Psychology of Sport & Exercise 66 (2023) 102374

Contents lists available at ScienceDirect

Psychology of Sport & Exercise

journal homepage: www.elsevier.com/locate/psychsport

Associations between physical activity and proactive control and the modulating role of working memory

Tian Ren [a,b], Xuejian Ye [a], Zheng Li [a], Qingyi Li [a], Xinyuan Zhang [a], Wenjie Dou [a], Xi Jia [a], Bao-ming Li [a], Chunjie Wang [a,c,*]

[a] *Institute of Brain Science and Department of Physiology, School of Basic Medical Sciences, Hangzhou Normal University, Hangzhou, China*
[b] *Jing Hengyi School of Education, Hangzhou Normal University, Hangzhou, China*
[c] *Zhejiang Key Laboratory for Research in Assessment of Cognitive Impairments, Hangzhou, China*

ARTICLE INFO

Keywords:
Physical activity
Dual mechanisms of control
Proactive control
Working memory
Young adults

ABSTRACT

Accumulating evidence indicates positive associations between physical activity (PA) and cognitive control. Proactive control, the ability to maintain goal-relevant information in preparation of upcoming task demands, is a critical component of cognitive control. However, little research has examined the association between PA and proactive control. To address this issue, a total of 132 university students were recruited and divided into two groups based on reported regular PA during past week. All participants completed two common cognitive control tasks: the AX Continuous Performance Task (AX-CPT) and the Cued Task-Switching Paradigm (CTS). In comparison with the low PA group, the high PA group showed greater proactive control efficiency on both tasks. Moreover, proactive control indices significantly correlated between the two tasks for the high but not for the low PA group. Further, working memory significantly modulated the association between PA and proactive control efficiency of CTS. Although the present cross-section design does not allow us to test the causal relationship between PA and proactive control, these findings may have important implications for developing effective intervention strategies which aim to promote proactive control through increasing PA or to promote PA through increasing proactive control. Moreover, individual differences in working memory are important to consider when we aim to design such interventions.

1. Introduction

Accumulating evidence suggests that reductions in physical activity (PA) are risk factors for various chronic diseases, which are in turn related to substantial societal economic burdens worldwide (Anderson & Durstine, 2019). By contrast, active participation in PA can bring benefits to physical and mental health (Stewart et al., 2017; Yang & D’Arcy, 2022). Recently, more and more researchers have paid attention to the association between PA and cognitive functions (Daly et al., 2015; Ludyga et al., 2022; Möhring et al., 2022; Muntaner-Mas et al., 2022). For example, increased PA has been found to be associated with better cognitive performance in attention, inhibitory control and task switching (Ludyga et al., 2022; Möhring et al., 2022; Trevillion et al., 2022). All these kinds of tasks are thought to engage processes of cognitive control, suggesting that participation in PA may be associated with better cognitive control.

Cognitive control refers to multiple cognitive processes engaged to regulate and coordinate goal-directed behavior. Notably, the main processes of cognitive control vary across situations. According to the dual mechanisms of cognitive control theory, cognitive control can be deployed into two distinct modes: proactive control and reactive control (Braver, 2012). These two types of cognitive control are engaged in different time courses. Proactive control occurs earlier. It involves preparatory, sustained activation of task rules and goal representations before goal-relevant stimuli occurs, operating in a top-down manner. In contrast, reactive control is engaged at a later stage. It involves transient activation of goal information after goal-relevant stimuli has occurred, operating in a bottom-up manner. Specifically, the top-down nature of proactive control results in it being a more effective process while consuming more demands on cognitive resources (Braver, 2012). It has been reported that good proactive control is essential for a variety of goal-oriented behaviors, such as attention, inhibition, academic skills,

---

* Corresponding author. Institute of Brain Science and Department of Physiology, School of Basic Medical Sciences, Hangzhou Normal University, Hangzhou. 311121, Zhejiang Province, China.

E-mail address: cjwang@hznu.edu.cn (C. Wang).

https://doi.org/10.1016/j.psychsport.2022.102374
Received 15 July 2022; Received in revised form 29 November 2022; Accepted 28 December 2022

and emotional regulation (Colomé et al., 2022; Hoorelbeke et al., 2016; C. Wang et al., 2021). In contrast, deficits in proactive control has been often observed in either the etiology or symptomology of various neuropsychological disorders that have difficulty in attention, inhibition, or other cognitive control abilities (Chidharom et al., 2021; Sidlauskaite et al., 2020; Valadez et al., 2021).

Although the extant literature has provided abundant evidence that active participation in PA is associated with better cognitive control, the majority of previous studies have focused on individual cognitive skills such as inhibitory control and task switching (Daly et al., 2015; Ludyga et al., 2022; Muntaner-Mas et al., 2022). Few research has been dedicated to examine the relationship between PA and the temporal dynamics in cognitive control modes (Braver, 2012). Interestingly, several previous studies have reported that better cognitive control observed in individuals actively participating in PA is often accompanied by favorable changes in the allocation of top-down neural resources (Belcher et al., 2021; Cirillo et al., 2017; C.-H. Wang et al., 2019). Given that the feature of proactive control lies in top-down control and relevant neural resources (Braver, 2012; Rainey et al., 2021), it seems reasonable to speculate that increased levels of PA is associated with better proactive control. Taking into account the critical role of proactive control in various goal-oriented cognitive control processes, investigation of this issue would advance our understanding of the relationship between PA and cognitive control.

To test this hypothesis, the present study administered two commonly used proactive control tasks: the AX Continuous Performance Task (AX-CPT) and the Cued Task-Switching Paradigm (CTS). The AX-CPT probes proactive control in the context of response inhibition (Gonthier et al., 2019), while the CTS probes proactive control in the context of task switching (Kubota et al., 2020). An interesting question is whether PA would be associated with better proactive control on both tasks. Prior research has reported some consistency in proactive control across tasks like AX-CPT and CTS, indicating that individuals who understand the advantages of using proactive control may consistently do so across different cognitive demands (Kubota et al., 2020; Zhou et al., 2022). Thus, we examined whether PA would be associated with a general advantage on proactive control in both tasks. Examining this question clarifies to what extent the association between PA and proactive control is stable or dependent on individual tasks. Besides, a recent study reported that as experience with proactive control increased, individuals could show greater consistency in proactive control engagement across inhibition and switching tasks (Zhou et al., 2022). Hence, we also explored whether PA would be associated with greater consistency in proactive control engagement across tasks. Furthermore, it has been suggested that the use of proactive control critically depend on working memory, as it requires continuous and active maintenance of goal-related information so as to optimally orient behavior (Zhou et al., 2022). Individuals with high working memory were also found to be more efficient in engaging proactive control than those with low working memory (Wiemers & Redick, 2018). Hence, we further explored whether individual difference in working memory would modulate the relationship between PA and proactive control. Addressing these issues would provide more clear evidence for the relationship between PA and cognitive control, which may provide useful information for developing more effective intervention strategies for promoting cognitive control or PA.

2. Methods

2.1. Participants

A total of 135 university students were recruited from the authors' university. Self-reports indicated that all subjects had no hearing loss, had normal or corrected-to-normal visual acuity, and had no history of psychiatric or neurological disorder. The sample size was based on a priori Power analysis using G*Power 3.1 with an α level of 0.05 and a power of 0.80, which showed that to detect a group difference with a medium effect size ($d = 0.50$), 128 participants would be required (about 64 participants in each group). To be more conservative, we decided to include 10 additional participants participating in this study. Three participants were excluded from analysis due to that they failed to complete all the behavioral tasks or could not remember the duration or frequency of their PA during last seven days. Consequently, 132 subjects constituted the final sample (mean age = 20.67 years, SD = 1.96, range = 18–26 years, 84 females). This study was approved by the Research Ethics Review Board of the authors' affiliated institution and was performed in accordance with rules laid down in the 1964 Declaration of Helsinki. Participants signed the consent form indicating they were voluntarily to participate in the study. None of the data reported below have been published previously or are under consideration elsewhere.

2.2. Materials

2.2.1. Physical activity

For each participant, the short version of the International Physical Activity Questionnaire (IPAQ) was used to estimate habitual practice of physical activities in a typical week (Lee et al., 2011). The good reliability and validity of the scale have been well approved among multiple sociocultural backgrounds (Craig et al., 2003). There are seven items that measure PA at three intensity levels: (1) vigorous-intensity activity such as aerobics, (2) moderate-intensity activity such as leisure cycling, (3) walking or light activity. These activities were further weighted by their energy requirements defined in Metabolic Equivalent Task (MET) to generate a composite score measuring total PA. More specifically, scores in each intensity level was calculated by multiplying the MET score of an activity by the minutes performed over a week (vigorous activity = 8.0 METs, moderate activity = 4.0 METs, and walking = 3.3 METs), and then total PA was calculated by the summation of vigorous, moderate, and walking activity in MET-minutes.

2.2.2. Proactive control

The proactive control tasks described below were based on a recent study on the development of proactive control in school-age children (Zhou et al., 2022). As the participants of this study were young adults, time limits of the cues and probes were adapted according to two previous studies examining proactive control in adult participants (Li et al., 2018; Shi et al., 2020).

AX-CPT. In this task, participants were presented with sequences of animal pictures, including pairs of cues and probes, and were instructed to press either a left (F) or right response key (J) on a QWERTY keyboard at the probe onset (Fig. 1). A target response was required when an X target (giraffe) occurred after an A cue (panda), while a non-target response was required if any other cue-probe cases occurred (AY, BX, BY). The response key assignment was counterbalanced across participants. AX trials made up half of the total trials, and AY, BX, and BY trials appeared equally for the remaining half trials. The task consisted of a practice session with one block (8 trials) and an experimental session with four blocks (30 trials per block). Each trial began with a fixation displayed on the center of the screen for 500 ms; followed by a cue animal picture for 500 ms, a blank interval for 1500 ms, a probe animal picture up to 1500 ms, and a second blank interval for 500 ms. Error rates and trimmed mean reaction times (RTs) of correct responses were calculated for each condition where trials with RTs above or below 3 SD from the individuals' mean were excluded. Similar to previous research using AX-CPT (Gonthier et al., 2019; Zhou et al., 2022), proactive control index (PCI) was calculated as (AY - BX)/(AY + BX) separately for RTs and error rates. A correction was made for trials where errors were equal to zero such that (error + 0.5)/(frequency of trials + 1). A higher value was indicative of greater efficiency in proactive control.

CTS. In this task, participants were instructed to flexibly switch between shape and color rules (Fig. 2). The shape rule required participants to classify a stimulus as a house or a tree, while the color rule

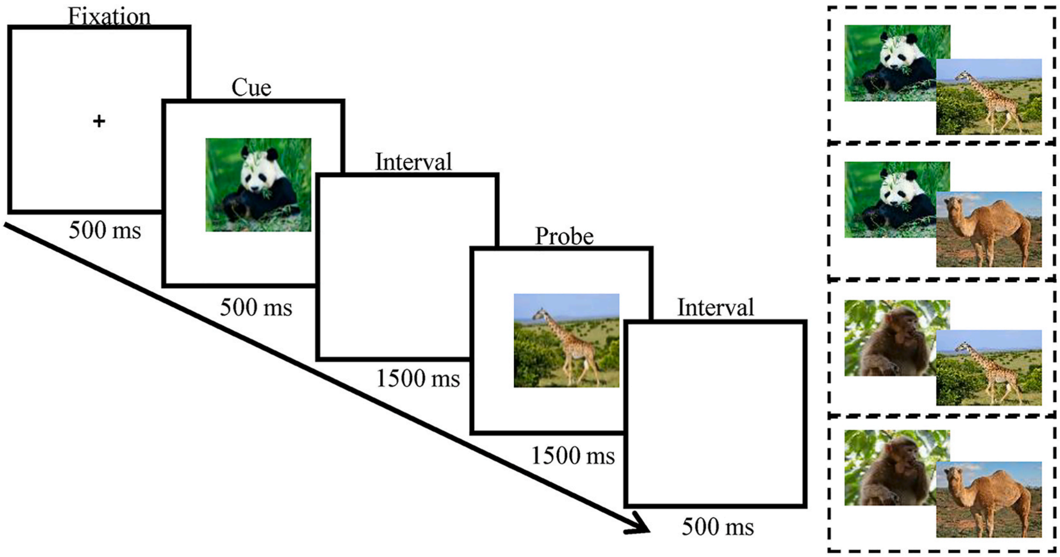

Fig. 1. Illustration of AX-CPT. On the left an example AX trial is presented (presented first with a panda and then a giraffe). On the right the four possible trial types and corresponding correct responses are presented. Participants are instructed to press a left button for AX trials, and press a right button for the other three types of trials.

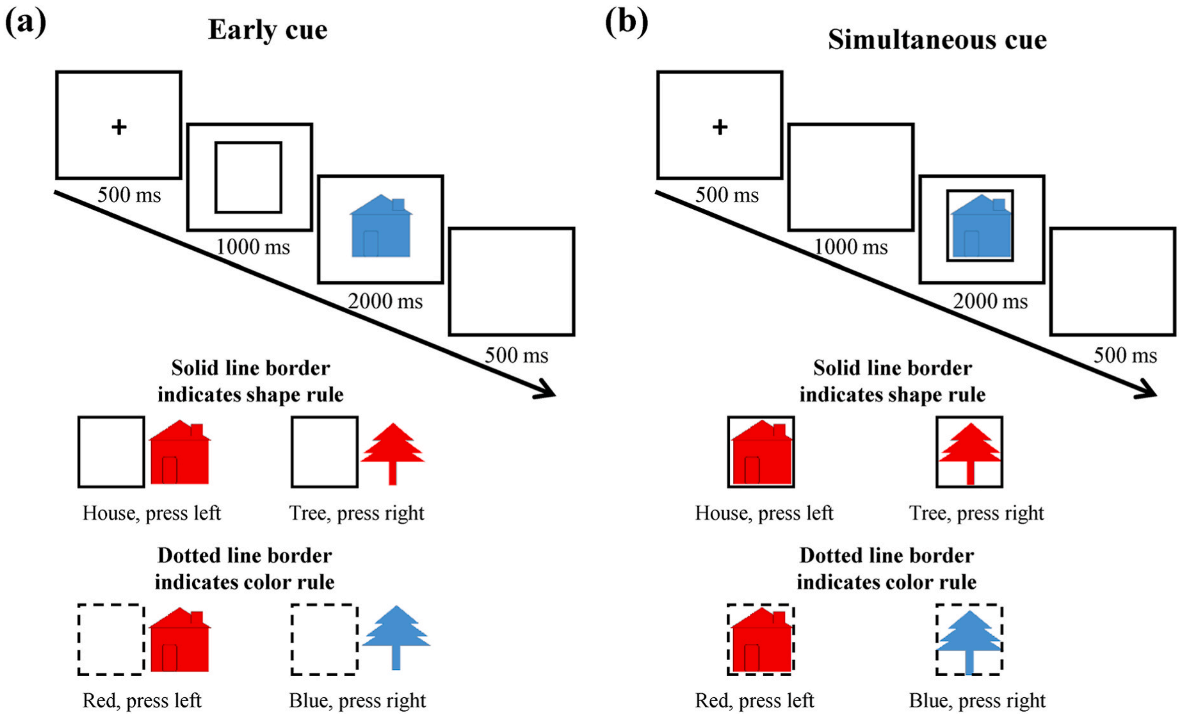

Fig. 2. Illustration of CTS. (**a**) In the early cue blocks, task cue is presented 1000 ms before target onset. A cue with a solid border required the participants to decide whether a picture showed a house (left button) or a tree (right button), while a cue with a dotted border required the participants to decide whether a picture was red (left button) or blue (right button). (**b**) In the simultaneous cue blocks, task cue (a solid or dotted border) is presented at the same time as the target.

required participants to classify a stimulus as red or blue. There were four types of stimuli that were assigned to either a left (F) or right response key (J), depending on the respective category. The response key assignment was counterbalanced across participants. The task consisted of a practice session with two blocks (20 trials per block) and an experimental session with six blocks (40 trials per block). In each trial, participants switched tasks based on an informative border (solid or dotted lines) that either signalled shape or color rules. In half blocks (for both practice and formal experimental sessions), the presentation of the informative border was 1000 ms earlier than the target stimulus, which made proactive preparation possible. In the other half, the presentation of the informative border was at the same time as the target stimulus, rendering proactive preparation impossible. Similarly, error rates and trimmed mean reaction times (RTs) of correct responses were calculated for each condition where trials with RTs above or below 3 SD from the individuals' mean were excluded. Similar to previous research using CTS (Kubota et al., 2020; Zhou et al., 2022), PCI was calculated by subtracting mean RTs or error rates of trials under the early cue condition from trials under the simultaneous cue condition. A higher value was indicative of greater efficiency in proactive control. Moreover, in each block, half of the trials were switch trials (i.e., the task rule of the present trial was different from the previous one) and the other half were non-switch trials (i.e., the task rule of the present trial was the same as the previous one). Then task switching cost calculated by subtracting mean RTs or errors of non-switch trials from switch trials was further used to measure task switching ability (Davidson et al., 2006). A lower value was indicative of higher task switching ability.

2.2.3. Working memory

Backward Digit Span. In this task, a series of digits (1–9) were presented on the center of the screen at a rate of one digit per second. Participants were instructed to recall the digits in the reverse order. The task started with three digits, and each length was tested with two independent trials. The length on the next trial would increase by one if either one or both trials at a same length were recalled correctly. The task would be discontinued if a participant failed in both trials at a same length. According to previous work (C. Wang et al., 2021; Zhou et al., 2022), working memory was determined by the maximum digit length the participant reached.

Animal Span. In this task, a series of animal pictures was presented on the center of the screen. Participants were instructed to judge whether an animal picture is upright or upside-down within 3000 ms (press the right button for upright and the left button for upside-down). Then, the participants were instructed to recall the animal pictures in order. The task started with two animal pictures, and each length was tested with two independent trials. The length on the next trial would increase by one if either one or both trials at a same length were recalled correctly. The task would be discontinued if a participant failed in both trials at a same length. Based on previous research (Loosli et al., 2012; C. Wang et al., 2021), working memory was determined by the maximum animal length the participant reached.

2.2.4. Fluid intelligence

Previous research has provided evidence that fluid intelligence may affect working memory and the use of proactive control (Braver, 2012; Kubota et al., 2020). Therefore, the present study included fluid intelligence as a control variable. For each participant, fluid intelligence was assessed by the Raven's Standard Progressive Matrices. In order to shorten the testing time, we followed the procedure used by Jaeggi et al. (2008) to divide the Raven test into two sets (30 items per set, including one practice item per set). The subjects just finished one set of the test with a 10-min time limit. The dependent variable was the number of correct responses.

2.3. Experimental procedure and statistical analysis

The participants were tested one-by-one in a quiet room of the authors' university. They first participated in the IPAQ in order to get an estimate of PA levels in a typical week. Then they completed the other five cognitive tasks, and the order of the tasks was counterbalanced across participants. To test the three hypotheses we proposed, participants were median split by total PA scores into a high PA group and a low PA group, with 66 participants in each group. Chi-square test and independent-samples *t*-test were used to examine whether the two groups differ significantly in gender distribution, age, working memory spans and intelligence.

With respect to performance of AX-CPT, we ran a set of ANOVAs for RTs of correct responses and error rates separately using Condition (AX, AY, BX, BY) as a within-subject factor, and Group (high or low PA) as a between-subject factor. Similarly, to test difference in performance of CTS, we ran a set of ANOVAs for RTs of correct responses and error rates separately using Cue type (early or simultaneous cue) and Switch type (non-switch or switch) as two within-subject factors, and Group (high or low PA) as a between-subject factor. Sphericity was assessed using the Mauchly's test. In the case of rejection of the sphericity hypothesis, the Greenhouse-Geisser correction was applied if the epsilon value was lower than 0.75, and the Huynh-Feldt correction was applied if the epsilon value was 0.75 or greater. If a significant main or interaction effect was identified, post-hoc comparisons were conducted using Bonferroni corrections.

As the two proactive control tasks were adapted from a previous study focused on children (Zhou et al., 2022), we calculated reliability and concurrent validity of PCI for the two tasks. For reliability, split-half correlations with Spearman–Brown correction were used. For concurrent validity, Pearson correlations between individual proactive control scores were computed. Pearson correlational analyses between proactive control scores were also conducted separately for each group to test whether PA modulated the consistency in proactive control engagement. The Fisher's r-to-Z transformation was used to test the difference between the correlation coefficients obtained for each group. To test whether working memory significantly modulated the association between PA and proactive control, hierarchical multiple regression analysis was conducted separately for PCI of AX-CPT and PCI of CTS. In these analyses, age, intelligence (standardized scores) and gender (dummy coded: 1 = girl; 0 = boy) were entered as covariates in the first step, working memory (standardized scores) and group (dummy coded: 1 = high PA; 0 = low PA) were entered in the second step, and the interaction between working memory and group was entered in the last step. Post-hoc simple slope tests were used to test the direction and strength of significant interaction effects.

3. Results

3.1. High and low PA groups

The PA levels in our sample had a mean of 2571 METs in a typical week and the range of values was from 226 to 10378 METs. Based on this distribution, subjects were split into a high PA group and a low PA group. Overall, participants in the high PA group performed vigorous PA at least 60 min and total PA at least 2500 METs in a typical week, while participants in the low PA group performed vigorous PA no more than 50 min and total PA less than 2500 METs in a typical week. The mean PA for the high and low PA groups are displayed in Table 1. An independent-samples *t*-test yielded a significant difference on total PA between the two groups ($t_{84.501} = 13.42$, $p < 0.001$, Cohen's $d = 2.34$). Thus, the average PA scores were reliably different in the two groups. No significant group differences were found in term of age, gender distribution, backward digit span, animal span and Raven intelligence scores ($p > 0.05$).

3.2. Performance of AX-CPT

Descriptive statistics of AX-CPT and CTS are presented in Table 2. As for RTs, the Mauchly's test of sphericity was significant ($p < 0.001$) and the epsilon value was less than 0.75. Thus, a Greenhouse-Geisser correction was applied to the df. There was a significant main effect of Condition ($F_{2.101,\ 273.181} = 229.29$, $p < 0.001$, partial $\eta^2 = 0.64$). Post-hoc comparisons revealed that RTs of AY trials were longer than those of BX, BY, and AX trials ($p_{corrected} < 0.001$), RTs of AX trials were longer than those of BX and BY trials ($p_{corrected} < 0.001$), and RTs of BX trials were longer than those of BY trials ($p_{corrected} = 0.02$). There was also a significant main effect of Group ($F_{1,\ 130} = 25.01$, $p < 0.001$, partial $\eta^2 = 0.16$), where the high PA group was significantly faster than the low PA group. A Condition × Group interaction was also present ($F_{2.101,\ 273.181} = 7.41$, $p < 0.001$, partial $\eta^2 = 0.05$). Post-hoc comparisons showed that the group differences in RTs of BX and BY trials were larger than those of AX and AY trials (AX: $t_{91.975} = 3.15$, $p_{corrected} = 0.008$, Cohen's $d = 0.55$; AY: $t_{130} = 3.42$, $p_{corrected} = 0.003$, Cohen's $d = 0.59$; BX: $t_{100.354} = 5.55$, $p_{corrected} < 0.001$, Cohen's $d = 0.96$; BY: $t_{101.108} = 5.17$, $p_{corrected} < 0.001$, Cohen's $d = 0.89$). To test proactive control efficiency, we calculated PCI in term of RTs. As shown in Fig. 3a, a significantly higher PCI was observed for the high than the low PA group ($t_{120.370} = 3.92$, $p < 0.001$,

Table 1
Characteristics of research participants.

	Low PA		High PA		Group difference
	Mean (SD)	Range	Mean (SD)	Range	
Total PA	1187 (611)	226–2453	3955 (1560)	2580–10378	$t_{84.501} = 13.42, p < 0.001$
Age (in year)	20.70 (1.96)	18–26	20.65 (1.98)	18–26	$t_{130} = 0.13, p = 0.90$
Gender (males, total)	(25, 66)		(23, 66)		$\chi^2 = 0.13, p = 0.72$
Backward digit span	7.08 (1.76)	4–13	7.59 (2.30)	4–13	$t_{121.825} = 1.45, p = 0.15$
Animal span	5.21 (1.12)	3–9	5.12 (1.78)	2–10	$t_{130} = 0.35, p = 0.73$
Raven intelligence	26.32 (2.36)	18–30	25.80 (2.71)	16–30	$t_{130} = 1.16, p = 0.25$

Note: SD, standard deviation.

Table 2
Descriptive statistics of AX-CPT and CTS.

AX-CPT		Low PA		High PA	
		Mean (SD)	Range	Mean (SD)	Range
RTs	AX	506 (126)	326–1011	452(59)	359–607
	AY	668 (139)	406–1022	587 (135)	410–1057
	BX	505 (169)	188–1006	374(92)	228–612
	BY	477 (152)	214–983	367(82)	225–621
Errors	AX	0.03 (0.05)	0–0.25	0.02 (0.03)	0–0.22
	AY	0.04 (0.06)	0–0.25	0.05 (0.06)	0–0.21
	BX	0.04 (0.07)	0–0.50	0.04 (0.05)	0–0.25
	BY	0.01 (0.04)	0–0.20	0.01 (0.03)	0–0.16
CTS		Low PA Mean (SD)	Range	High PA Mean (SD)	Range
RTs					
Non-switch	Early cue	721 (166)	509–1202	594 (102)	390–884
	Simultaneous cue	883 (159)	561–1292	875 (147)	489–1184
Switch	Early cue	747 (161)	522–1187	602 (106)	394–951
	Simultaneous cue	912 (163)	590–1348	916 (149)	513–1156
Errors					
Non-switch	Early cue	0.10 (0.10)	0–0.48	0.09 (0.09)	0–0.43
	Simultaneous cue	0.15 (0.15)	0–0.55	0.13 (0.11)	0–0.45
Switch	Early cue	0.11 (0.10)	0–0.43	0.10 (0.09)	0–0.48
	Simultaneous cue	0.16 (0.14)	0–0.50	0.14 (0.11)	0–0.53

Note: SD, standard deviation.

Cohen's $d = 0.68$).

As for error rates, the Mauchly's test of sphericity was significant ($p < 0.001$) and the epsilon value was greater than 0.75. Thus, a Huynh–Feldt correction was applied to the df. There was also a significant main effect of Condition ($F_{2.301,\ 299.180} = 13.86$, $p < 0.001$, partial $\eta^2 = 0.10$). Post-hoc comparisons revealed that the participants committed fewer errors on AX than AY trials ($p_{corrected} < 0.001$). In addition, they committed fewer errors for BY than the other three types of trials ($p_{corrected} < 0.05$). The main effect of Group or Condition × Group interaction did not reach significant. We further calculated PCI in term of errors and did not find significant group difference ($t_{129.699} = 0.41$, $p = 0.68$, Cohen's $d = 0.07$, Fig. 3b).

3.3. *Performance of CTS*

As for RTs, the Mauchly's test of sphericity was not significant ($p > 0.05$). Hence, sphericity was assumed. There was a significant main effect of Cue type ($F_{1,\ 130} = 251.01$, $p < 0.001$, partial $\eta^2 = 0.66$), where the participants responded faster for the early than the simultaneous cue condition. There was also a significant main effect of Switch type ($F_{1,\ 130} = 49.56$, $p < 0.001$, partial $\eta^2 = 0.28$), where the participants responded faster on non-switch than switch trials. Importantly, a significant Cue type × Switch type × Group interaction was detected ($F_{1,\ 130} = 6.48$, $p = 0.01$, partial $\eta^2 = 0.05$). To test this interaction effect, we calculated difference scores between early and simultaneous cue conditions for non-switch and switch trials separately and a higher value was indicative of greater efficiency in proactive control. As shown in Fig. 3c, the high PA group had significantly higher PCI than the low PA group on both non-switch ($t_{130} = 3.45$, $p_{corrected} = 0.002$, Cohen's $d = 0.60$) and switch trials ($t_{116.122} = 4.36$, $p_{corrected} < 0.001$, Cohen's $d = 0.76$). Besides, the high PA group had significantly higher PCI on switch than non-switch trials ($t_{65} = 4.67$, $p_{corrected} < 0.001$, Cohen's $d = 0.58$), while no such difference was present in the low PA group ($t_{65} = 0.45$, $p_{uncorrected} = 0.66$, Cohen's $d = 0.06$). Finally, we calculated difference scores between non-switch and switch conditions under early and simultaneous cue conditions separately and a lower switching cost was indicative of higher task switching ability. As shown in Fig. 3d, the high PA group had lower RT switching costs under the early than the simultaneous cue condition ($t_{65} = 4.67$, $p_{corrected} < 0.001$, Cohen's $d = 0.58$), with no such difference for the low PA group ($t_{65} = 0.45$, $p_{uncorrected} = 0.66$, Cohen's $d = 0.05$). Besides, the high PA group showed a tendency of lower RT switching costs than the low PA group under the early cue condition ($t_{130} = 2.12$, $p_{uncorrected} = 0.04$, Cohen's $d = 0.37$) but not under the simultaneous cue condition ($t_{130} = -1.17$, $p_{uncorrected} = 0.25$, Cohen's $d = 0.21$).

As for error rates, the Mauchly's test of sphericity was not significant ($p > 0.05$). Hence, sphericity was assumed. There was a significant main effect of Cue type ($F_{1,\ 130} = 15.24$, $p < 0.001$, partial $\eta^2 = 0.11$), where the participants committed fewer errors for the early than the simultaneous cue condition. The main effect of Switch type was also significant ($F_{1,\ 130} = 10.01$, $p = 0.002$, partial $\eta^2 = 0.07$), where the participants committed fewer errors on non-switch than switch trials. No other main or interaction effects reached significant. Neither PCI nor switching cost in term of errors showed any significant differences (Fig. 3e and 3f).

3.4. *Consistency in proactive control engagement*

Split-half reliability and concurrent validity were provided in Table 3. With respect to split-half reliability, PCI of AX-CPT based on errors and PCI of CTS based on switch errors were the only measures that did not yield acceptable reliability coefficients (<0.70). With respect to concurrent validity, PCI of AX-CPT based on RTs correlated significantly with PCI of AX-CPT based on error rates. Similarly, PCI measures in the CTS correlated significantly with each other. This pattern of results indicates high convergent validity of proactive control within tasks.

With respect to the correlations of proactive control indices

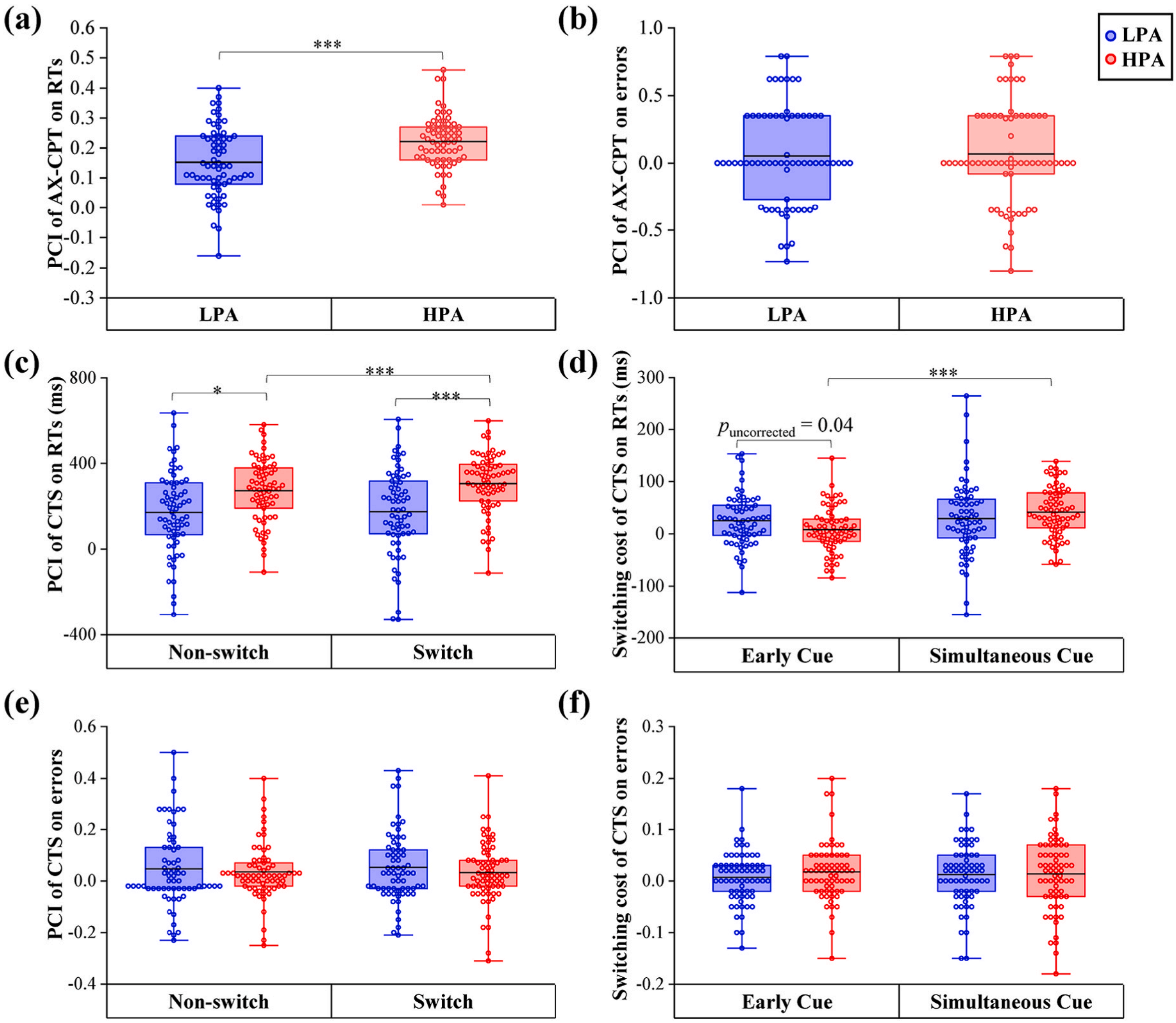

Fig. 3. Behavioral performance for proactive control and task switching. (**a**) PCI of AX-CPT based on RTs for each group. (**b**) PCI of AX-CPT based on errors for each group. (**c**) PCI of CTS based on RTs for each group. (**d**) Switching cost of CTS based on RTs for each group. (**e**) PCI of CTS based on errors for each group. (**f**) Switching cost of CTS based on errors for each group. Each dot represents the data of each subject. LPA, low PA group; HPA, high PA group; $^{***}p \le 0.001$; $^{*}p \le 0.05$.

Table 3
Split-half reliability and concurrent validity of AX-CPT and CTS.

PCI	AX-CPT (RTs)	AX-CPT (Errors)	CTS (Non-switch RTs)	CTS (Non-switch errors)	CTS (Switch RTs)	CTS (Switch errors)
AX-CPT (Errors)	0.31***					
CTS (Non-switch RTs)	0.12	−0.05				
CTS (Non-switch errors)	−0.01	−0.01	0.49***			
CTS (Switch RTs)	0.10	−0.08	0.93***	0.46***		
CTS (Switch errors)	−0.02	0.02	0.49***	0.82***	0.44***	
Split-half reliability	0.79	0.33	0.81	0.74	0.81	0.62

Note: $^{***}p \le 0.001$.

separately for each group, the HPA group showed significant correlations between PCI of AX-CPT based on RTs and PCI of CTS based on RTs (non-switch trials: $r(66) = 0.38$, $p = 0.002$; switch trials: $r(66) = 0.30$, $p = 0.02$, Fig. 4). However, no such correlations were found for the LPA group (non-switch trials: $r(66) = -0.22$, $p = 0.08$; switch trials: $r(66) = -0.23$, $p = 0.06$). We compared the coefficients of these correlations using the Fisher r-to-z transformation. The results showed significant group differences for the correlation coefficients (non-switch trials: $z = 3.50$, $p = 0.0005$; switch trials: $z = 3.05$, $p = 0.002$). Group differences in both correlations could survive Bonferroni correction for the number of correlations (0.05/15 for six proactive control measures). The group differences in correlation coefficients remained significant after controlling for the effects of age, gender, and intelligence. Hence, participants with high PA were more likely to be consistent in their recruitment of proactive control across tasks than those with low PA. There were no other significant group differences in correlation coefficients between proactive control measures.

3.5. *The role of working memory*

Regarding to working memory, the backward digit span was positively related to the animal span across all participants ($r(132) = 0.38$, p

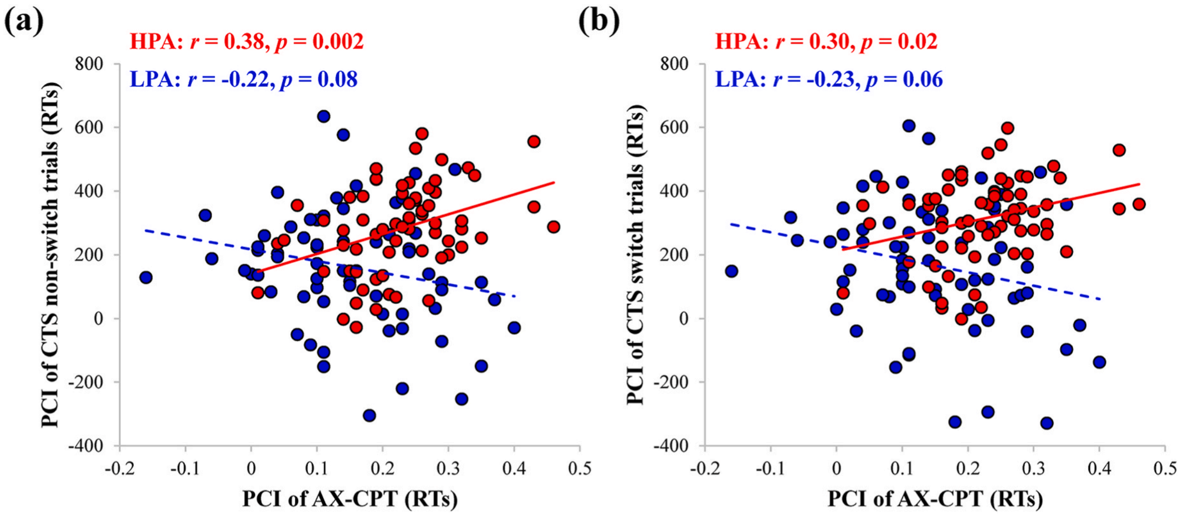

Fig. 4. Group differences in the associations between proactive control indices across tasks. (**a**) A stronger positive correlation between PCI of AX-CPT based on RTs and PCI of CTS non-switch trials based on RTs was observed for the high ($r(66) = 0.38$, $p = 0.002$) than the low PA group ($r(66) = -0.22$, $p = 0.08$). (**b**) A stronger positive correlation between PCI of AX-CPT based on RTs and PCI of CTS switch trials based on RTs was observed for the high ($r(66) = 0.30$, $p = 0.02$) than the low PA group ($r(66) = -0.23$, $p = 0.06$). LPA, low PA group; HPA, high PA group.

< 0.001). Then a composite score was computed by standardizing and averaging the two working memory scores to obtain a domain-general estimate of working memory capacity. Hierarchical multiple regression analysis was conducted to investigate whether working memory modulated the association between PA and proactive control. As PCI of AX-CPT based on errors and PCI of CTS based on switch errors did not show acceptable reliability coefficients, we used the other four proactive control measures as dependent variables in the regression analyses. As shown in Table 4, our results showed a significant interaction between group and working memory in predicting PCI of CTS based on RTs for both non-switch ($\Delta R^2 = 0.05$, $F(1,125) = 8.51$, $p = 0.004$) and switch trials ($\Delta R^2 = 0.04$, $F(1,125) = 7.12$, $p = 0.009$). Both interaction effects could survive Bonferroni correction for the number of regression models (0.05/4 for the four dependent variables). In order to further examine the nature of the interaction effects, simple slopes *t* tests at two levels of moderator (high or low working memory) were computed. As illustrated in Fig. 5, the results indicated a significant group difference in PCI scores of CTS for individuals with high working memory (non-switch trials: $t(31) = 4.61$, $p < 0.001$; switch trials: $t(31) = 5.28$, $p < 0.001$) but not for those with low working memory (non-switch trials: $t(31) = 0.89$, $p = 0.37$; switch trials: $t(31) = 1.44$, $p = 0.15$). No significant interaction between group and working memory was detected in predicting PCI of AX-CPT based on RTs or PCI of CTS based on errors ($p > 0.05$).

Table 4
Summary of the hierarchical regression analyses.

Predictors	Dependent variables			
	PCI$_{RT}$ of AX-CPT	PCI$_{RT}$ of CTS non-switch trials	PCI$_{RT}$ of CTS switch trials	PCI$_{errors}$ of CTS non-switch trials
Step 1				
Age	−0.004	8.63	10.73	−0.01
Intelligence	0.01	10.92	2.73	0.02
Gender	0.02	−40.9	−59.04	−0.01
R^2	0.02	0.01	0.02	0.03
$F(3,128)$	0.74	0.62	0.99	1.50
Step 2				
Age	−0.003	10.62	13.6	−0.01
Intelligence	0.01	12.91	6.88	0.02
Gender	0.03	−39.25	−57.07	−0.01
Group	0.08***	117.96***	146.4***	0.004
Working memory	0.03*	30.18	27.11	−0.01
R^2	0.19	0.15	0.2	0.04
ΔR^2	0.17	0.14	0.18	0.002
$\Delta F(2,126)$	13.41***	10.43***	14.25***	0.15
Step 3				
Age	−0.002	14.71	17.93	−0.01
Intelligence	0.01	13.16	7.15	0.02
Gender	0.03	−39.8	−57.65	−0.01
Group	0.08***	120.96***	149.58***	0.01
Working memory	−0.003	−45.61	−53.23	−0.05
Group × Working memory	0.04	100.89**	106.94**	0.05
R^2	0.21	0.2	0.25	0.06
ΔR^2	0.02	0.04	0.04	0.02
$\Delta F(1,125)$	2.50	6.53**	7.12**	2.51

Note: The numbers corresponding to each independent variable indicate unstandardized regression coefficients (β). ***$p \leq 0.001$; **$p \leq 0.01$.

Task switching cost based on RTs for the early cue condition was marginally correlated with PCI of CTS switch trials based on RTs across all participants ($r(132) = -0.17$, $p = 0.06$). Multiple regression analysis did not detect any significant interaction effect when utilizing task switching cost as a moderator ($p > 0.05$).

4. Discussion

The main objective of the present study was to examine the association between PA and proactive control and the potential modulating role of working memory in this relationship. First, we found that the high PA group was more efficient to engage proactive control than the low PA group on both AX-CPT and CTS (Fig. 3a and 3c). Second, we found that the high PA group showed greater consistency in proactive control engagement across tasks than the low PA group (Fig. 4a and b). Finally, we found that working memory significantly modulated the association between PA and proactive control efficiency of the CTS (Fig. 5a and b). Altogether, these findings add new evidence to the association between PA and cognitive control in young adults, which may have important implications for developing effective intervention strategies to promote cognitive control or PA in young adults.

As for AX-CPT, our results are consistent with previous studies that found PA-related benefits in response speed (Cirillo et al., 2017; Gothe, 2021; Gothe et al., 2017). It is possible that the faster response speed in young adults led to a more active lifestyle. Another interpretation is that the RTs were shortened in young adults who experienced a more active lifestyle. The lack of group differences in accuracy may be due to that

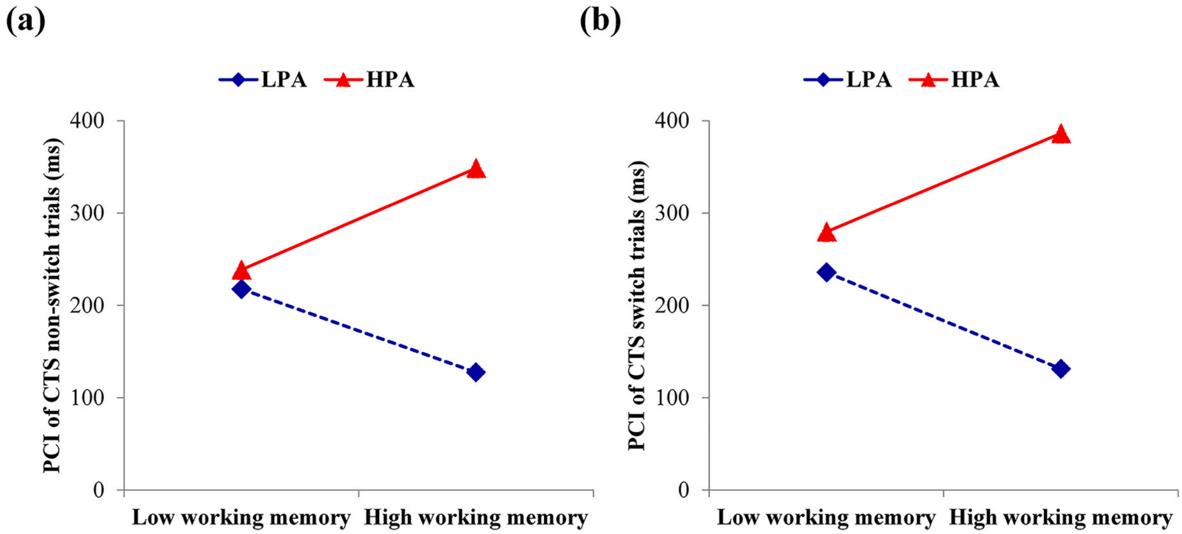

Fig. 5. The modulating role of working memory. (**a**) A significant group difference in PCI scores of CTS non-switch trials was found for individuals with high working memory ($t(31) = 4.61$, $p < 0.001$) but not for those with low working memory ($t(31) = 0.89$, $p = 0.37$). (**b**) A significant group difference in PCI scores of CTS switch trials was found for individuals with high working memory ($t(31) = 5.28$, $p < 0.001$) but not for those with low working memory ($t(31) = 1.44$, $p = 0.15$). LPA, low PA group; HPA, high PA group.

accuracy typically yield less variability than RTs among young adults. Importantly, this study found that group differences in RTs of BX and BY trials were larger than those of AX and AY trials, indicating that people with greater PA may be more efficient at using valid cues to prepare their responses to incoming targets (e.g. a B cue indicates a non-target response for the subsequent probe while an A cue cannot inform the participants the exact response for the subsequent probe). Consistent with this conjecture, a significantly higher PCI based on RTs was found in young adults with high PA than those with low PA (Fig. 3a). Previous research has suggested that individuals with greater PA are better at allocating top-down attention and show more efficiency in maintaining goal setting (Belcher et al., 2021; Pontifex et al., 2011; Shi et al., 2020). Importantly, top-down attention and goal setting are critical aspects of proactive control (Lucenet & Blaye, 2019; Rainey et al., 2021). Therefore, PA may be associated with better proactive control via more flexible allocation of top-down attentional resources and more efficient goal setting. However, further longitudinal research is warranted to test the potential cause-effect relationships. Additionally, previous studies have reported that PA has positive influences on the structure and function of the prefrontal region (Barha et al., 2020; Northey et al., 2020; Shi et al., 2022). Importantly, the prefrontal region is critical to the implementation of proactive control (Braver, 2012). Hence, PA-related changes in brain structure and function of the prefrontal region may be a potential neural mechanism underlying the positive relationship between physical activity and proactive control.

As for CTS, the present study found an interesting Cue-by-Group interaction. While the two groups showed no significant differences under the simultaneous cue condition, young adults with high PA were faster than those with low PA under the early cue condition. Hence, individuals with greater PA may be more efficient at engaging proactive control in a switching situation, which further benefits processing speed. Our findings may help reconcile the discrepant results about the association between PA and task switching in the extant literature. For instance, a previous study by Kamijo and Takeda (Kamijo & Takeda, 2010) reported a positive association between PA and task switching performance when proactive control is possible, while another study by Egger et al. (2018) reported no significant association between PA and task switching performance when proactive control is impossible. Previous neuroimaging studies have suggested that PA may be associated with better top-down control of bottom-up processes through potential integration of the prefrontal region with other regions involved in large-scale brain networks, such as the default-mode network and corticolimbic systems (Belcher et al., 2021). Importantly, it has been suggested that demanding cognitive functions such as task switching benefit from the coordination and integration of multiple large-scale brain networks that foster efficient information transmission among multiple cognitive processes (Gratton et al., 2012; C. Wang et al., 2020). It is plausible that, by strengthening integration among large-scale brain systems to improve top-down control of bottom-up processes, individuals with greater PA developed a stronger ability to utilize valid cues to prepare appropriate responses in a switching situation.

In the present study, the association between PA and proactive control is further highlighted by the finding that proactive control indices significantly correlated between tasks in participants with high PA but not in those with low PA (Fig. 4). Thus, not only are young adults with high PA more likely to engage proactive control, but they are also more susceptible to do so consistently across tasks when proactive control is beneficial. In contrast, although young adults with low PA did use proactive control in both tasks, they showed low capacity to engage proactive control consistently across tasks. A previous study reported that young adults who had greater consistency in prefrontal oscillatory activity during the proactive cue period showed more consistent behavioral performance in the subsequent reaction period (P. S. Cooper et al., 2017). Besides, two recent studies provide evidence that stimulating the prefrontal region with transcranial direct current stimulation can influence prefrontal brain activity during the proactive cue period, which may contribute to greater efficiency in proactive control during an AX-CPT task (M. Boudewyn et al., 2019; M. A. Boudewyn et al., 2020). Taking into account that PA has been consistently shown to produce functional or structural changes in the prefrontal region (Barha et al., 2020; Northey et al., 2020; Shi et al., 2022), it is plausible to assume that PA-related changes in the prefrontal region may contribute to greater consistency in prefrontal activity during the proactive cue period and thereby promote greater consistency in proactive control engagement across tasks. It is worthwhile for future studies to investigate whether prefrontal brain activity may modulate consistency in proactive control engagement across tasks in individuals with different levels of PA.

Finally, we found that working memory modulated the relationship between PA and proactive control. For young adults with high working memory, higher PA was associated with greater efficiency in proactive control on CTS (Fig. 5). This relationship, however, was not found in those with low working memory. Given that proactive control greatly relies on continuous and active maintenance of task-relevant information in working memory (Wiemers & Redick, 2018), individuals with high working memory capacity may have more cognitive resources to efficiently determine when proactive control should be recruited. Accordingly, they may acquire more benefits in proactive control engagement from PA. Alternatively, high working memory capacity may lead people with greater efficiency in proactive control to be more physically active. Our results are consistent with the results of Boudewyn et al. (2019), who found evidence that young adults with higher working memory show larger behavioral benefits in proactive control after stimulating the prefrontal region with transcranial direct current stimulation (i.e. 'the rich get richer'). Taken their and our findings together, the largest beneficial effects of some interventions may be seen in those with high working memory capacity. It may have important implications for developing specific interventions targeting at those with the greatest capacity to benefit. However, the present study did not find a significant interaction between PA and working memory in predicting proactive control of AX-CPT. This result may arise from the less working memory demands in AX-CPT than CTS. The CTS required participants not only to hold the cue information in mind and prepare for the upcoming targets when possible, but also to hold two separate sets of task rules in mind and switch between them. In contrast, although the AX-CPT also required participants to hold the cue information in mind and prepare for upcoming targets, it required participants to maintain only a single set of task rules.

Additionally, a substantial body of evidence supports the positive association between PA and working memory (Donnelly et al., 2016; Muntaner-Mas et al., 2022; Rathore & Lom, 2017). However, the present study did not find a similar positive association between PA and working memory. We do not believe that our findings do contrast previous findings, for results may have differed due to implementing varying methodological approaches. First, measures used to assess working memory vary considerably across studies. For example, a previous study by Cooper et al. (2012) utilized the reaction time of a Sternberg paradigm to measure working memory, while our study utilized the maximum memory span to measure working memory. Second, age groups and population characteristics differed widely among studies, making comparisons rather challenging. Specifically, a recent meta-analysis reported that the beneficial effect of PA on working memory was more remarkable for the old than the young adult participants (Rathore & Lom, 2017). Thus, the potential association between PA and working memory may be partly covered up by age.

The current study has several limitations. First, the results were based on a cross-sectional design, which did not allow for conclusions about the directionality of the relationship between PA and proactive control. Previous research has provided evidence for a robust bidirectional link between PA and cognitive control in a large sample of older adults tracked over time (Daly et al., 2015). Future research should consider to examine the causal relationships between PA and proactive control using a longitudinal design. Second, although IPAQ has been widely used, it has been reported that there are differences in PA measured by the accelerometer and IPAQ (Shephard, 2003). Future research should combine multiple methods to define PA so as to extend the present findings. Finally, the current study only focused on the associations between PA and proactive control, and such associations could be influenced by other cognitive abilities untested. For example, previous research has suggested that the use of proactive control not only depends on working memory, but also involves cognitive abilities such as metacognition (Chevalier & Blaye, 2016) and sustained attention (Staub et al., 2014). Interestingly, PA has been shown to benefit metacognition (Álvarez-Bueno et al., 2017) and sustained attention (Trevillion et al., 2022). Broader measures on multiple cognitive abilities are recommended in future studies to address the relationships between PA and proactive control more comprehensively.

To summarize, this study revealed a positive association between PA and proactive control in young adults. Specifically, in comparison with young adults with low PA, those with higher PA not only showed better proactive control on each task separately, but also showed greater consistency in proactive control efficiency across tasks. Besides, working memory significantly modulated the group difference in proactive control efficiency. Although the causal association between PA and proactive control cannot be concluded merely by these preliminary results, our study suggests that active participating in PA may be effective to improve proactive control or improving proactive control may lead people to be more physically active. Besides, such intervention effects may vary among individuals with different working memory capacities.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

Data availability

Data will be made available on request.

Acknowledgments

This research was supported by grants to CJ from National Natural Science Foundation of China (32000780), Zhejiang Provincial Natural Science Foundation of China (LQ21C090006), Starting Research Fund from Hangzhou Normal University (2020QDL006), the Cultivation Project of Provincial Characteristic Key Discipline in the College of Education of Hangzhou Normal University (20JYXK035), and grants to ZL from the basic research program of Department of Education of Zhejiang Province (Y202147900).

References

Álvarez-Bueno, C., Pesce, C., Cavero-Redondo, I., Sánchez-López, M., Martínez-Hortelano, J. A., & Martínez-Vizcaíno, V. (2017). The effect of physical activity interventions on children's cognition and metacognition: A systematic review and meta-analysis. *Journal of the American Academy of Child & Adolescent Psychiatry, 56*(9), 729–738.

Anderson, E., & Durstine, J. L. (2019). Physical activity, exercise, and chronic diseases: A brief review. *Sports Medicine and Health Science, 1*(1), 3–10.

Barha, C. K., Best, J. R., Rosano, C., Yaffe, K., Catov, J. M., & Liu-Ambrose, T. (2020). Sex-specific relationship between long-term maintenance of physical activity and cognition in the health ABC Study: Potential role of hippocampal and dorsolateral prefrontal cortex volume. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences, 75*(4), 764–770.

Belcher, B. R., Zink, J., Azad, A., Campbell, C. E., Chakravartti, S. P., & Herting, M. M. (2021). The roles of physical activity, exercise, and fitness in promoting resilience during adolescence: Effects on mental well-being and brain development. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging, 6*(2), 225–237.

Boudewyn, M., Roberts, B. M., Mizrak, E., Ranganath, C., & Carter, C. S. (2019). Prefrontal transcranial direct current stimulation (tDCS) enhances behavioral and EEG markers of proactive control. *Cognitive Neuroscience, 10*(2), 57–65.

Boudewyn, M. A., Scangos, K., Ranganath, C., & Carter, C. S. (2020). Using prefrontal transcranial direct current stimulation (tDCS) to enhance proactive cognitive control in schizophrenia. *Neuropsychopharmacology, 45*(11), 1877–1883.

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences, 16*(Issue 2), 106–113.

Chevalier, N., & Blaye, A. (2016). Metacognitive monitoring of executive control engagement during childhood. *Child Development, 87*(4), 1264–1276.

Chidharom, M., Krieg, J., Marques-Carneiro, E., Pham, B.-T., & Bonnefond, A. (2021). Investigation of electrophysiological precursors of attentional errors in schizophrenia: Toward a better understanding of abnormal proactive control engagement. *Journal of Psychiatric Research, 140*, 235–242.

Cirillo, J., Finch, J. B., & Anson, J. G. (2017). The impact of physical activity on motor preparation in young adults. *Neuroscience Letters, 638*, 196–203.

Colomé, À., Núñez-Peña, M. I., & González-Gómez, B. (2022). *Proactive control of attention in math-anxious individuals*. Psychological Research, 2015.

Cooper, S. B., Bandelow, S., Nute, M. L., Morris, J. G., & Nevill, M. E. (2012). The effects of a mid-morning bout of exercise on adolescents' cognitive function. *Mental Health and Physical Activity, 5*(2), 183–190.

Cooper, P. S., Wong, A. S. W., McKewen, M., Michie, P. T., & Karayanidis, F. (2017). Frontoparietal theta oscillations during proactive control are associated with goal-updating and reduced behavioral variability. *Biological Psychology, 129*, 253–264.

Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J. F., & Oja, P. (2003). International physical activity questionnaire: 12-Country reliability and validity. *Medicine & Science in Sports & Exercise, 35*(8), 1381–1395.

Daly, M., McMinn, D., & Allan, J. L. (2015). A bidirectional relationship between physical activity and executive function in older adults. *Frontiers in Human Neuroscience, 8*(1), 1–9.

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

Donnelly, J. E., Hillman, C. H., Castelli, D., Etnier, J. L., Lee, S., Tomporowski, P., Lambourne, K., & Szabo-Reed, A. N. (2016). Physical activity, fitness, cognitive function, and academic achievement in children: A systematic review. *Medicine & Science in Sports & Exercise, 48*(6), 1197.

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

Gonthier, C., Zira, M., Colé, P., & Blaye, A. (2019). Evidencing the developmental shift from reactive to proactive control in early childhood and its relationship to working memory. *Journal of Experimental Child Psychology, 177*, 1–16.

Gothe, N. P. (2021). Examining the effects of light versus moderate to vigorous physical activity on cognitive function in African American adults. *Aging & Mental Health, 25* (9), 1659–1665.

Gothe, N. P., Kramer, A. F., & McAuley, E. (2017). Hatha yoga practice improves attention and processing speed in older adults: Results from an 8-week randomized control trial. *Journal of Alternative & Complementary Medicine, 23*(1), 35–40.

Gratton, C., Nomura, E. M., Pérez, F., & D'Esposito, M. (2012). Focal brain lesions to critical locations cause widespread disruption of the modular organization of the brain. *Journal of Cognitive Neuroscience, 24*(6), 1275–1285.

Hoorelbeke, K., Koster, E. H. W., Demeyer, I., Loeys, T., & Vanderhasselt, M.-A. (2016). Effects of cognitive control training on the dynamics of (mal)adaptive emotion regulation in daily life. *Emotion, 16*(7), 945–956.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences, 105*(19), 6829–6833.

Kamijo, K., & Takeda, Y. (2010). Regular physical activity improves executive function during task switching in young adults. *International Journal of Psychophysiology, 75* (3), 304–311.

Kubota, M., Hadley, L. V., Schaeffner, S., Könen, T., Meaney, J. A., Auyeung, B., Morey, C. C., Karbach, J., & Chevalier, N. (2020). Consistent use of proactive control and relation with academic achievement in childhood. *Cognition, 203*, Article 104329.

Lee, E. S., Yeatman, J. D., Luna, B., & Feldman, H. M. (2011). Specific language and reading skills in school-aged children and adolescents are associated with prematurity after controlling for IQ. *Neuropsychologia, 49*(5), 906–913.

Li, Y., Liu, F., Zhang, Q., Liu, X., & Wei, P. (2018). The effect of mindfulness training on proactive and reactive cognitive control. *Frontiers in Psychology, 9*(JUN).

Loosli, S. V., Buschkuehl, M., Perrig, W. J., & Jaeggi, S. M. (2012). Working memory training improves reading processes in typically developing children. *Child Neuropsychology, 18*(1), 62–78.

Lucenet, J., & Blaye, A. (2019). What do I do next? The influence of two self-cueing strategies on children's engagement of proactive control. *Cognitive Development, 50*, 167–176.

Ludyga, S., Mücke, M., Andrä, C., Gerber, M., & Pühse, U. (2022). Neurophysiological correlates of interference control and response inhibition processes in children and adolescents engaging in open- and closed-skill sports. *Journal of Sport and Health Science, 11*(2), 224–233.

Möhring, W., Klupp, S., Ludyga, S., & Grob, A. (2022). Executive functions in children engaging in open-and closed-skilled sports. *Psychology of Sport and Exercise*, Article 102218.

Muntaner-Mas, A., Mora-Gonzalez, J., Cabanas-Sánchez, V., Pintado, L. B., Salmon, J., Hillman, C. H., Castro-Piñero, J., Perales, J. C., Veiga, O. L., & Esteban-Cornejo, I. (2022). Prospective associations between physical fitness and executive function in adolescents: The UP&DOWN study. *Psychology of Sport and Exercise, 61*, Article 102203.

Northey, J. M., Rattray, B., Pumpa, K. L., Pryor, D. J., Fraser, M. A., Shaw, M. E., Anstey, K. J., & Cherbuin, N. (2020). Objectively measured physical activity is associated with dorsolateral prefrontal cortex volume in older adults. *NeuroImage, 221*, Article 117150.

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

Rainey, V. R., Stockdale, L., Flores-Lamb, V., Kahrilas, I. J., Mullins, T. L., Gjorgieva, E., Morrison, R. G., & Silton, R. L. (2021). Neural differences in the temporal cascade of reactive and proactive control for bilinguals and monolinguals. *Psychophysiology, 58* (6).

Rathore, A., & Lom, B. (2017). The effects of chronic and acute physical activity on working memory performance in healthy participants: A systematic review with meta-analysis of randomized controlled trials. *Systematic Reviews, 6*(1), 1–16.

Shephard, R. J. (2003). Limits to the measurement of habitual physical activity by questionnaires. *British Journal of Sports Medicine, 37*(3), 197–206.

Shi, D., Geng, F., Hao, X., Huang, K., & Hu, Y. (2022). Relations between physical activity and hippocampal functional connectivity: Modulating role of mind wandering. *Frontiers in Human Neuroscience, 16*(October), 1–10.

Shi, D., Geng, F., Hu, Y., & Xu, Q. (2020). Physical activity modulates the effect of cognitive control on episodic memory. *Frontiers in Psychology, 11*(April).

Sidlauskaite, J., Dhar, M., Sonuga-Barke, E., & Wiersema, J. R. (2020). Altered proactive control in adults with ADHD: Evidence from event-related potentials during cued task switching. *Neuropsychologia, 138*(December 2019), Article 107330.

Staub, B., Doignon-Camus, N., Bacon, É., & Bonnefond, A. (2014). Age-related differences in the recruitment of proactive and reactive control in a situation of sustained attention. *Biological Psychology, 103*, 38–47.

Stewart, R. A. H., Held, C., Hadziosmanovic, N., Armstrong, P. W., Cannon, C. P., Granger, C. B., Hagström, E., Hochman, J. S., Koenig, W., & Lonn, E. (2017). Physical activity and mortality in patients with stable coronary heart disease. *Journal of the American College of Cardiology, 70*(14), 1689–1700.

Trevillion, C., Malmberg, L.-E., & Esser, P. (2022). Working memory, sustained attention, and physical activity: An intraindividual study. *Psychology of Sport and Exercise, 60*, Article 102161.

Valadez, E. A., Troller-Renfree, S. V., Buzzell, G. A., Henderson, H. A., Chronis-Tuscano, A., Pine, D. S., & Fox, N. A. (2021). Behavioral inhibition and dual mechanisms of anxiety risk: Disentangling neural correlates of proactive and reactive control. *JCPP Advances, 1*(2).

Wang, C., Hu, Y., Weng, J., Chen, F., & Liu, H. (2020). *Modular segregation of task-dependent brain networks contributes to the development of executive function in children.* NeuroImage, 206.

Wang, C., Li, B., & Yao, Y. (2021). Proactive control mediates the relationship between working memory and math ability in early childhood. *Frontiers in Psychology, 12*, 1612.

Wang, C.-H., Moreau, D., Yang, C.-T., Lin, J.-T., Tsai, Y.-Y., & Tsai, C.-L. (2019). The influence of aerobic fitness on top-down and bottom-up mechanisms of interference control. *Neuropsychology, 33*(2), 245.

Wiemers, E. A., & Redick, T. S. (2018). Working memory capacity and intra-individual variability of proactive control. *Acta Psychologica, 182*, 21–31.

Yang, G., & D'Arcy, C. (2022). Physical activity and social support mediate the relationship between chronic diseases and positive mental health in a national sample of community-dwelling Canadians 65+: A structural equation analysis. *Journal of Affective Disorders, 298*, 142–150.

Zhou, H., Li, Z., & Wang, C. (2022). Development of proactive control in school-age children and its relationship with working memory. *Current Psychology*, 1–13.