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Original Article

Effects of combined physical and cognitive training on executive function of adolescent shooting athletes: A functional near-infrared spectroscopy study

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ABSTRACT

Individual executive function improvement through physical and cognitive training is a research hotspot in physical education and cognitive science. However, few studies have evaluated whether combined physical and cognitive training (CPCT) has greater benefits for executive function performance and cerebral oxygenation in adolescent athletes than cognitive training alone. This study randomly assigned 33 adolescent shooting athletes to a CPCT ($n = 17$) or computerized cognitive training (CCT, $n = 16$) group and compared their executive function after six weeks of training. All subjects were assessed using the 2-back, task-switching, and Stroop tests before and after training. The prefrontal cortex oxygenated hemoglobin (Oxy-Hb) activation level was monitored while executing the three tasks using functional near-infrared spectroscopy. Our results showed that the CPCT and CCT groups similarly improved their updating function as indicated by the 2-back task accuracy. The CPCT group significantly improved the switching function in the task-switching test accuracy, while the CCT group did not. However, both groups did not improve in behavioral performance as indicated by the inhibition function in the Stroop task. Cerebral oxygenation, indicated by the oxy-Hb activation level in the frontal pole area of the prefrontal lobe, significantly improved in the CPCT group during the three cognitive tasks, whereas the CCT group showed no change. These findings indicated that CPCT endowed greater advantages in task-switching in the behavioral performance of the executive function than CCT. Moreover, CPCT was superior to CCT in increasing task-efficient cerebral oxygenation during the activation of the prefrontal cortex in adolescent shooting athletes.

Introduction

Executive function refers to the ability to monitor and manage multiple cognitive processes in a goal-oriented manner. It includes a series of higher-order cognitive processes, among which three independent components, switching, updating, and inhibition, have received significant attention.[1,2] Executive function plays a crucial role in mental health and activities of daily living. Early research on executive function was conducted in patients with Alzheimer's disease[3] and attention-deficit/hyperactivity disorder.[4] An increasing number of studies have been conducted on executive function in healthy populations,[5] including athletes.[6] Shooting athletes experience significantly intense physical and mental stress during shooting. To overcome this stress, considerable physiological demands are placed on the body. Furthermore, these athletes need to monitor and manage multiple cognitive processes, including attention to autonomic control, concentrated focus on target cues, and inhibition of environmental distractions.[7,8] The best performance of shooting athletes requires inhibition of irrelevant cognitive processes and an increase in relevant cognitive processes.[9] Therefore, effectively enhancing the executive function of shooting athletes is an important goal for researchers and coaches.

Previous research has revealed that regular human behavioral patterns have a major impact on the neurocognitive system.[10,11] Consequently, increasing attention is being paid to improving executive function through physical and cognitive training and the potential underlying mechanisms.[12,13] Cognitive performance improvement after cognitive exercise may be related to changes in brain structure and function, as reflected by increased cortical thickness and gray matter volume and improved structural and functional connectivity and neural activity.[14] Physical exercise impacts cognition by affecting molecular activities related to energy metabolism management and synaptic

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Abbreviation

combined physical and cognitive training CPCT
computerized cognitive training CCT
oxygenated hemoglobin Oxy-Hb
functional near-infrared spectroscopy fNIRS
number *n*
rating of perceived exertion RPE
cerebral regions of interest ROIs
left L
right R
middle M
frontal pole area FPA
dorsolateral prefrontal cortex DLPFC
ventrolateral prefrontal cortex VLFPC
light-emitting diode LED
fNIRS Optodes' Location Decider fOLD
analysis of variance ANOVA

plasticity.[15] These changes were reflected in the dentate gyrus of the hippocampus,[16] prefrontal cortex,[17] and motor cortex.[18] Since the cognitive changes induced by cognitive training differ from those induced by physical training, researchers attempted to combine both to increase the beneficial effects of exercise on the individual's cognition, proposing an adaptive capacity model. This model suggests that combined physical and cognitive training (CPCT) could produce additive or synergistic effects,[19] and CPCT might be associated with greater improvements in cognitive performance than any of them alone.[20]

Based on the above findings, an increasing number of studies have examined the effectiveness of CPCT in cognitive capacity enhancement. Several randomized controlled trials indicated that, compared to single training, combined training was usually associated with greater cognitive benefits for healthy elderly subjects,[21] healthy adults,[22] and subjects with mild cognitive impairment.[23] Moreover, several systematic reviews and meta-analyses suggested that CPCT was associated with improved overall cognitive ability in healthy older adults[24] and older adults with mild cognitive impairment or dementia.[25,26]

Several studies used cognitive neuroscience techniques such as functional near-infrared spectroscopy (fNIRS) to explore the neurobiological mechanisms by which CPCT affected cognitive function. For example, Ji et al.[27] used fNIRS in older adults and found that the Stroop behavioral performance following CPCT as part of an acute aerobic exercise scheme was similar to that following cognitive or physical training alone, but the oxygenated hemoglobin (Oxy-Hb) level in the prefrontal cortex of the combined group was higher.[27] However, a recent study indicated that acute CPCT or physical or cognitive training alone was similarly effective in improving executive function and cerebral oxygenation of the prefrontal cortex in older adults.[28]

The fNIRS study described above principally investigated CPCT as part of acute aerobic exercise, whereas the effect of long-term CPCT on executive function remains to be clarified. Furthermore, previous studies primarily enrolled older individuals as research subjects, and few have evaluated whether the effects of long-term CPCT could be extrapolated to the adolescent athlete population. Puberty is a critical transitional physical and mental development stage during which adolescent athletes' lifestyle and behavioral patterns gradually develop. Therefore, the present study employed fNIRS in adolescent shooting athletes to compare the effects of long-term CPCT and cognitive training alone on executive function and underlying brain mechanisms. We hypothesized that CPCT would improve executive function performance in adolescents more effectively than computerized cognitive training (CCT) alone (Hypothesis 1), and this improvement will be reflected in the prefrontal cortex activation level (Hypothesis 2).

Methods

Participants

Thirty-four shooting athletes were recruited from the Guangzhou Sports School of Guangdong Province to participate in this study. Athletes were included if they met the criteria of age between 12 and 18 years, being right-handed, having normal vision, the experience shooting-specific training of at least two years, and if able to fit into the physical and cognitive training prescreening. Any athletes who had any history of brain injury, cardiovascular, metabolic, or neurological disease, and any surgery one year prior to baseline assessment and involved in any other physical and cognitive training program were excluded. Participants were allocated randomly (via a computer-generated algorithm) to either the CPCT group or the CCT group. Thirty-three athletes (age 13–18) completed pre- and post-assessments in both CPCT group ($n = 17$) and CCT group ($n = 16$) that were included in the statistical analysis. The study procedures were carried out following the Declaration of Helsinki. The study protocol was approved by the Ethics Committee of the Guangzhou Sport University (approval no.: 2021LCLL-25) and registered at Chinese Clinical Trial Registry (https://www.chictr.org.cn/). The parents or guardians of all participants provided written informed consent.

Training procedure

The subjects underwent 2-back, Stroop, and task-switching executive function tests before and after the intervention. The rating of perceived exertion (RPE) was measured in the CPCT group before and after each exercise session. The CCT group performed no physical exercise. They completed computer-based cognitive tasks. Both groups underwent three 30-min training sessions per week for six weeks.

CPCT

The CPCT training integrated the executive function subsystems (inhibition, switching, and updating) with physical activities, resulting in three intervention pairs: (1) Jogging and updating tasks. The participants' updating function was improved through 1-, 2-, and 3-back tasks. The participants exhibited a predetermined braking response following the numbers announced by the coach during jogging. For instance, when the athletes heard the coach announce a number different from the previous one, they stopped immediately, stood, and then restarted jogging. (2) Quick short steps in place and switching tasks. The "large/small," "odd/even," and "large/small or odd/even" switching of the more-odd switching paradigm were used to train the switching function. The participants performed small steps continuously. When the coach randomly shouted out a number from 1 to 9 (excluding 5), the participants judged if it was large or small and odd or even, and immediately touched the corresponding marker with their hands. (3) Jumping jacks in place and inhibition tasks. The Stroop task was used to improve the participants' inhibition control function. The coach randomly drew a card containing a colored word while the participants performed slow jumping jacks. The subjects touched the corresponding marker they considered consistent the word meaning and color, only the word meaning, or only the word color. The task execution and difficulty progressed gradually based on the participant's performance. The study controlled the load at a medium intensity, and the subjects reported the perceived exertion between alternating blocks.

CCT

The three executive function subfunction tasks (Stop signal,[29] Wisconsin card sorting,[30] and Corsi block tapping[31]) were used as interventions. The participants needed to sequentially complete sets of these cognitive tasks on a computer during the intervention. The tasks were designed to gradually increase the difficulty based on the subjects' performances by controlling the appearance and disappearance times of the task conditions.

Measurements of executive functions

The executive functions were measured using the Stroop, 2-back, and task-switching tests. The experimental procedures were composed using E-prime software 3.0 (Psychology Software Tools) with task stimuli presented on a computer screen and behavioral responses recorded by the keyboard.

2-Back task

The experimental tasks employed 0–9 Arabic numerals as stimuli, with each number appearing independently at the center of the computer screen. The trials began with a visual checkpoint "+" for 300 ms, followed by an interval of 700 ms, and then the numeral stimuli for 1 000 ms each. Responses were required within a limited time. The participants were asked to watch and memorize the numbers carefully, pressing the "F" key if the presented number was the same as the second last one; otherwise, they pressed the "J" key. This experiment included six warm-up trials and 24 formal tests. The formal test was divided into two blocks, each consisting of 12 judgment trials and a 30-ms rest between blocks.

Switching task

The switching task consists of non-switching and switching conditions. The test was divided into three sections: the first and second sections were non-switching conditions, and the third section was a switching condition. The first section was a football pattern judgment, which required the participants to press the "F" key if there were more footballs on the left side of the picture and press the "J" key if there were more on the right. The second section was a bullseye pattern judgment, which required the participants to press the "F" key if there were more bullseyes at the top of the picture and press the "J" key if there were more at the bottom. The third section contained a mixed presentation of footballs and bullseyes, which required the participants to perform a "left/right" judgment if the football pattern appeared on the screen and perform "top/bottom" judgment if the bullseye pattern appeared on the screen. The pictures on the computer screen had a thick midline to distinguish between the left/right or top/bottom.

The trial started with a visual checkpoint "+" for 800 ms, followed by an interval of 2 000 ms, and then pictures were displayed at the center of the computer screen for 2 200 ms. The participants were required to respond to the pictures of two patterns by pressing the key within a limited time. The 32 warm-up trials before the formal test included eight football pattern judgments, eight bullseye pattern judgments, and 16 switching judgments of the two patterns. The formal test comprised 80 trials, 20 football pattern judgments, 20 bullseye pattern judgments, and 40 mixed football and bullseye pattern judgments. Ten trials constituted a block, with a 30-ms interval between blocks.

Stroop task

The Chinese characters for "red," "green," and "blue," written in red, green, or blue, were randomly displayed on the computer screen. The Stroop task included congruent and incongruent conditions. In the congruent condition, the meaning and color of the word were the same; for instance, the word "blue" was written in blue color. In the incongruent condition, the word was in a different color than its meaning; for instance, the word "red" was written in blue. The subjects were instructed to ignore the meaning of the word and press the "J" key if the character color was red, press the "K" key if it was green, and press the "L" key if it was blue.

The trial began with a visual checkpoint "+" for 500 ms, followed by an interval of 1 300 ms, and then the colored character for 200 ms. The participants were required to respond to the colored words by pressing the key within a limited time. The Stroop task consisted of a warm-up experiment of 20 trials and a formal experiment of 40 trials. Ten trials constituted a block, with a 20-ms resting interval between blocks.

fNIRS recordings

An fNIRS platform (NIRSport; NIRx Medical Technology LLC, Glen Head, NY, USA) was used to monitor changes in Oxy-Hb concentration signals in the prefrontal cortex while the subjects performed the tasks. This imaging system comprised eight illumination sources and eight detectors, constituting 20 channels. The probe covered eight cerebral regions of interest (ROIs), including the left, right, and middle frontal pole area (L-, R-, M-FPA) of the prefrontal lobe; left, right, and middle dorsolateral prefrontal cortex (L-, R-, M-DLPFC); left and right ventrolateral prefrontal cortex (L-, R-VLFPC). The near-infrared light-emitting diode (LED) had wavelengths of 760 and 850 nm. The sampling rate was approximately 7.18 Hz. The cap center positioning standard was based on the international 10–20 reference system. The brain regions were determined using the fNIRS Optodes' Location Decider (fOLD) and the maximum probability distribution of ROIs in the high-density international 10–20 system (see Fig. 1 and Supplementary Table S1).[32,33] The subjects were instructed to limit excessive movements, such as head shaking, frowning, gnashing, or speaking, during the detection process to decrease external noise interference on the fNIRS signal.

Demographic variables

We recorded the participants' basic information (sex, age, height, weight, years of sports, and sports level) using an anthropometric information questionnaire. The participants' daily physical activity level was monitored using the International Physical Activity Questionnaire.[34] The RPE scale[35] determined the degree of perceived exertion in the CPCT group during exercise. The score range was 6–20, and the perceived medium-intensity load correlated with a score of 13–15.

Statistical analysis

Excel 2020 software (Microsoft) was used to sort and summarize the

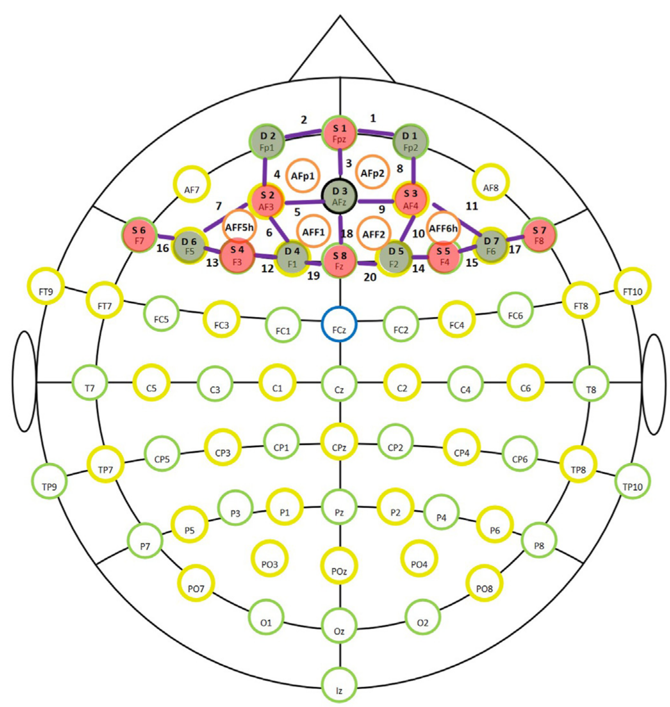

Fig. 1. A brain regions montage. Sources (S) and detectors (D) were situated according to the international 10–20 system. The purple lines and numbers represent channels.

collected anthropometric data. The behavioral data were organized using E-merge software (Psychology Software Tools). Raw Oxy-Hb data from all channels were processed using nirsLAB analysis software (NIRx Medical Technology LLC, Glen Head, NY, USA). Repeated-measures analysis of variance (ANOVA) was performed using IBM SPSS Statistics for Windows, Version 23.0 (IBM Corp., Armonk, NY, USA). Figures were generated using GraphPad Prism, Version 8.0.

This study used response time, response accuracy, and Oxy-Hb as dependent variable indicators for the three subfunctions of executive function. We performed a 2 (group: CPCT and CCT) × 2 (time: pre-test and post-test) repeated-measures ANOVA. A simple effect test was performed if an interaction between the time and group was detected. Paired *t*-tests were also used to test for differences between the pre- and post-test in each group. All statistical analyses with a *p*-value < 0.05 were considered significant.

Results

Basic information and physical characteristics of the participants

The basic characteristics of the two groups were similar (Table 1). The mean RPE score after the exercises was 14.24 ± 0.83, corresponding to a medium-intensity load.

Behavioral assessment results

The behavioral performances of three tasks for CPCT and CCT groups are summarized in the Supplementary Table S2.

2-Back task

For the accuracy indicator, the time main effect was significant ($F_{[1,31]} = 17.981, p < 0.001$). Paired *t*-tests results indicated that the post-test performance was significantly better than the pre-test performance (CPCT group, $p = 0.003$; CCT group, $p = 0.026$). Regarding the response time indicator, the group and time main effects and their interaction were insignificant (Fig. 2A and B). These data demonstrate that both groups significantly enhanced the updating function in the accuracy indicator.

Task-switching task

The dependent variables in the task-switching task were the accuracy and response time under the three conditions: non-switch, switch, and switch cost (switch cost = switch − non-switch).

For the accuracy indicator in the switch task, the interaction between the group and time was significant ($F_{[1,31]} = 8.335$, $p = 0.007$). The simple effect test results revealed that the post-test was significantly superior to the pre-test in the CPCT group ($p = 0.020$), whereas the test results were similar in the CCT group. For the response time indicator, the group and time main effects and their interaction were insignificant.

For the accuracy indicator in the non-switch task, the time main effect ($F_{[1,31]} = 4.972$, $p = 0.033$) was significant. The paired *t*-tests results revealed that the post-test was superior to the pre-test in the CPCT group ($p = 0.044$), while the test results were similar in the CCT group. For the response time indicator, the time main effect was significant ($F_{[1,31]} = 28.921$, $p < 0.001$). The paired *t*-tests results indicated that the post-test results were significantly better than the pre-test results in both groups (CPCT group, $p = 0.001$; CCT group, $p = 0.005$).

Regarding switch costs, the accuracy indicator showed that the interaction between the group and time was significant ($F_{[1,31]} = 4.974$, $p = 0.033$). But the simple effect test results indicated that the post-test results were insignificantly better than the pre-test results in both groups. For the response time indicator, the time main effect was significant ($F_{[1,31]} = 4.775$, $p = 0.037$). However, the pre- and post-test results were similar in both groups (Fig. 2C and D).

These results suggest that the CPCT group significantly improved the accuracy when executing the switch and non-switch tasks, while the CCT group did not. Both groups significantly improved their response times when executing non-switch tasks.

Stroop task

The dependent variables in the Stroop task were accuracy and response time under three conditions: congruent, incongruent, and interference cost (incongruent – congruent). The results show that there were insignificant interactions or main effects for all conditions, indicating that neither treatment improved the behavioral performance of the inhibition function in this cohort (Fig. 2 E and F).

fNIRS results

Oxy-Hb hemodynamic changes related to three tasks in all ROIs for CPCT and CCT groups are summarized in the Supplementary Table S3. This article reports the statistical test outcomes for brain ROIs with significant interaction effects (Fig. 3).

2-Back task

In the middle FPA, the interaction between the group and time was marginally significant ($F_{[1,31]} = 3.659, p = 0.065$). The simple effects test results revealed that Oxy-Hb hemodynamic change related to 2-back was significantly greater in the post-test than pre-test in the CPCT group ($p = 0.004$), but not in the CCT group (Fig. 3A, B, and C).

Task-switching

In the left FPA, the interaction between the group and time ($F_{[1,31]} = 7.859$, $p = 0.009$) was significant. The simple effect test results showed that Oxy-Hb hemodynamic change related to switch cost was significantly greater in post-test than pre-test in the CPCT group ($p = 0.001$), but not in the CCT group (Fig. 3D, E, and F).

Stroop task

For the left FPA, a significant interaction between the group and time ($F_{[1,31]} = 7.923$, $p = 0.008$) was observed. The simple effect test results revealed that Oxy-Hb hemodynamic change related to Stroop interference was significantly greater in post-test than pre-test in the CPCT group ($p = 0.040$), but not in the CCT group. In the middle FPA, the interaction between the group and time was marginally significant ($F_{[1,31]} = 3.910$, $p = 0.057$). The simple effect test results showed that the post-test result was significantly superior to the pre-test result in the CPCT group ($p = 0.018$), but not in the CCT group (Fig. 3G, H, I, and J).

In summary, the fNIRS results showed that the CPCT led to significant changes in Oxy-Hb signals in the middle FPA during the 2-back task execution, in the left and middle FPA while executing the Stroop task, and in the left FPA during task-switching execution. In contrast, no training-induced alterations were observed in the CCT group.

Table 1
Participants' characteristics.

Characteristic	CPCT (n = 17)	CCT (n = 16)	t	p
Age (years)	14.94 ± 1.89	14.81 ± 2.07	0.187	0.853
Height (cm)	169.53 ± 6.62	168.06 ± 8.66	0.549	0.587
Weight (kg)	62.94 ± 14.14	61.88 ± 13.63	0.220	0.827
Sex	7 F, 10 M	8 F, 8 M	/	/
RPE score	14.24 ± 0.83	/	/	/
Sports level (0/1/2)[a]	6/7/4	3/7/6	/	/
Physical activity (MET-min/ week)	2 773.82 ± 632.90	2 964.38 ± 490.07	−0.963	0.343
Sports specific training duration (years)	4.35 ± 1.90	4.34 ± 1.77	0.014	0.989

Data are expressed as mean ± standard deviation (*SD*). Females: F; Males: M.
[a] Sport level (0/1/2) indicates no sports level, national level 1, and national level 2 athletes, respectively.

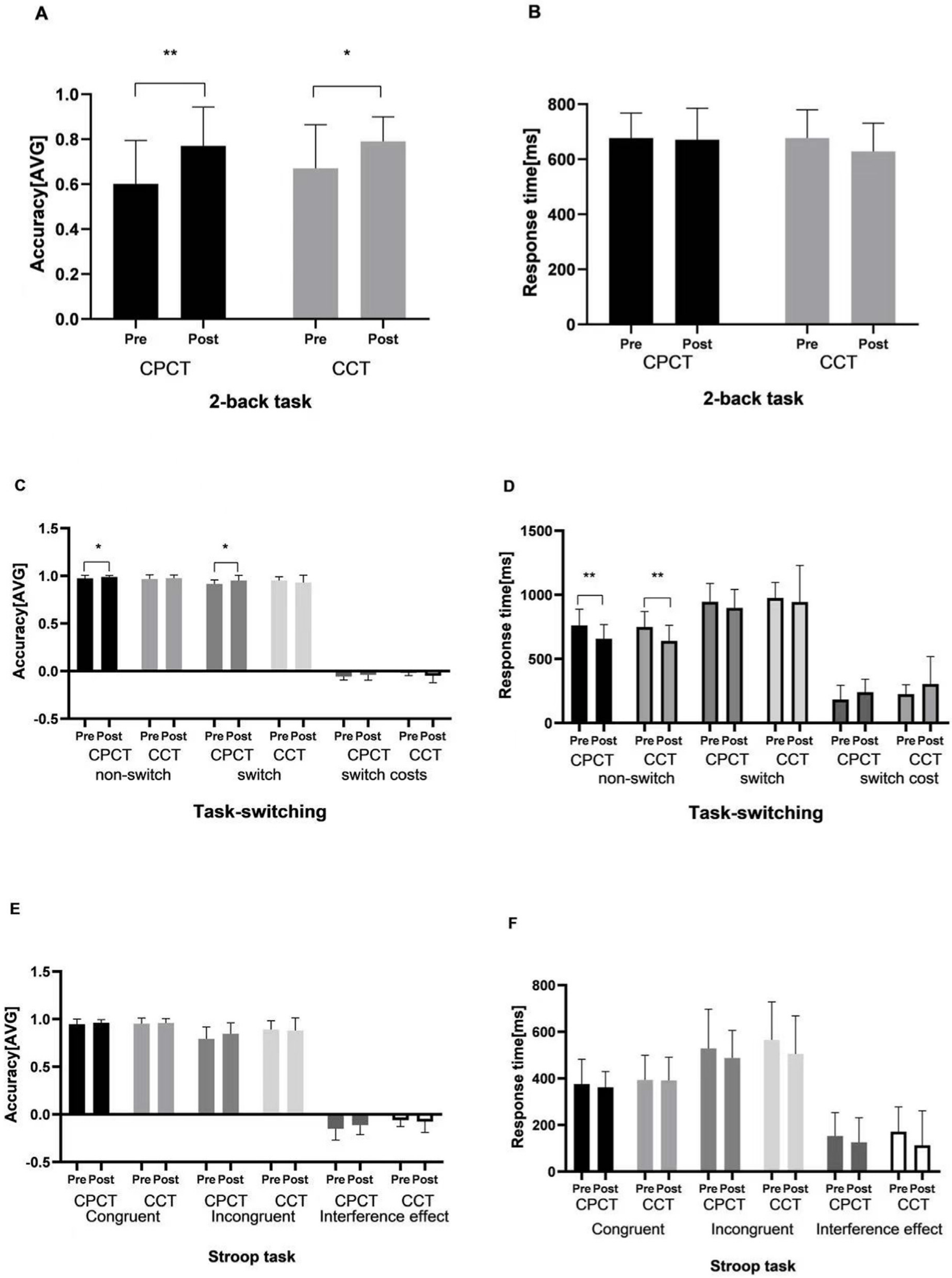

Fig. 2. Behavioral results in the 2-back, task-switching, and Stroop tasks. (A) accuracy of the 2-back task; (B) reaction time in the 2-back task; (C) accuracy of task-switching task; (D) reaction time in the task-switching task; (E) accuracy of the Stroop task; (F) reaction time in the Stroop task. Data are expressed as mean ± standard deviation (*SD*). * indicates $p < 0.05$; ** indicates $p < 0.01$. combined physical and cognitive training: CPCT; computerized cognitive training: CCT.

Discussion

The behavioral results revealed that among three executive functions, CPCT exhibited advantages over CCT only in the switching function. These results partially support our hypothesis 1 and suggest that executive function enhancement by combined training might be affected by task characteristics among adolescent shooting athletes.

We found that both CCT and CPCT training improved the updating

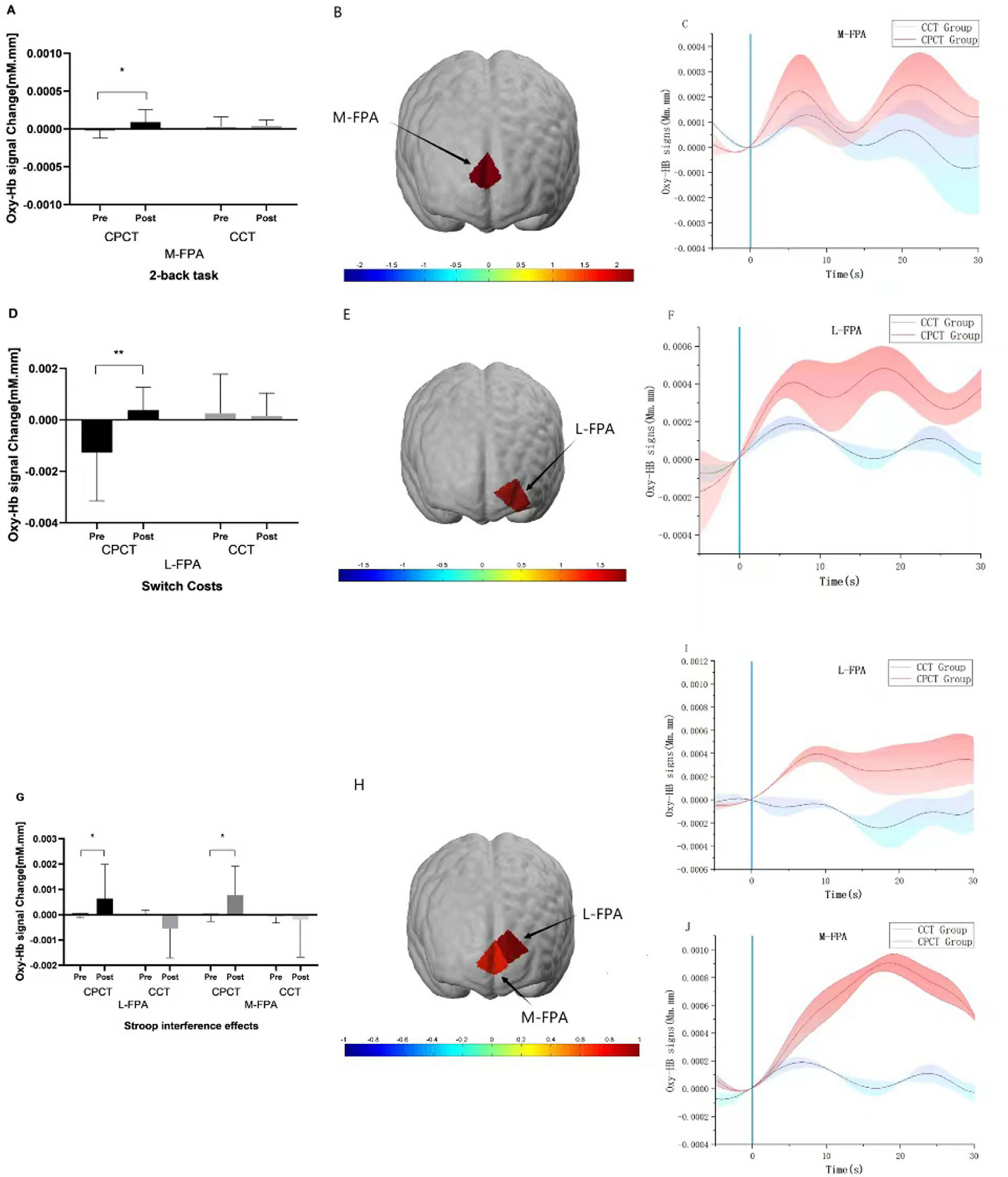

Fig. 3. Comparison of prefrontal cortex Oxy-Hb measurements between two groups of three tasks. (A) Oxy-Hb measurements, (B) t-map of Oxy-Hb signal contrast activation and (C) Waveforms of Oxy-Hb of M-FPA between the two groups in the 2-back task; (D) Oxy-Hb measurements, (E) t-map of Oxy-Hb signal contrast activation and (F) Waveforms of Oxy-Hb of L-FPA of between two groups in theTask-switching; (G) Oxy-Hb measurements, (H) t-map of Oxy-Hb signal contrast activation and (I, J) Waveforms of Oxy-Hb of L-FPA and M-FPA between two groups in the Task-switching. Data are expressed as mean ± standard deviation (*SD*). * indicates $p < 0.05$; ** indicates $p < 0.01$. oxygenated hemoglobin: Oxy-Hb; left: L; right: R; middle: M; frontal pole area: FPA.

function During training, both groups required participants to memorize the numbers that appeared previously and make correct judgments, extremely similar to the updating function test tasks. Moreover, CPCT requires memorizing the numbers and performing the correct moderate-intensity physical responses to complete the task; the ability to manage such motor complexity and information load is important for the updating function.[36] However, we did not observe a superior training effect for CPCT over CCT. These findings were consistent with a previous report of older adults that found that cognitive training alone or combined cognitive and physical training could similarly ameliorate the individual's behavioral performance of updating function.[14]

For the switching function, CPCT was more efficient than CCT in improving the behavioral performance of switching and no-switching tasks. These results agree with the findings of a study that compared the effects of CPCT and single cognitive training on individuals' switching functions performance.[37] Our findings were also consistent with data from a 4-month investigation in which combined training promoted multiple cognitive domains in healthy adults more than CCT.[22] Based on the above results, combined training presents several advantages over single training in older adults, adults, and adolescents.

However, our results showed that CPCT and CCT did not substantially affect the inhibitory control function when executing the Stroop task. The behavioral outcomes of this study were inconsistent with those of previous reports on elderly subjects. For example, Ji et al. found that single or combined training improved individual behavioral performance in inhibitory control ability.[27] Similarly, an acute effect study suggested that performance improvements in the inhibitory control task through CPCT could be as effective as physical or cognitive training alone.[28] The inhibitory control performance of the adolescent shooting athletes in this study may not have improved considerably because, in contrast to other components of executive functions, inhibitory control appears to emerge in infancy and develop rapidly in early childhood.[38] Additionally, athletes possess certain advantages regarding inhibitory control performance compared to non-athletes, and those at higher athletic levels have better inhibitory ability than those at lower levels.[6,39,40] Consequently, adolescent shooting athletes already at a relatively high inhibitory ability level might not show significant improvements in behavioral performance after CPCT or CCT.

Prior research has shown that increased Oxy-Hb level in the prefrontal cortex of the brain is associated with higher executive function.[13,41] Our fNIRS results showed that Oxy-Hb related to three cognitive tasks significantly improved in the CPCT group in the prefrontal cortex, but not in the CCT group. These results support our hypothesis 2 that CPCT was more advantageous for improving individual brain mechanisms than CCT for executive function. Our findings are consistent with previous studies that found a greater degree of prefrontal cortex Oxy-Hb level increase after CPCT than after single training.[27,42] These findings indicated that CPCT was more beneficial for the individual's executive function than CCT at the neural level, confirming an adaptive process of the prefrontal cortex during CPCT.

Findings from this study suggested that all assessed brain regions in the CPCT group exhibited enhanced activation and that the left FPA played a key role in the task-switching and Stroop tasks. This might be related to age; the brain gradually shifts from right lateralization to enhanced left hemisphere activity with age, particularly between 7 and 18 years.[43,44] The adolescent shooting athletes' age in this study was 13–18 years. Therefore, the activity in their left-brain regions was enhanced after cognitively engaging in aerobic exercise, resulting in increased blood oxygen content. Our results align with Byun et al., who, using fNIRS, found increased neural activation in the left FPA after acute aerobic exercise.[41] Besides, we observed middle FPA activation during the 2-back and Stroop tasks. Studies have demonstrated that aerobic exercise enhanced FPA neural activities because FPA is primarily related to integrating multiple higher-order behavioral goals[45] and decision-making[46,47] functions. Moreover, one study reported that FPA is the functional cerebral area recruited by the brain to perform complex tasks.[48] One might infer from this that CPCT primarily activates the middle and left FPA, as participants repeatedly stimulate the FPA to simultaneously complete the complex components of the CPCT task.

However, unlike the CPCT group, the CCT group showed no improvement in the neural activation level in any studied brain region after training. The CCT in this group was strictly controlled during training; the participants remained seated with minimal physical movement. Therefore, the brains of the CCT group were relatively suppressed, possibly contributing to the lack of beneficial influence on the blood oxygen content in the various brain regions. It could be deduced that the enhanced FPA activation level in the CPCT group after training was related to the participants' enhanced neural activity in response to the medium-intensity physical exercise load. Several studies reported that aerobic exercise could cause neurotransmitters such as dopamine and norepinephrine to increase in the brain[49] and that these neurotransmitters can stimulate brain nerve activities, thereby boosting cognitive function.

In summary, considering either the impact of exercise on neural activity or the influence of complex cognitive engagement on brain structure and function, CPCT was beneficial in improving the executive function of adolescent shooting athletes. Although brain activation and improved behavioral operations performance were not synchronized, our results provide valid evidence for the performance enhancement adolescent shooting athletes gained by performing CPCT. Interestingly, our research subjects showed varying degrees of training-induced improvements even though they were athletes with strong cognitive abilities.[50] Thus, our findings support the adaptive capacity model theory at the neurological level,[19] suggesting that the integration of cognitive and physical training activities could generate additive or synergistic effects.

Limitations

This study had some limitations. First, the sample size was relatively small. Including a larger sample in future studies could help detect additional differences between the effects of such distinct training types. Second, despite using CCT for comparison, this study did not include a blank group without any training or a pure physical training group. Such control groups should be included in future studies to obtain more objective results and confirm the effect of cognitive training on executive function in adolescent athletes. Third, the study intervention lasted six weeks. This relatively short duration may have influenced the results. Long-term intervention programs should be designed in future studies. Moreover, pre-, during-, and post-tests could compare the benefits of intervention time on executive function and determine the lasting effect of CPCT on executive function. Finally, due to the complexity of the human brain, involving genomics, cell and synapse effects on the whole organ, this study is limited to exploring the plasticity of the human brain using only the fNIRS technique. Future research should use multiple cognitive neuroscience approaches, combined with neurobiological techniques, to explore more deeply the macro and micro manifestations and modulators of brain plasticity in athletes.

Conclusions

This study found that six weeks of CPCT and CCT training similarly improved updating function in adolescent shooting athletes. The CPCT group significantly improved the switching function, while the CCT group did not. However, there was no improvement in the behavioral performance of inhibitory functions in either group. Oxy-Hb activation levels in the FPA significantly improved in the CPCT group during the three cognitive tasks, while the CCT group showed no change. If confirmed in larger, longer, well-controlled future studies of shooting athletes and other sports disciplines, the suggested CPCT could help enhance executive function skills in many professional athletes.

Ethical approval statement

Parents or guardians of all participants completed and provided an informed consent form confirming that they understood the details and specific requirements of the test. The study protocol was approved by the Ethics Committee of the Guangzhou Sport University (approval no.: 2021LCLL-25) and registered at Chinese Clinical Trial Registry (https://www.chictr.org.cn/).

Submission statement

All authors have read and agree with manuscript content. This manuscript will not be submitted for review or publication elsewhere while it is being reviewed for this journal.

Authors' contributions

Min Hu contributed to the design and drafting of the manuscript. Mingqiang Xiang contributed to the analysis and interpretation of the data, as well as writing and revising the manuscript critically. Guanru Li, Jianuo Ye, Meng Wu and Ruiping Xu contributed to the acquisition of the data. All authors participated in drafting the manuscript, and read and approved the final version of the manuscript.

Conflict of interest

Min Hu is an Editorial Board Member for Sports Medicine and Health Science and was not involved in the editorial review or the decision to publish this article. The authors declare no conflicts of interest relevant to the content of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smhs.2023.02.004.

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