

RESEARCH ARTICLE

The impact of acute aerobic exercise combined with cognitive tasks on the executive function performance of Chinese college students

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Abstract

Background: Acute exercise benefits executive function (EF), but findings on cognitively engaging physical activity are inconsistent, particularly among college students, highlighting the need to clarify the combined effects of physical exertion (PE) and cognitive engagement (CE).

Objective: This study explores the effects of acute aerobic exercise combined with cognitive tasks on EF among Chinese college students and clarifies the differential effects of PE and CE on EF.

Methods: A 2 × 2 within-subject design was adopted, with PE (high vs. low) and CE (high vs. low) as factors. Sixteen Chinese college students completed EF tests (2-back, Stroop, more-odd shifting) before and after four interventions: high PE + high CE, high PE + low CE, low PE + high CE, and low PE + low CE. Both subjective and objective measures of PE and CE were collected throughout the experiment.

Results: Results showed that high PE + high CE induced the highest cognitive engagement and significantly improved college students' working memory accuracy and inhibitory control performance; however, no significant effect on cognitive flexibility was observed.

Conclusion: In conclusion, cognitively engaging physical activity may provide greater short-term benefits for partial core components of college students' EF than single aerobic exercise or a cognitive task alone, making it a feasible dual-task intervention to enhance college students' EF and reduce sedentary behavior.

Keywords: Executive function; Cognitive engagement; Acute aerobic exercise

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1. Introduction

The beneficial effects of acute exercise on executive function have been consistently demonstrated.^{1,2} Currently, increasing attention is being directed toward the role of cognitive engagement (CE) in enhancing executive function through acute exercise.³

It is proposed that cognitively engaging physical activity (CEPA), which involves contextual interference, mental control, and discovery, is more effective than simple, repetitive aerobic exercise in improving cognitive abilities, especially executive function.⁴ CEPA exists in two forms: one involves the acquisition and execution of complex motor skills⁵, while the other comprises physical activity with artificially structured rules for simple tasks that increase cognitive demands (Exergame).³ These two forms of

activity may promote executive function through distinct mechanisms. The enhancement of executive function in the former may stem from learning skills required for physical activities. Their cognitive abilities, represented by executive function, are trained while individuals master the complex motor skills required for physical activities, thereby achieving improvement.⁶ The latter usually involves processes such as updating (remembering specific signals), inhibition (making opposite actions in response to prompts), and shifting (making different actions in response to different signals) in rule-based settings. While playing Exergame, cognitive abilities are also “trained,” resulting in cognitive improvement.⁷

However, even when focusing solely on acute interventions, findings have been inconsistent in CEPA studies. During childhood and adolescence, executive function undergoes rapid changes with growth and development, and external factors, such as increased physical activity in school-age children, have led to greater research in this age group. Best⁸ found that acute CEPA can improve individual executive function and physical exertion (PE), with CE not the primary factor driving these changes. Similar results have validated this conclusion in subsequent studies.^{9,10} However, Egger *et al.*¹¹ achieved significantly different effects when using a 2 (PE: high/low) $\times$ 2 (CE: high/low) experimental design to intervene in school-age children. The results showed that the positive benefits of performance changes under low CE conditions were greater than those in the high CE group.¹¹ The results of a meta-analysis indicate that the high heterogeneity of current results comes from intervention forms (e.g., aerobic exercise, complex skill exercise, sports games) and control forms (e.g., blank control, academic learning).³

Moreover, extant research in this field has disproportionately focused on school-age children, adolescents, and older adults¹²—populations widely recognized to garner cognitive benefits from physical activity—leaving a critical gap in understanding how CEPA modulates executive function in college students, a population with unique behavioral and cognitive characteristics that render CEPA interventions particularly meaningful.^{13,14} College students are a distinct group facing dual challenges: chronic sedentary lifestyles driven by prolonged screen time, sedentary study, and limited physical activity,^{15,16} which not only impairs physical health but also poses long-term risks to cognitive maintenance; and persistent high academic cognitive load from coursework, examinations, and independent study, creating an urgent need for efficient, low-cost interventions to preserve executive function amid cognitive fatigue.^{17,18} Beyond these practical imperatives, college students

exhibit relatively stable executive function compared with developing children and cognitively declining older adults, making them an ideal model to test the core effects of CEPA—if positive benefits emerge in this population, the intervention’s efficacy may be generalized to groups with greater cognitive plasticity (e.g., school-age children). This study thus addresses the aforementioned literature gap by focusing on college students. Its findings are expected to fill the empirical gap in CEPA research within this understudied population, while also offering targeted practical implications for a group that would benefit from integrated physical and cognitive health interventions.

In natural or quasi-experimental contexts, it is not possible to fully isolate or control for additional factors that may affect the effectiveness of the intervention, such as motor control requirements, social interaction, and individual differences among participants.¹⁹ Therefore, results obtained under strict control in a laboratory context may help clarify some contradictions in the current research. It is difficult to fully integrate CE factors into physical activities in laboratory settings. A more realistic approach is the dual-task paradigm, which involves the simultaneous performance of physical and cognitive tasks.²⁰ Several existing studies have adopted this design, including those by Kamijo and Abe¹⁹ and Ji *et al.*²¹ In this study, we redesigned the cognitive task and used Sudoku as an intervention, replacing previous cognitive training. This is because cognitive training is consistent with the pre- and post-tasks in the study, both of which are computer-based button response tasks, which can easily cause psychological fatigue among participants and affect the intervention effect.¹⁹ Moreover, as a logic-based game, Sudoku requires individuals to exert a certain level of cognitive effort to complete.²² Neuroimaging evidence further demonstrates activation of the prefrontal cortex, a key brain region underlying executive function, during Sudoku performance.²³

Based on these rationales, this study adopts a within-subject design and uses a 2 (PE: high/low) $\times$ 2 (CE: high/low) intervention to explore the impact of acute intervention with different intensities of physical activity and CE on executive function. Based on previous research results, we hypothesize that CEPA interventions can yield the greatest benefits, and that high PE interventions can result in greater improvements in acute interventions than high CE interventions.

2. Methods

2.1. Participants

Sixteen participants aged 18–24 years (21.35 ± 2.67 ; 10

females) were recruited from Zhejiang University. They did not have any prohibited diseases that would prevent them from participating in the study, and all participants signed an informed consent form. The ethical approval for this study was obtained from the Department of Humanities and Social Sciences at Zhejiang University.

The sample size calculation was based on a previous study that used a within-subject design to explore the impact of exercise combined with mathematical learning on executive function, with an effect size of $f = 0.8$.¹⁰ Using a conservative estimate with a different intervention, we scaled down the effect to $f = 0.4$.¹⁰ The primary hypothesis was tested using a repeated-measures analysis of variance (ANOVA), and the sample size was estimated a priori based on 80% power and a two-tailed alpha of 0.05. This calculation indicated that 16 samples would be sufficient for the analysis (G*Power3.1).²⁴

2.2. Laboratory procedure

When the participants first arrived at the laboratory, they completed an informed consent form and the International Physical Activity Questionnaire Short to assess their physical activity level and received instructions for performing the functional tests. These tasks were conducted before and after subsequent interventions. Subsequently, formal intervention was initiated. Four conditions were designed based on different levels of PE and CE. Each participant was required to complete four conditions: (i) high PE + high CE, (ii) high PE + low CE, (iii) low PE + high CE, and (iv) low PE + low CE. Participants completed the 2-back, Stroop, and more-odd shifting tasks on the laboratory computer before the intervention (T0) and after the intervention (T1).

The order of the four intervention conditions was counterbalanced across all participants to eliminate potential order effects on the study outcomes. All four interventions for each participant were administered at the same fixed time of day on separate days, with an interval of at least four days between consecutive intervention sessions. Results from the International Physical Activity Questionnaire-Short Form indicated that all participants exhibited a moderate level of habitual physical activity. Prior to each intervention session, participants were instructed to abstain from moderate-to-vigorous physical activity lasting more than 30 min, maintain 7–9 h of nocturnal sleep, and refrain from alcohol and caffeine consumption for the entire preceding day.

2.3. Interventions

Four conditions were designed based on two factors: PE (high/low) and CE (high/low). High PE was operationalized

as cycling on an ergometer (894E; MONARK, Sweden), whereas low PE involved sitting quietly on the ergometer. High CE involved solving Sudoku puzzles on a tablet, while low CE required participants to watch Sudoku-related videos on a tablet. Accordingly, four conditions were defined: (i) solving Sudoku while cycling (high PE+ high CE), (ii) watching Sudoku-related videos while cycling (high PE+ low CE), (iii) solving Sudoku while sitting on a cycle ergometer (low PE+ high CE), and (iv) watching Sudoku-related videos while sitting on a cycle ergometer (low PE+ low CE). Each intervention lasted 20 min.

In the high PE condition, heart rate was maintained between 55% and 65% of maximum using a heart rate monitor (Polar V800 with H10 chest strap; Polar, Finland). The target heart rate was calculated using **Equation 1**²⁵:

$$\text{Target HR} = (\text{HR}_{\text{max}} - \text{HR}_{\text{rest}}) \times \text{intensity} + \text{HR}_{\text{rest}} \quad (1)$$

where $\text{HR}_{\text{max}} = 220 - \text{age}$. When heart rate fell within this range, participants engaged in moderate-intensity physical activity. Research has demonstrated that moderate-intensity physical activity within a single intervention session yields the greatest beneficial effects on executive function.¹² During the intervention, researchers monitored participants' heart rate in real time and provided prompts when necessary to keep it within the prescribed range.

2.4. Cognitive tasks

2.4.1. Working memory

Working memory, as a core component of executive function, was assessed using a 2-back task. Five English letters (B, D, L, Y, P) were used as stimuli and were presented sequentially at the center of the screen for 1,500 ms, each followed by a white fixation point (“+”). After the fixation, the next stimulus appeared. Participants were required to indicate whether the current letter matched the one presented two trials earlier (i.e., from the third stimulus onward). If the letters matched, participants pressed the “F” key; if not, they pressed the “L” key. The formal test consists of two parts, each with 25 test trials. Performance was evaluated based on mean reaction time and accuracy rate. Shorter reaction times and higher accuracy rates were interpreted as better working memory performance.

2.4.2. Inhibition

Inhibitory control was assessed using the Stroop task, following established protocols.¹³ Each trial began with the presentation of a red fixation cross (“+”) to signal the start of the task. Subsequently, a color word appeared at the center of the screen. Participants were instructed to respond based on the congruency between the word's meaning and its font color: they pressed the “F” key when

the color and meaning were congruent, and the “J” key when they were incongruent. For example, if a red-colored “green” character appears, they should press “J”; if a red-colored “red” character appears, they should press the “F” key. Participants were seated with their hands positioned on the keyboard before the task began. The experiment consisted of 80 trials in total, including 40 congruent and 40 incongruent trials. Performance was evaluated using mean reaction time and accuracy. The Stroop interference effect, defined as the difference in reaction time between incongruent and congruent trials, served as the primary index of inhibitory control, with smaller differences indicating better inhibitory performance.

2.4.3. Cognitive flexibility

Cognitive flexibility was assessed using a more-odd task-switching paradigm. In the experiment, a series of numbers (1–9, excluding 5) was displayed in the center of the screen, and participants were required to make judgments according to predefined rules. The tasks consisted of three choices: (i) magnitude judgment, in which numbers were displayed in black and participants pressed the “F” key if the number was greater than 5 or the “J” key if it was less than 5; (ii) parity judgment, in which numbers were displayed in green and participants pressed the “F” key for odd numbers and the “J” key for even numbers; and (iii) switching judgment, in which participants performed magnitude judgments for black numbers and parity judgments for green numbers.

Participants were instructed to respond as quickly and accurately as possible. The formal experiment comprised three blocks presented in the order A, B, and C. Blocks A and B (non-switching condition) each included 16 trials and did not require task switching, whereas Block C (switching condition) included 32 trials and required participants to alternate between rules. Performance was evaluated using mean reaction time and accuracy for both switching and non-switching conditions. Cognitive flexibility was indexed by the switch cost, defined as the difference in reaction time between the switching and non-switching conditions, with smaller differences indicating greater cognitive flexibility.

2.5. Manipulation check

To test the success of the experimental manipulation, subjective and objective methods were used to collect data on PE and CE. The Rating of Perceived Physical Exertion (RPE) scale was used as the subjective measurement of PE²⁶, while heart rate data collected from the Polar V800 and H10 chest strap served as the objective indicator of PE. For CE, the Rating of Perceived Cognitive Engagement (RCE)

scale developed by Benzing *et al.*⁹ was used as the subjective measure. Although no relevant reliability or validity tests were conducted, this method has been used in multiple studies and has been validated to some extent.^{9,27} Objective assessment of CE was conducted using time-domain measures of heart rate variability (HRV), which have been reported to be particularly sensitive to CE-related changes.²⁸ HRV was used to assess autonomic nervous system function.⁹ Therefore, based on previous research, we chose three time points for measurement: 5 min before the intervention, 20 min into the intervention, and 5 min after the intervention. HRV data were collected using a Polar V800 and an H10 chest strap. Cardiac interbeat intervals were exported from Polar FlowSync (version 4.0), preprocessed, and analyzed with Kubios²⁹ (version 3.5.0; Finland). The root mean square of successive differences (RMSSD) was calculated as a measure of HRV.

2.6. Statistical analyses

Data were analyzed using the Statistical Package for Social Sciences software (version 25). ANOVAs were conducted to test manipulated variables, and Bonferroni post hoc tests were used to compare specific differences between different groups. Changes in the three components of executive function were analyzed using a repeated-measures multivariate ANOVA with a 4 (intervention types) $\times$ 2 (test timing) within-subjects design. The significance level for all analyses was set at $p < 0.05$.

3. Results

3.1. Manipulation check

The manipulation check indicated significant differences in PE and CE among different conditions. Specifically, in terms of PE, both subjective RPE and objective heart rate data indicated that interventions with high PE have significantly higher PE than conditions with low PE (RPE: $F = 56.330$, $p < 0.001$, $\eta^2 = 0.738$; heart rate during: $F = 246.618$, $p < 0.001$, $\eta^2 = 0.925$) (Table 1). The results of the post hoc test showed no significant difference between the high PE + high CE group and the high PE + low CE group (RPE: $p = 0.788$; heart rate during: $p = 0.584$). The low PE + high CE group and the low PE + low CE group also showed no significant differences (RPE: $p = 0.283$; heart rate during: $p = 0.284$). Regarding CE, subjective RCE data indicated differences across conditions ($F = 5.954$, $p = 0.001$, $\eta^2 = 0.229$). The post hoc test showed that the CE of the high PE + high CE group was significantly higher than that of the high PE + low CE group ($p = 0.033$) and the low PE + low CE group ($p < 0.001$). The CE of the low PE + high CE group was significantly

higher than that of the low PE + low CE group ($p = 0.008$). Objective HRV indicators showed significant differences in intervention types ($F = 14.137$, $p < 0.001$, $\eta^2 = 0.414$). The post hoc test indicated that the CE of the high PE + high CE group was significantly higher than that of other interventions (RMSSD post: high PE + low CE: $p = 0.011$; low PE + high CE: $p < 0.001$; low PE + low CE: $p < 0.001$). The CE of the high PE + low CE group was significantly higher than that of the two interventions without high PE (RMSSD post: low PE + high CE: $p = 0.002$; low PE + low CE: $p = 0.016$).

The results indicate that cycling and solving Sudoku puzzles can manipulate PE and CE. During cycling, participants maintained a heart rate of approximately 65% HR_{max} , which falls within the prescribed heart rate range for moderate-intensity physical activity. Although the subjective and objective data on CE were not completely consistent, it can be concluded that cycling while solving Sudoku induces greater CE than cycling or solving Sudoku alone.

3.2. Executive function

Separate analyses were conducted on accuracy and reaction time for the 2-back task. For reaction time, the main effect of intervention type was non-significant ($F = 0.864$, $p = 0.467$, $\eta^2 = 0.054$), whereas the main effect of test timing

reached statistical significance ($F = 21.937$, $p < 0.001$, $\eta^2 = 0.594$); the interaction effect between intervention type and test timing was non-significant ($F = 0.115$, $p = 0.951$, $\eta^2 = 0.008$).

For accuracy, the main effect of intervention condition ($F = 3.313$, $p = 0.028$, $\eta^2 = 0.181$) and the main effect of test timing ($F = 8.887$, $p = 0.009$, $\eta^2 = 0.372$) were significant, while the condition $\times$ test timing interaction exhibited a near-significant trend ($F = 2.683$, $p = 0.061$, $\eta^2 = 0.150$). Simple effect analysis further elucidated the specific group differences and pre-post change patterns: at pre-test, accuracy in both the high PE + high CE group ($p = 0.045$) and the high PE + low CE group ($p = 0.010$) was significantly lower than that in the low PE + high CE group; no significant intergroup differences in accuracy were observed across all intervention conditions at post-test (Figure 1). Within-group pre-post changes showed that only the high PE + high CE intervention improved 2-back accuracy ($p = 0.002$) (Figure 1).

Combined findings from the accuracy and reaction time measures revealed a post-intervention improvement trend in working memory performance exclusive to the two high PE intervention conditions, with this trend more pronounced in the high PE + high CE condition.

Separate analyses were conducted on accuracy and the

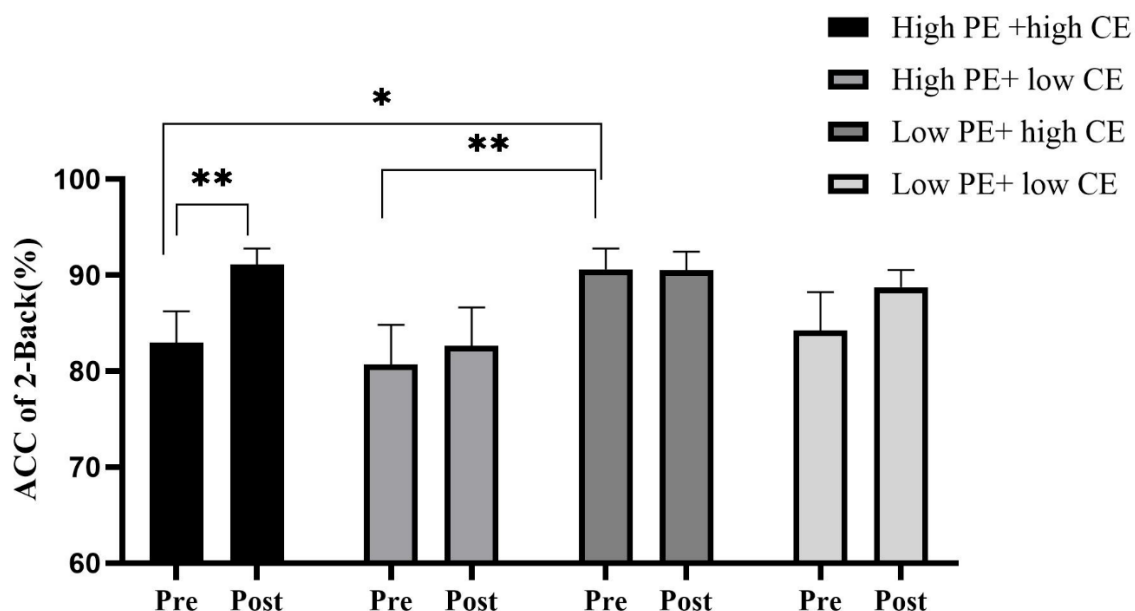


Figure 1. Simple effect analysis of 2-back test accuracy

Note: Statistical significance determined at $*p < 0.05$ and $**p < 0.01$.

Abbreviations: CE: Cognitive engagement; PE: Physical exertion.

Table 1. Descriptive statistics and analysis of variance of the manipulation check

Parameters	High PE + high CE	High PE + low CE	Low PE + high CE	Low PE + low CE	<i>F, p, η^2</i>
Physical exertion					
RPE	14.06 ± 1.44	14.25 ± 2.41	8.19 ± 2.04	7.44 ± 1.82	56.330, <0.001, 0.738
HR pre	80.19±11.21	76.69 ± 10.16	77.06 ± 8.29	79.50 ± 8.07	0.572, 0.635, 0.028
HR during	134.19 ± 9.24	135.88 ± 8.65	74.50 ± 7.08	77.81 ± 9.49	246.618, <0.001, 0.925
HR post	83.31 ± 20.86	85.06 ± 9.04	73.75 ± 6.35	76.25 ± 9.11	2.968, 0.039, 0.129
Cognitive engagement					
RCE	13.13 ± 1.67	11.38 ± 2.03	12.00 ± 2.34	9.81 ± 2.86	5.954, 0.001, 0.229
RMSSD pre	34.06 ± 16.03	43.19 ± 24.91	37.50 ± 14.49	36.38 ± 17.29	0.694, 0.559, 0.034
RMSSD during	3.44 ± 1.67	4.63 ± 2.75	44.06 ± 20.00	41.69 ± 19.41	40.978, <0.001, 0.672
RMSSD post	19.69 ± 6.06	31.19 ± 15.00	45.44 ± 14.81	42.06 ± 11.56	14.137, <0.001, 0.414

Abbreviations: CE: Cognitive engagement; HR: Heart rate; PE: Physical exertion; RCE: Rating of Perceived Cognitive Engagement; RMSSD: Root mean square of successive differences; RPE: Rating of Perceived Physical Exertion.

Stroop interference effect for the Stroop task. In terms of consistent trial accuracy, the main effect of the condition was not significant ($F = 1.562, p = 0.212, \eta^2 = 0.094$). The main effect of test timing ($F = 0.992, p = 0.335, \eta^2 = 0.062$) and the interaction effect ($F = 0.355, p = 0.786, \eta^2 = 0.023$) were not significant. In terms of inconsistent trial accuracy, the main effect of the conditions with inconsistent trial accuracy was not significant ($F = 1.562, p = 0.212, \eta^2 = 0.094$). Neither the main effect of the test timing ($F = 0.254, p = 0.621, \eta^2 = 0.017$) nor the interaction effect ($F = 0.391, p = 0.760, \eta^2 = 0.025$) was significant.

For the Stroop interference effect, the main effect of conditions was not significant ($F = 1.622, p = 0.198, \eta^2 = 0.098$). The main effect of test timing ($F = 12.261, p = 0.003, \eta^2 = 0.450$) and the interaction effect ($F = 4.079, p = 0.012, \eta^2 = 0.214$) were significant. The simple effect test results (Figure 2) indicated that, across the test timing, the improvement effect of the high PE + high CE condition on the Stroop interference effect after intervention was significantly greater than that of the low PE + low CE condition ($p = 0.026$). Within-group pre-post changes showed that only the high PE + high CE intervention improved the individual's inhibitory control performance ($p = 0.001$).

Based on indicators of accuracy and reaction time, a high PE + high CE condition can significantly improve an individual's inhibitory control performance. The other three conditions showed no improvement in the individual's inhibitory control performance, and there was no difference among the conditions.

The accuracy and response time of the more-odd shifting task were verified under different conditions. In terms of the non-switching trial accuracy, the main effect of the conditions ($F = 1.775, p = 0.166, \eta^2 = 0.106$), the main effect of test timing ($F = 0.644, p = 0.435, \eta^2 = 0.041$), and the interaction effect ($F = 1.540, p = 0.217, \eta^2 = 0.093$) were not significant. In terms of switching trial accuracy, the main effect of the conditions ($F = 0.488, p = 0.692, \eta^2 = 0.032$), the main effect of test timing ($F = 3.333, p = 0.088, \eta^2 = 0.182$), and the interaction effect ($F = 0.192, p = 0.901, \eta^2 = 0.013$) were not significant. In terms of response time, the main effect of the conditions ($F = 0.766, p = 0.519, \eta^2 = 0.049$), the main effect of test timing ($F = 11.289, p = 0.004, \eta^2 = 0.429$), and the interaction effect ($F = 0.082, p = 0.969, \eta^2 = 0.005$) were not significant. Based on indicators of accuracy and reaction time, there was no difference in the impact of different intervention types on the cognitive flexibility of university students.

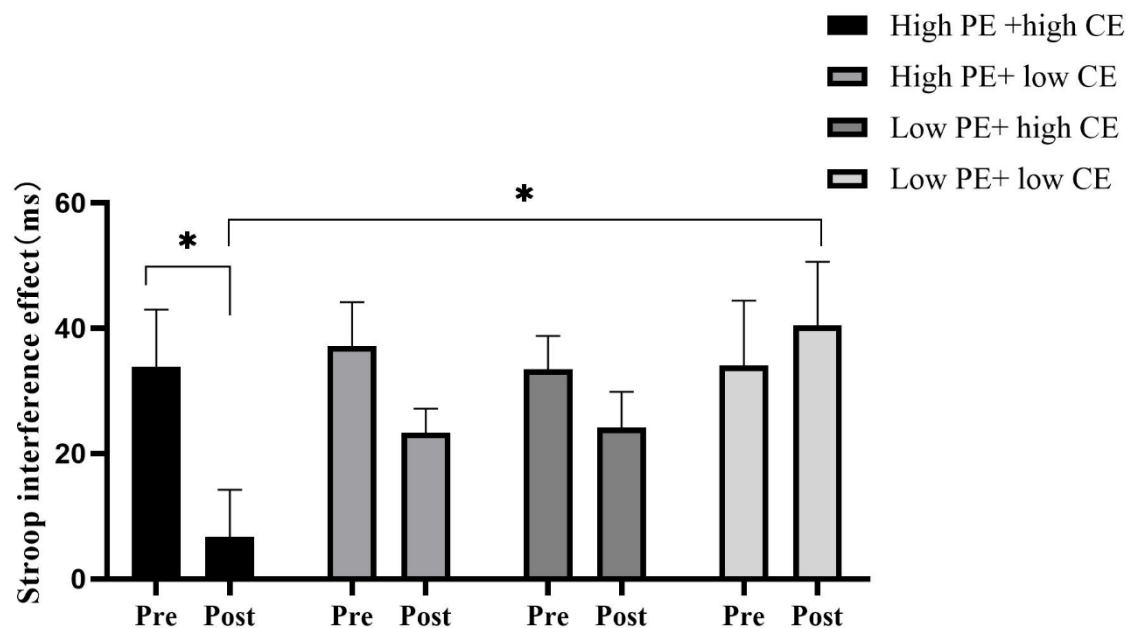


Figure 2. Simple effect analysis of the Stroop interference effect

Note: Statistical significance determined at $*p < 0.05$.

Abbreviations: CE: Cognitive engagement; PE: Physical exertion.

4. Discussion

The main purpose of this study was to explore the impact of CEPA on executive function in university students. Overall, the findings indicated that the intervention modality combining physical exercise with cognitive tasks demonstrated greater potential to enhance executive function performance compared with physical exercise interventions alone.

Current research suggests that there are two possible pathways through which physical activity can promote executive function. The first, which is widely supported, proposes that exercise-induced changes in energy metabolism can increase the availability of growth factors (such as brain-derived neurotrophic factors) in the brain, and enhance brain plasticity by strengthening the underlying system, including synaptogenesis and angiogenesis in brain regions related to executive function and memory.³⁰ The second pathway involves the influence of physical activity on CE.³¹ In this context, CE has been manipulated based on Tomporowski's⁴³ proposal (contextual interference, mental control, and discovery)⁴ and the CE activity features proposed by Vazou.³ Accordingly, previous studies have designed different CEPA interventions^{11,27,32,33}; however, findings remain inconsistent across studies. Overall, current

research findings support activities that involve top-down cognitive control, complex multi-limb sequencing, rapid decision-making, and non-automated motor behavior.³⁴ Interventions of approximately 20 min in duration³, performed at moderate intensity and incorporating social interaction, have been shown to produce beneficial effects on executive function.³⁵ However, these findings are largely derived from quasi-experimental studies conducted in naturalistic settings, which are constrained by participant characteristics and ecological validity.

In recent years, researchers have focused on the cognitive benefits of CEPA for other age groups and have also adopted acute interventions in laboratory settings, mostly in the form of a dual-task paradigm, which involves completing cognitive tasks while exercising.^{19,21} Existing studies have found that CEPA can lead to individual fatigue due to the need for excessive cognitive resources, both in children and adolescents^{32,33}, as well as in adults¹⁹, thereby offsetting the benefits of physical activity. To prevent this situation, in this study, CE tasks were selected to avoid traditional intervention methods in laboratory settings, and Sudoku was chosen, which increased the individual's perceived interest and may have accounted for the inconsistent results. This study found that combining exercise with cognitive tasks can improve performance on working memory and inhibitory control. Thus, in future

intervention designs, it is necessary to consider individual emotional factors, as emotions may affect executive function.^{34,36}

More research is needed on the cognitive benefits of physical activity among university students, as they often engage in sedentary behavior for extended periods.¹⁴ Compared to the elderly or children and adolescents, the executive function of university students is relatively stable, but they are also affected by unhealthy habits that affect their future work and life in middle or elderly age.¹⁷ Current research suggests that more university students who participate in physical activity exhibit better executive function.^{18,37} However, there is currently a lack of integration of CE into physical activity, and little exploration of the impact of PE and CE on executive function. The results of this study confirm that the 20-min PE + CE task does not impair subsequent executive function and yields greater cognitive benefits than either simple physical activity or cognitive engagement alone. This suggests that college students can engage in physical exercise while completing cognitive tasks that rely on logical reasoning and sustained attention (e.g., Sudoku)—a task similar to the one used in this study—without experiencing significant mental fatigue that would impair subsequent cognitive performance. This finding holds important implications for college students, who often face high academic pressure during specific semesters due to academic schedules. If students abandon physical activity to devote more time to academic learning, they may increase sedentary behavior, which is detrimental to the long-term maintenance of executive function. Although the cognitive task in this study was Sudoku (a logical reasoning task) and cannot be directly equated with review or memorization tasks that rely on verbal memory and associative processing, our results still provide a valuable reference for designing integrated physical and cognitive activity patterns for college students. It suggests that college students may be able to combine moderate-intensity aerobic exercise with low-to-moderate difficulty cognitive tasks with processing characteristics similar to Sudoku (e.g., logical problem-solving, focused attention tasks) during fragmented time (e.g., between classes, after self-study). This integrated pattern can help reduce sedentary behavior while maintaining CE and, indirectly, create more favorable physical and cognitive conditions for subsequent academic learning involving review and memorization.

In addition, HRV was also used in this study to quantify individual CE in different conditions. The measurement of CE has long been an unresolved issue in CEPA research. Unlike the consensus on measuring PE based on heart rate, there is currently no gold standard

for measuring or evaluating CE. There are currently two evaluation methods: subjective evaluation and objective measurement. Subjective evaluations include observations by others⁸ and self-evaluation.²⁷ Currently, only Benzing *et al.*⁹ have proposed using HRV after intervention for objective measurement. In this study, we used RCE and HRV as evaluation methods for CE and found differences compared with previous studies. The RCE and HRV data for the low PE + high CE and high PE + low CE groups were inconsistent, possibly due to the heart rate's impact on HRV. Even after intervention, there was a significant difference in heart rate between the high PE and low PE groups. Therefore, our research results confirm that the combination of high PE + high CE yielded the highest CE, but we cannot compare the differences between the low PE + high CE and the high PE + low CE interventions. Future studies should consider incorporating additional physiological indicators, such as eye-tracking measures and electroencephalography³⁸, to enable more comprehensive and objective quantification of CE.

This study is not without limitations. In terms of CE manipulation, although designating Sudoku solving as a high-CE task and watching Sudoku tutorial videos as a low-CE task is intuitively rational, the two conditions are not equivalent across multiple dimensions. Drawing on recent research paradigms for CE manipulation in laboratory-based interventions, most extant studies modulate CE by adjusting the quantity or presentation frequency of cognitive stimuli within the context of a single, uniform task.^{39,40} In this regard, future research could achieve more rigorous control over CE levels by varying the frequency or difficulty of cognitive stimuli while maintaining a consistent cognitive task framework. Additionally, the present study only examined the short-term effects following a single 20-min intervention. It remains unclear whether such effects can be transferred to real-world learning task scenarios or sustained over an extended time horizon.

5. Conclusion

In the dual-task context of combined physical activity and CE, the synergistic intervention of high PE and a high-difficulty cognitive challenge may yield short-term benefits for the accuracy of working memory and the processing efficiency of inhibitory control.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization: Weizhong Dong

Formal analysis: Kangni Wang, Weizhong Dong

Methodology: Kangni Wang

Writing–original draft: Kangni Wang, Weizhong Dong

Writing–review & editing: Weizhong Dong

Ethics approval and consent to participate

This study was approved by the Medical Ethics Committee of the Department of Psychology and Behavioral Sciences at Zhejiang University (ID: [2023]025), and all participants provided informed consent.

Consent for publication

Written informed consent was obtained from all participants for the publication of their data.

Availability of data

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- Hillman C, Snook E, Jerome G. Acute cardiovascular exercise and executive control function. *Int J Psychophysiol.* 2003;48(3):307-314.
doi: 10.1016/S0167-8760(03)00080-1
- Pontifex MBM, Amanda LC, Madison CG, et al. A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychol Sport Exerc.* 2019;40:1-22.
doi: 10.1016/j.psychsport.2018.08.015
- Vazou S, Pesce C, Lakes K, Smiley-Oyen A. More than one road leads to Rome: A narrative review and meta-analysis of physical activity intervention effects on cognition in youth. *Int J Sport Exerc Psychol.* 2019;17(2):153-178.
doi: 10.1080/1612197X.2016.1223423
- Tomporowski PD, McCullick B, Pendleton DM, Pesce C. Exercise and children's cognition: The role of exercise characteristics and a place for metacognition. *J Sport Health Sci.* 2015;4(1):47-55.
doi: 10.1016/j.jshs.2014.09.003
- Best J. Effects of Physical Activity on Children's Executive Function: Contributions of Experimental Research on Aerobic Exercise. *Dev Rev.* 2010;30(4):331-351.
doi: 10.1016/j.dr.2010.08.001
- Tomporowski P, Pesce C. Exercise, sports, and performance arts benefit cognition via a common process. *Psychol Bull.* 2019;145(9):929-951.
doi: 10.1037/bul0000200
- Egger F, Benzing V, Conzelmann A, Schmidt M. Boost your brain, while having a break! The effects of long-term cognitively engaging physical activity breaks on children's executive functions and academic achievement. *PLoS ONE.* 2019;14(3):e0212482.
doi: 10.1371/journal.pone.0212482
- Best JR. Exergaming Immediately Enhances Children's Executive Function. *Dev Psychol.* 2012;48(5):1501-1510.
doi: 10.1037/a0026648
- Benzing V, Heinks T, Eggenberger N, Schmidt M. Acute Cognitively Engaging Exergame-Based Physical Activity Enhances Executive Functions in Adolescents. *PLoS ONE.* 2016;11(12):e0167501.
doi: 10.1371/journal.pone.0167501
- Vazou S, Smiley-Oyen A. Moving and academic learning are not antagonists: acute effects on executive function and enjoyment. *J Sport Exerc Psychol.* 2014;36(5):474-485.
doi: 10.1123/jsep.2014-0035
- Egger F, Conzelmann A, Schmidt M. The effect of acute cognitively engaging physical activity breaks on children's executive functions: Too much of a good thing? *Psychol Sport Exerc.* 2018;36:178-186.
doi: 10.1016/j.psychsport.2018.02.014
- Ludyga S, Gerber M, Brand S, Holsboer-Trachsler E, Puhse U. Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology.* 2016;53(11):1611-1626.
doi: 10.1111/psyp.12736
- Gilmour AM, MacDonald MJ, Cox A, Fairclough SJ, Tyler R. Investigating Ecological Momentary Assessed Physical Activity and Core Executive Functions in 18- to 24-Year-Old Undergraduate Students. *Int J Environ Res Public Health.* 2023;20(20):6944.
doi: 10.3390/ijerph20206944
- Wu Y, Van Gerven P, de Groot R, Eijnde B, Winkens B, Savelberg H. Effects of breaking up sitting with light-intensity physical activity on cognition and mood in university students. *Scand J Med Sci Sports.* 2023;33(3):257-266.
doi: 10.1111/sms.14277
- Memon A, Gupta C, Crowther M, Ferguson S, Tuckwell G, Vincent G. Sleep and physical activity in university students: A systematic review and meta-analysis. *Sleep Med Rev.* 2021;58:101482.

- doi: 10.1016/j.smr.2021.101482
16. You Y, Mo L, Tong J, Chen X, You Y. The role of education attainment on 24-hour movement behavior in emerging adults: evidence from a population-based study. *Front Public Health*. 2024;12.
doi: 10.3389/fpubh.2024.1197150
17. Lynch J, O'Donoghue G, Peiris C. Classroom Movement Breaks and Physically Active Learning Are Feasible, Reduce Sedentary Behaviour and Fatigue, and May Increase Focus in University Students: A Systematic Review and Meta-Analysis. *Int J Environ Res Public Health*. 2022;19(13):7775.
doi: 10.3390/ijerph19137775
18. Salas-Gómez D, Fernández-Gorgojo M, Pozueta A, et al. Physical Activity Is Associated With Better Executive Function in University Students. *Front Hum Neurosci*. 2020;14.
doi: 10.3389/fnhum.2020.00011
19. Kamijo K, Abe R. Aftereffects of Cognitively Demanding Acute Aerobic Exercise on Working Memory. *Med Sci Sports Exerc*. 2019;51(1):153-159.
doi: 10.1249/MSS.0000000000001763
20. Lauenroth A, Ioannidis A, Teichmann B. Influence of combined physical and cognitive training on cognition: a systematic review. *BMC Geriatr*. 2016;16(1).
doi: 10.1186/s12877-016-0315-1
21. Ji Z, Feng T, Mei L, Li A, Zhang C. Influence of acute combined physical and cognitive exercise on cognitive function: an NIRS study. *PeerJ*. 2019;7:e7418.
doi: 10.7717/peerj.7418
22. Devine S, Otto A. Information about task progress modulates cognitive demand avoidance. *Cognition*. 2022;225:105107.
doi: 10.1016/j.cognition.2022.105107
23. Ashlesh P, Deepak K, Preet K. Role of prefrontal cortex during Sudoku task: fNIRS study. *Transl Neurosci*. 2020;11(1):419-427.
doi: 10.1515/tnsci-2020-0147
24. Faul F, Erdfelder E, Buchner A, Lang A. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. *Behav Res Methods*. 2009;41(4):1149-1160.
doi: 10.3758/BRM.41.4.1149
25. Dong W, Hu L, Hu Q. The recovery effect of acute aerobic exercise and music intervention on working memory under mental fatigue. *Exp Brain Res*. 2025;243(9).
doi: 10.1007/s00221-025-07140-6
26. Borg G. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377-381.
doi: 10.1249/00005768-198205000-00012
27. Schmidt M, Benzing V, Kamer M. Classroom-Based Physical Activity Breaks and Children's Attention: Cognitive Engagement Works! *Front Psychol*. 2016;7.
doi: 10.3389/fpsyg.2016.01474
28. Mukherjee S, Yadav R, Yung I, Zajdel D, Oken B. Sensitivity to mental effort and test-retest reliability of heart rate variability measures in healthy seniors. *Clin Neurophysiol*. 2011;122(10):2059-2066.
doi: 10.1016/j.clinph.2011.02.032
29. Tarvainen M, Niskanen J, Lipponen J, Ranta-Aho P, Karjalainen P. Kubios HRV--heart rate variability analysis software. *Comput Methods Programs Biomed*. 2014;113(1):210-220.
doi: 10.1016/j.cmpb.2013.07.024
30. Gómez-Pinilla F, Hillman C. The influence of exercise on cognitive abilities. *Compr Physiol*. 2013;3(1):403-428.
doi: 10.1002/j.2040-4603.2013.tb00485.x
31. Pesce C. Shifting the Focus From Quantitative to Qualitative Exercise Characteristics in Exercise and Cognition Research. *J Sport Exerc Psychol*. 2012;34(6):766-786.
doi: 10.1123/jsep.34.6.766
32. Gallotta MC, Emerenziani GP, Franciosi E, Meucci M, Guidetti L, Baldari C. Acute physical activity and delayed attention in primary school students. *Scand J Med Sci Sports*. 2015;25(3):e331-338.
doi: 10.1111/sms.12310
33. Gallotta MC, Guidetti L, Franciosi E, Emerenziani GP, Bonavolonta V, Baldari C. Effects of varying type of exertion on children's attention capacity. *Med Sci Sports Exerc*. 2012;44(3):550-555.
doi: 10.1249/MSS.0b013e3182305552
34. Bedard C, Bremer E, Graham JD, Chirico D, Cairney J. Examining the Effects of Acute Cognitively Engaging Physical Activity on Cognition in Children. *Front Psychol*. 2021;12.
doi: 10.3389/fpsyg.2021.653133
35. Pesce C, Crova C, Cereatti L, Casella R, Bellucci M. Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. *Ment Health Phys Act*. 2009;2(1):16-22.
doi: 10.1016/j.mhpa.2009.02.001
36. Brosch T, Scherer K, Grandjean D, Sander D. The impact of emotion on perception, attention, memory, and decision-making. *Swiss Med Wkly*. 2013;143(1920):w13786.
doi: 10.4414/sm.2013.13786
37. Passarello N, Varini L, Liparoti M, et al. Boosting effect of regular sport practice in young adults: Preliminary results

- on cognitive and emotional abilities. *Front Psychol.* 2022;13. doi: 10.3389/fpsyg.2022.957281
38. Li S. Measuring Cognitive Engagement: An Overview of Measurement Instruments and Techniques. *Int J Psychol Educ Stud.* 2022;8(3):63-76. doi: 10.52380/ijpes.2021.8.3.239
39. Anzeneder S, Zehnder C, Martin-Niedecken AL, Schmidt M, Benzing V. Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge? *Psychol Sport Exerc.* 2023;66:102404. doi: 10.1016/j.psychsport.2023.102404
40. Anzeneder S, Zehnder C, Schmid J, Martin-Niedecken AL, Schmidt M, Benzing V. Dose-response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition. *Scand J Med Sci Sports.* 2023;33(8):1439-1451. doi: 10.1111/sms.14370