibitory control RTs	−0.023 (−0.165 to 0.191)	−0.013 (−0.070 to 0.243)	−0.102 (−0.245 to −0.056)**	−0.016 (−0.157 to 0.069)
Working memory RTs	−0.008 (−2.441 to 3.169)	−0.080 (−1.126 to 5.108)	−0.147 (−5.721 to −1.660)**	−0.011 (−0.448 to 0.312)
Cognitive flexibility RTs	−0.029 (−2.013 to 0.621)	−0.059 (−2.145 to 0.474)	−0.128 (−2.125 to −0.340)**	−0.029 (−0.338 to −0.58)*

RT, reaction time; MVPA, moderate-to-vigorous physical activity; Q1, MVPA < 25th percentile; Q2, MVPA ≥ 25th percentile and <50th percentile; Q3, MVPA ≥ 50th percentile and <75th percentile; Q4, MVPA ≥ 75th percentile; **P* < 0.05, ***P* < 0.01.



cognitive flexibility RTs. The optimal MVPA range of 59.02–60.88 min/day showed the most pronounced benefits for all measured executive functions.

4 Discussion

Isochronous Substitution Analysis revealed that replacing 30 min of sedentary behavior with 30 min of MVPA significantly reduced reaction times (RTs) in adolescents' EF tasks (*P* < 0.05). In other words, the study on the relationship of LPA and MVPA on executive function RTs during physical activities has found that MVPA has a more significant promoting association on executive function. This study initially identified an inverted U-shaped relationship between daily MVPA levels and executive function performance. From a neurobiological mechanism perspective, this phenomenon may be attributed to cortical plasticity induced by increased cerebral blood flow, which is modulated by factors such as exercise duration and intensity. Specifically, sustained 60 min MVPA sessions likely optimize executive function enhancement by inducing structural adaptations (e.g., in the prefrontal cortex) through prolonged neural activation. This duration-dependent neuroplastic

improvement may explain the observed peak cognitive benefits within this time window (35, 36).

MVPA and TPA showed significant negative associations with inhibitory function RTs (*P* < 0.05), indicating shorter RTs (better performance) with higher activity levels. While, LPA exhibited no significant correlation with inhibitory RTs. Further study found that MVPA showed an inverted “U” -shaped association with the level of inhibitory function RTs of adolescents. Previous studies paid more attention to the relationship between physical activity and inhibitory function RTs of adolescents, while relatively few studies were conducted on the relationship between MVPA and inhibitory function among adolescents. Booth et al. (3) studied the relationship between physical activity and inhibitory function RTs of 4,755 adolescents, showing that compared with adolescents who lacked physical activity, the level of inhibitory function performance of adolescents who have been engaged in medium and high intensity physical activity for a long time was better. A comparative study on physical activity and inhibitory function among Finnish adolescents in Europe found that with the increase of MVPA, the inhibitory function level of adolescents showed a gradual upward trend (37). Ben-Zeev et al. (38) found that MVPA had a significant positive association on inhibitory function in adolescents (*P* < 0.05). In view of previous research analysis, long-term physical activity has a promoting relationship on the inhibitory function of adolescents, and MVPA had a more significant association inhibitory function.

Both MVPA and LPA were associated with improved working memory performance in adolescents, with MVPA demonstrating a stronger dose-response relationship compared to LPA. At present, the research on the correlation between MVPA and working memory among adolescents has been fully confirmed by most scholars. Valken-borghs et al. (39) found that the time increase of MVPA was conducive to the improvement of adolescents' working memory (*P* < 0.05). A Randomized Controlled Trial (RCT) on working memory in adolescents showed that long-term MVPA in adolescents had a significantly positive impact on working memory performance, and the difference was statistically significant (*P* < 0.05) (38). From the perspective of brain structure, the study analyzed the changing trends of the prefrontal lobe during the completion of working memory tasks across different age groups. The research revealed that the right prefrontal lobe plays a dominant role in 5–6-year-old children during test tasks, while in adults, the left prefrontal lobe is significantly more active during task completion (22). Combined with the results of previous studies and the results of this study, it was found that long-term physical activity had a certain promoting association on the working memory performance of

adolescents, and MVPA was more significantly relationship with working memory level than LPA among adolescents.

The results of this study showed that both MVPA and TPA were positively associated with improved cognitive flexibility performance in adolescents. MVPA demonstrated a stronger association with cognitive flexibility enhancement compared to TPA ($P < 0.05$). Early studies mainly focused on the correlation between TPA and cognitive flexibility RTs, but there were few studies on the associations of different physical activity levels on cognitive flexibility RTs. A study showed that the time of MVPA intervention of adolescents for 9 months had a significant improvement association on cognitive flexibility RTs by paired sample *t* test after intervention. Meanwhile, compared with the independent sample *t* test, the cognitive flexibility RTs of adolescents in the MVPA intervention group was significantly better than that in the control group, and the difference was statistically significant ($P < 0.05$) (1). Another study on the improvement of MVPA intervention with cognitive flexibility of adolescents in RCT showed that after exercise intervention, the level of cognitive flexibility among adolescents in the intervention group was better than that in the control group, and the difference was statistically significant ($P < 0.05$) (40). Combined with the results of previous studies and the results of this study, long-term regular physical activity was significantly positive on the improvement of adolescents' cognitive flexibility performance level, and MVPA had a better relationship on the improvement of cognitive flexibility level among adolescents.

4.1 Strengths and limitations

On the one hand, many previous studies have investigated the association between PA and EF in adolescents. However, their sample sizes were small and unrepresentative. The strengths of this study include the large sample size ($N = 4,991$) and representative data on the association between PA and EF of adolescents in China. Additionally, we compared the differences between the effects of LPA, MVPA on the EF of adolescents.

On the other hand, this study does have some limitations. As a cross-sectional investigation, it cannot establish a causal relationship between PA and EF, particularly the inability to infer causality.

5 Conclusions

Compared with daily LPA time, this study provided evidence that adolescents' daily MVPA time had a more significant improvement on their inhibitory function, working memory and cognitive flexibility. After controlling for other influencing factors, a "U-shaped" relationship existed between MVPA time and inhibition function RTs, working memory RTs, and cognitive flexibility RTs of adolescents, and an MVPA of 59.02–60.88 min/day had the improvement of the inhibition function, working memory, and cognitive flexibility of adolescents.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Ethics statement

The studies involving humans were approved by the Human Experiment Ethics Committee of East China Normal University (approval No. HR761–2022). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

YL: Conceptualization, Data curation, Investigation, Writing – original draft. XY: Data curation, Investigation, Software, Writing – original draft. YS: Data curation, Formal analysis, Methodology, Writing – original draft. FZ: Methodology, Resources, Visualization, Writing – review & editing. CB: Investigation, Software, Supervision, Writing – review & editing. YG: Software, Writing – review & editing. PS: Methodology, Writing – review & editing. HJ: Software, Writing – review & editing. YH: Formal analysis, Writing – review & editing. HL: Formal analysis, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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