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Research Paper

# Acute aerobic exercise improves inhibitory control in individuals with test anxiety: evidence from event-related potentials

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ABSTRACT

It remains unclear whether acute aerobic exercise can effectively mitigate the inhibitory control deficits caused by test anxiety. This study investigated the effects of 30 min of moderate-intensity acute aerobic exercise on inhibitory control and related neural activities in individuals with high test anxiety. Forty participants were randomly assigned to an aerobic exercise group or a seated-reading control group, completing pre- and post-intervention assessments spaced one week apart. Statistical analyses using a series of repeated-measures ANOVAs revealed that, compared to the control group, the exercise group showed a significant reduction in self-reported test anxiety. Behaviorally, exercise led to significantly faster reaction times across both congruent and incongruent trials, coupled with a specific reduction in the Flanker conflict effect (RT difference between conditions), indicating enhanced interference control. Electrophysiologically, analysis of event-related potentials demonstrated that acute exercise modulated key cognitive components: N2 amplitude was significantly reduced and P3 amplitude was significantly enhanced in both task conditions following exercise, with no comparable changes in the control group. These findings suggest that acute aerobic exercise can enhance inhibitory control and alleviate test anxiety in university students.

## 1. Introduction

Test anxiety is a situationally specific anxiety disorder characterized by excessive worry, intrusive thoughts, psychological confusion, tension, and physiological arousal in evaluative situations [1]. Test anxiety is typically evoked in educational settings when a student believes that his or her intellectual, motivational, and social capabilities and capacities are taxed or exceeded by demands stemming from the test situation [2].Numerous studies have found that test anxiety is prevalent across various educational stages [3–5] and can affect students at different stages of the learning and testing cycle. Test anxiety has been shown to negatively impact students in multiple areas, including physiological responses, cognitive functions, academic performance, and psychological well-being [2,6,7]. Research indicates that individuals with high test anxiety often exhibit excessive worry and cognitive and emotional deficits [1,8–10], manifesting as a range of emotional, physical, and behavioral symptoms, from increased heart rate and muscle tension to concentration difficulties, sleep disturbances, and negative self-talk [11]. Despite having studied the relevant material, students with test anxiety may perform poorly in exams or avoid taking exams altogether. Even more concerning is the potential for a vicious cycle in which test anxiety perpetuates and exacerbates itself, leading to ongoing and reinforced symptoms that have a sustained negative impact on academic performance [12–14].

Inhibitory control, a key aspect of executive function, allows individuals to suppress or ignore irrelevant information through attentional regulation while maintaining focus on task-relevant information [15]. This cognitive ability is crucial for effective learning and emotional regulation, thereby contributing to overall cognitive performance [16]. Impairments in inhibitory control can lead to significant cognitive dysfunction, such as distraction, impulsivity, and poor decision-making, which adversely affect both academic performance and emotional well-being. According to attentional control theory, test anxiety impairs inhibitory control—a core component of the central executive system—thereby compromising task performance. Previous research has demonstrated that higher levels of anxiety are often associated with deficits in inhibitory control [17], and that elevated anxiety can impair individuals' inhibitory control processes [18–21]. For instance, Zhang

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et al. [22] found that in a modified Flanker task, individuals with high test anxiety (HTA) exhibited significantly reduced inhibitory control efficiency when presented with test-related threat words as emotional distractors. Similarly, Zhang et al. [23], using event-related potential (ERP) techniques, showed that HTA individuals displayed inhibitory control deficits when confronted with test-related threat words in an emotional Stroop task. Recent research by Wei et al. [24] also identified pronounced inhibitory control deficits in both behavioral performance and EEG components during a Go/Nogo version of the Flanker task among HTA individuals. These findings suggest that individuals with test anxiety commonly exhibit deficits in inhibitory control, impairing their ability to suppress worry thoughts and distractions from test-irrelevant information, which may exacerbate test anxiety. Thus, improving the inhibitory control function in individuals with test anxiety may help alleviate their test anxiety.

Exercise intervention has emerged as a potential strategy in recent years, gaining considerable attention in the fields of education and mental health. Acute exercise, particularly moderate-to-high-intensity aerobic exercise, serves as an immediate intervention that can rapidly elevate levels of neurotransmitters such as dopamine, epinephrine and norepinephrine in the brain, thereby reducing negative emotional responses and improving mood [25–27]. Several reviews have highlighted the cognitive benefits of acute exercise interventions, especially aerobic exercise, with significant effects on enhancing executive functions, particularly inhibitory control [28–32]. In the context of test anxiety interventions, relaxation therapy is one of the commonly used strategies [1]. Studies have shown that a 15 min bout of moderate-intensity cycling, with intensity controlled through visual monitoring or prescribed pedaling cadence, can reduce test anxiety to a degree comparable to relaxation training, and may even provide superior stress-prevention benefits [33,34]. However, some studies have reported no significant reduction in self-reported test anxiety following a 10 min bout of physical activity [35] or a physical education class that included at least 20 min of activity [36]. Although both studies described their activities as moderate-to-vigorous, neither objectively monitored exercise intensity. The variability in these findings can be explained by several factors that modulate the efficacy of exercise interventions, such as exercise type, duration, intensity, timing of post-exercise assessment, and baseline anxiety levels, all of which can influence the outcomes. In particular, the intensity of exercise is critical; the activities and intensity of a typical physical education class may not be adequately monitored or adjusted to achieve effective intervention outcomes. Furthermore, there is a notable lack of research examining the effects of acute exercise on the inhibitory control function of individuals with test anxiety, which limits our understanding of the cognitive mechanisms underlying the intervention effects.

The Eriksen Flanker task has been widely used to measure inhibitory control [37]. This task requires participants to identify a target stimulus defined by its directional orientation (i.e., the direction of an arrow) while ignoring distracting stimuli surrounding the target. Generally, longer reaction times (RTs) and lower response accuracy on the Flanker task indicate deficits in inhibitory control.

ERP (Event-Related Potential) technology offers the distinct advantage of high temporal resolution, enabling precise observation of brain response differences across various time windows while participants were performing the task [38]. In this study, we leveraged the classic N2 and P3 components to examine the inhibitory control processes in individuals with high test anxiety (HTA) before and after the intervention. The N2 is a fronto-central, stimulus-locked component that typically occurs 200–350 ms after stimulus onset [39]. It likely reflects attentional control processes that help focus attention on task-relevant aspects [40]. Typically, larger N2 amplitudes are observed in incongruent trials compared to congruent ones. Some studies have found that individuals with high anxiety exhibit greater N2 amplitudes during inhibitory control tasks compared to those with low anxiety [18]. The P3 wave is a late ERP component, appearing 300 to 600 milliseconds post-stimulus in the parietal region. The P3 amplitude in the Flanker task is modulated by task difficulty, with smaller amplitudes observed in incongruent trials compared to congruent ones [41].

Given this research background, the present study aims to investigate the effects of a 30 min acute aerobic exercise on test anxiety levels and inhibitory control abilities in university students with high test anxiety. During the intervention, the exercise intensity was continuously monitored in real-time using heart rate to ensure it remained within a moderate intensity range. Inhibitory control processes were measured through both behavioral and ERP methods. We hypothesize that relative to a non-exercise control group, individuals with high test anxiety would show reduced test anxiety and enhanced inhibitory control following an acute bout of moderate-intensity aerobic exercise. Specifically,we expected that acute aerobic exercise would lead to improved task performance (i.e., faster reaction times and/or higher accuracy), and enhanced neurocognitive processing as reflected by altered amplitudes of ERP components associated with conflict monitoring (N2) and attention allocation (P3).

## 2. Methods

### *2.1. Participants*

Participants were recruited from Nanjing University through online advertisements and physical posters, comprising full-time undergraduate and graduate students. The allocation to experimental groups was concealed during the recruitment process. Individuals scoring above 20 on the Test Anxiety Scale (TAS) were identified as having high test anxiety [42]. Participants were further screened based on the following inclusion criteria: (1) self-reported right-handedness; (2) normal or corrected-to-normal vision; (3) a body mass index (BMI) within the normal range for Asian adults (18.5–22.9 kg/m$^2$); and (4) no history of psychiatric, neurological, cardiovascular diseases, or physical disabilities that would preclude participation in physical activity (i.e., all answers on the Physical Activity Readiness Questionnaire [PAR-Q] were "no"). Ultimately, 40 participants with high anxiety (mean TAS= 27.38) were selected and randomly assigned to either the aerobic exercise group or the control group. The aerobic exercise group consisted of 20 participants (11 females, 9 males), with a mean age of 21.40 $\pm$ 1.67 years, a mean TAS score of 28.05 $\pm$ 0.63 and a mean BMI of 20.62 $\pm$ 1.05 kg/m$^2$. The control group also comprised 20 participants (12 females, 8 males), with a mean age of 20.95 $\pm$ 1.61 years, a mean TAS score of 26.70 $\pm$ 0.63 and a mean BMI of 20.55 $\pm$ 1.08 kg/m$^2$.

The necessary sample size was estimated using G*Power 3.1 software [43] for a mixed-design ANOVA with one between-subjects factor (Group: Exercise vs. Control) and one within-subjects factor (Time: Pre-test vs. Post-test), with a significance level set at $\alpha$= 0.05 and a desired statistical power of (1$-\beta$)= 0.8. A medium effect size (f = 0.25) was used for the calculation, based on Cohen's conventions [44] and prior research on the impact of aerobic exercise on psychological and cognitive measures [45,46]. For the repeated-measures factor, a default correlation of 0.5 and nonsphericity correction ($\varepsilon$)= 1 were applied. The minimum required sample size was determined to be 34 participants (at least 17 per group). Both the aerobic exercise and control groups in this study consisted of 20 participants each, meeting the necessary sample size requirements for the experimental design. The study was approved by the Ethics Committee of the Psychology Department at Nanjing University. All participants provided informed consent prior to the experiment and were compensated for their participation.

### *2.2. Subjective assessment scales*

#### *2.2.1. TAS: Test Anxiety Scale (TAS)*

The Test Anxiety Scale (TAS) is an effective tool for distinguishing between individuals with varying levels of test anxiety [47]. The scale assesses individuals' attitudes toward exams, as well as their psychological and physical discomfort before and after exams. In this study, we utilized the Chinese version of the TAS [48], which has demonstrated good internal consistency reliability (Cronbach's alpha= 0.80).

### 2.3. Flanker paradigm

Participants completed a modified version of the Eriksen Flanker task, which included both congruent and incongruent trial types [49]. The task was administered in an electrically shielded, sound-attenuated laboratory room. Stimuli were presented on a 21-inch monitor positioned approximately 70 cm from the participant, using E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA). Participants were instructed to respond only to the direction of the central arrow, while ignoring the arrows on either side. A fixation cross "+" appeared in the center of the screen for 0.3 s, followed by a random blank screen lasting 1 to 1.5 s. Subsequently, the target and flanker stimuli were presented for 0.3 s. Each stimulus consisted of five arrows in a row, with the central arrow serving as the target stimulus and the flanking arrows as distractor stimuli. The Flanker task comprised two conditions: a congruent condition, in which the target and flanker arrows pointed in the same direction, and an incongruent condition, in which the target and flanker arrows pointed in opposite directions. The experiment included a total of 288 trials, divided into 2 blocks of 144 trials each, with a 2:1 ratio of congruent to incongruent trials. The entire task lasted approximately 25 min. The flowchart of each trial is illustrated in Fig. 1.

### 2.4. Aerobic exercise

The benefits of exercise typically exhibit an inverted-U response to exercise intensity [50]; for moderate-intensity exercise, a duration of 20–40 min is necessary for these improvements to manifest [51,52]. Therefore, a 30 min session of moderate-intensity acute aerobic exercise was administered during the second experimental session. According to the American College of Sports Medicine guidelines [53], moderate intensity is defined as 65–75% of the predicted maximum heart rate (HRmax), with a rating of perceived exertion (RPE) set at levels 12-14 ("somewhat hard" to "moderate") [54]. HRmax was calculated using the formula: HRmax= 220 - age (in years).

All exercise interventions were conducted on a treadmill. To ensure controlled exercise intensity, participants wore a heart rate monitor (Polar RS800CX; Polar Electro Oy, Kempele, Finland). After a 5 min warm-up, participants' heart rates were brought to the lower threshold of the target heart rate zone (65% HRmax) within 5 min; they then exercised within the target heart rate range (65–75%) for 25 min. During this period, perceived exertion was assessed every 2 min using the RPE scale. When participants' heart rates or RPE levels fell outside the moderate intensity range, the treadmill speed was adjusted accordingly. To minimize potential confounding effects of social interaction between participants and researchers during exercise, the RPE assessment procedure was explained to all participants before the exercise intervention. During the exercise intervention, participants verbally indicated their perceived exertion levels upon receiving a copy of the RPE scale.

Participants in the control group completed a 30 min seated control session in a quiet laboratory room. To prevent boredom and maintain compliance without inducing emotional stimulation, they were instructed to read neutral, sports-related magazines provided by the experimenter. All participants received the same set of printed magazines, and no electronic devices were used. Heart rate and RPE were not recorded in the control condition because no physical activity was involved.

### 2.5. Experimental procedure

The experiment consisted of two laboratory sessions conducted on separate days. Prior to the experiment, participants were instructed to refrain from engaging in intense physical exercise or consuming alcohol 24 hours before each session and to avoid caffeinated beverages within four hours. They were also advised to wear comfortable clothing and footwear.

#### 2.5.1. During the first session, participants provided demographic information and completed the Test Anxiety Scale (TAS)

They then performed the Flanker task, during which both behavioral and EEG data were recorded. This session served as the baseline assessment for anxiety and cognitive performance.

#### 2.5.2. The second session took place one week after the first to minimize potential practice effects

To control for circadian rhythm variations, all sessions were conducted at the same time of day for each participant. They were also advised to wear comfortable clothing and footwear. In this session, participants were randomly assigned to one of two groups: the intervention group completed 30 min of moderate-intensity aerobic exercise, while the control group engaged in 30 min of seated reading. Following a 10 min rest period for heart rate stabilization, participants completed the TAS questionnaire and performed the Flanker task again, with behavioral and EEG data collected. This session aimed to evaluate the

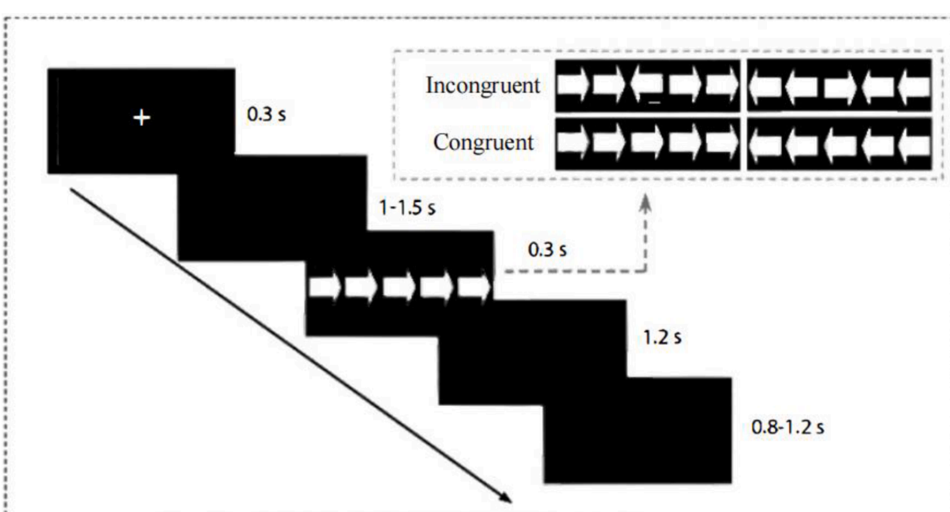


**Fig. 1.** Schematic diagram of the flanker paradigm.

effects of the intervention on test anxiety and cognitive performance.

#### 2.5.3. Evaluation stress manipulation

Following the classical evaluation stress paradigm [55], the instructions for each flanker task were designed to create an evaluative stress-testing context. The instructions stated:"Today, you are required to complete a standardized aptitude test. The results of this test are highly reliable and valid and can effectively predict your academic performance during university. Your test score will be calculated based on your response speed and accuracy. Furthermore, your scores will be ranked against other participants, and the top 15% will receive a reward of 100 CNY. Additionally, your performance will be recorded on video during the test, and the recordings will be used for expert analysis in research."

### 2.6. EEG data recording

EEG data were recorded using the ESI-64 EEG recording and analysis system (Scan 4.5, Neurosoft Labs, Inc.) manufactured by Neuroscan, USA. Scalp EEG was collected through 64 Ag/AgCl electrodes embedded in an electrode cap, following the international 10–20 system. Horizontal eye movements (HEOG) were recorded by placing electrodes 1 cm lateral to each eye, and vertical eye movements (VEOG) were recorded by placing electrodes 1 cm above and below the left eye. The left mastoid (M1) was used as a reference, and the AFz electrode served as the ground. The band-pass filter was set to 0.05–100 Hz, and the sampling rate was 1000 Hz. Scalp impedance was kept below 10 kΩ.

### 2.7. EEG data analysis

EEG data were processed using the open-source MATLAB-based tool EEGLAB [56]. The reference was changed from the unilateral mastoid to a bilateral mastoid reference. The original continuous EEG data were downsampled to 500 Hz, filtered with a 0.1 Hz high-pass and a 30 Hz low-pass filter, and a notch filter was used to remove the 50 Hz power line interference. EEG epochs were extracted using a 1200 ms window (200 ms pre-stimulus and 1000 ms post-stimulus), and baseline correction was performed using the pre-stimulus interval. Independent Component Analysis (ICA) [57] was applied to remove artifacts such as eye movements, blinks, and body movements from the preprocessed data. Epochs with amplitudes exceeding ±100 μV were excluded. After artifact rejection, trial loss remained low across sessions. The intervention group rejected 10.15 ± 8.80 trials at pre-test and 15.65 ± 15.32 at post-test, and the control group rejected 10.05 ± 7.33 and 10.60 ± 8.67 trials, respectively.

Previous ERP studies have shown that the N2 component is mainly fronto-central [39,58,59], while the P3 component is parietal [60–62]. Based on visual inspection of the ERP waveforms and topographical maps in this study, the N2 amplitude was quantified as the mean negative amplitude between 230 and 280 ms post-stimulus, and signals from Fz and FCz were extracted and averaged to obtain the N2 amplitude index. The P3 amplitude was quantified as the mean amplitude between 400 and 450 ms post-stimulus, and activity from CPz and Pz was extracted and averaged to derive the P3 amplitude index.

### 2.8. Statistical analysis

To examine the effect of acute exercise on test anxiety, a 2 (Group: Exercise, Control) × 2 (Time: Pre-test, Post-test) repeated-measures ANOVA was performed on TAS scores.

For behavioral performance, reaction time (RT) and accuracy were analyzed using a 2 (Group: Exercise, Control) × 2 (Time: Pre-test, Post-test) × 2 (Task Type: Congruent, Incongruent) repeated-measures ANOVA. To further quantify interference control, the Flanker conflict effect (incongruent RT − congruent RT) was computed for each participant and analyzed using a 2 (Group) × 2 (Time) repeated-measures ANOVA.

For ERP analyses, N2 and P3 amplitudes (averaged across their respective electrode clusters) were each analyzed using a 2 (Group: Exercise, Control) × 2 (Time: Pre-test, Post-test) × 2 (Task Type: Congruent, Incongruent) repeated-measures ANOVA.

When a significant interaction was detected, it was further examined using simple effects analyses. Significant simple effects were subsequently followed by post hoc pairwise comparisons. Bonferroni correction was applied to control the family-wise error rate for all pairwise comparisons stemming from a significant interaction. In the "Results" section, data are typically presented as mean ± standard error. Partial eta squared ($\eta^2$) effect sizes are reported for significant effects.

## 3. Results

### 3.1. Subjective emotion assessment

A 2 (Group: Exercise/Control) × 2 (Time: Pre-test/Post-test) repeated measures ANOVA was conducted with participants' TAS scores as the dependent variable. The results are presented in Table 1. The interaction between time and group was statistically significant, $F(1,38) = 10.24$, $p = .003$, $\eta^2 = .212$. Further simple effects analysis revealed that the TAS scores in the exercise group were significantly lower in the post-test compared to the pre-test ($p = .002$), with no significant differences observed in other comparisons. The main effect of group was not significant, $F(1,38) = .013$, $p = .911$, $\eta^2 < .001$, and the main effect of time was also not significant, $F(1,38) = 2.47$, $p = .124$, $\eta^2 = .061$.

### 3.2. Behavioral results

Table 2 presents the behavioral results for each group before and after the intervention, including reaction times and accuracy rates.

#### 3.2.1. Reaction time

A three-way repeated measures ANOVA was conducted with group (Exercise, Control) as the between-subjects variable, time (Pre-test, Post-test) and task type (Congruent, Incongruent) as within-subjects variables, and reaction time as the dependent variable. The results showed that the overall three-way interaction was significant, $F(1, 38) = 4.66$, $p = .037$, $\eta^2 = .109$. Therefore, simple two-way analyses were conducted separately for each task type.

Under the congruent condition, the Group × Time interaction was significant, $F(1, 38) = 10.15$, $p = .003$, $\eta^2 = .211$. Bonferroni-corrected pairwise comparisons showed that the exercise group responded significantly faster at post-test than at pre-test ($p < .001$), whereas no change was observed in the control group ($p = .81$).

Under the incongruent condition, the Group × Time interaction was also significant, $F(1, 38) = 11.39$, $p = .002$, $\eta^2 = .231$. Again, RTs decreased significantly from pre- to post-test in the exercise group ($p < .001$), while the control group showed no significant difference ($p = .91$).

(All other decompositions of the three-way interaction are available in the Supplementary Materials.)

#### 3.2.2. Accuracy rate

A three-way repeated measures ANOVA was conducted with group (Exercise, Control) as the between-subjects variable, task type

**Table 1**
TAS scores before and after intervention in the aerobic exercise group and control group (Mean ± SD).

| TAS | AE group (n = 20) | | | C group (n = 20) | | |
|---|---|---|---|---|---|---|
| Pre | 28.05 | ± | 0.63 | 26.70 | ± | 0.63 |
| Post | 25.85 | ± | 1.02 | 27.45 | ± | 1.02 |

Note: AE group,aerobic exercise group;C group,control group;

**Table 2**
Behavioral results on the flanker task for all groups pre- and post-intervention (Mean ± SD).

| Results | Condition | AE group (n = 20) | | | | | | C group (n = 20) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pre | | | Post | | | Pre | | | Post | | |
| RT | Congruent | 395.28 | ± | 34.44 | 361.20 | ± | 38.44 | 394.15 | ± | 75.62 | 392.50 | ± | 73.85 |
| | Incongruent | 455.00 | ± | 29.90 | 405.83 | ± | 45.72 | 456.46 | ± | 86.32 | 457.26 | ± | 100.64 |
| Flnaker conflict effect | | 59.72 | ± | 20.50 | 43.14 | ± | 19.65 | 64.31 | ± | 21.31 | 64.76 | ± | 32.71 |
| ACC | Congruent | 98.54% | ± | 4.15% | 98.07% | ± | 6.45% | 98.96% | ± | 2.46% | 99.38% | ± | 1.80% |
| | Incongruent | 93.18% | ± | 11.46% | 93.30% | ± | 11.16% | 90.23% | ± | 11.92% | 90.82% | ± | 10.97% |

Note: AE group,aerobic exercise group;C group,control group;RT,reaction time(ms);ACC,accuracy;Flanker conflicct effect (incongruent RT-congruent RT) indexes the cost of resolving response interference.

(Congruent, Incongruent) and time (Pre-test, Post-test) as within-subjects variables, and accuracy rate as the dependent variable. The results indicated that the main effect of group was not significant, F(1, 38)= .056, $p$= .814, $\eta^2$= .001. However, the main effect of task type was significant, F(1, 38)= 25.56, $p < .001$, $\eta^2$= .390, with accuracy rates for incongruent conditions (91.89% ± 1.69%) significantly lower than those for congruent conditions (98.74% ± 0.61%). The interactions and other main effects were not significant ($p > .05$).

### 3.2.3. Flanker conflict effect

A two-way repeated measures ANOVA was conducted with group (Exercise, Control) as the between-subjects variable, time (Pre-test, Post-test) as within-subjects variables, and Flanker conflict effect (incongruent RT – congruent RT) as the dependent variable. The results showed that the interaction between group and test phase was significant, F(1,38)= 4.66, $p$= .037, $\eta^2$= .109. Bonferroni post hoc tests indicated that the conflict effect for the exercise group was significantly reduced in the post-test compared to the pre-test, $p$= .005, whereas no significant change was observed in the control group, $p$= .936.

## 3.3. ERP results

### 3.3.1. N2 amplitude

Fig. 2 illustrates the topographic maps of the N2 wave during the

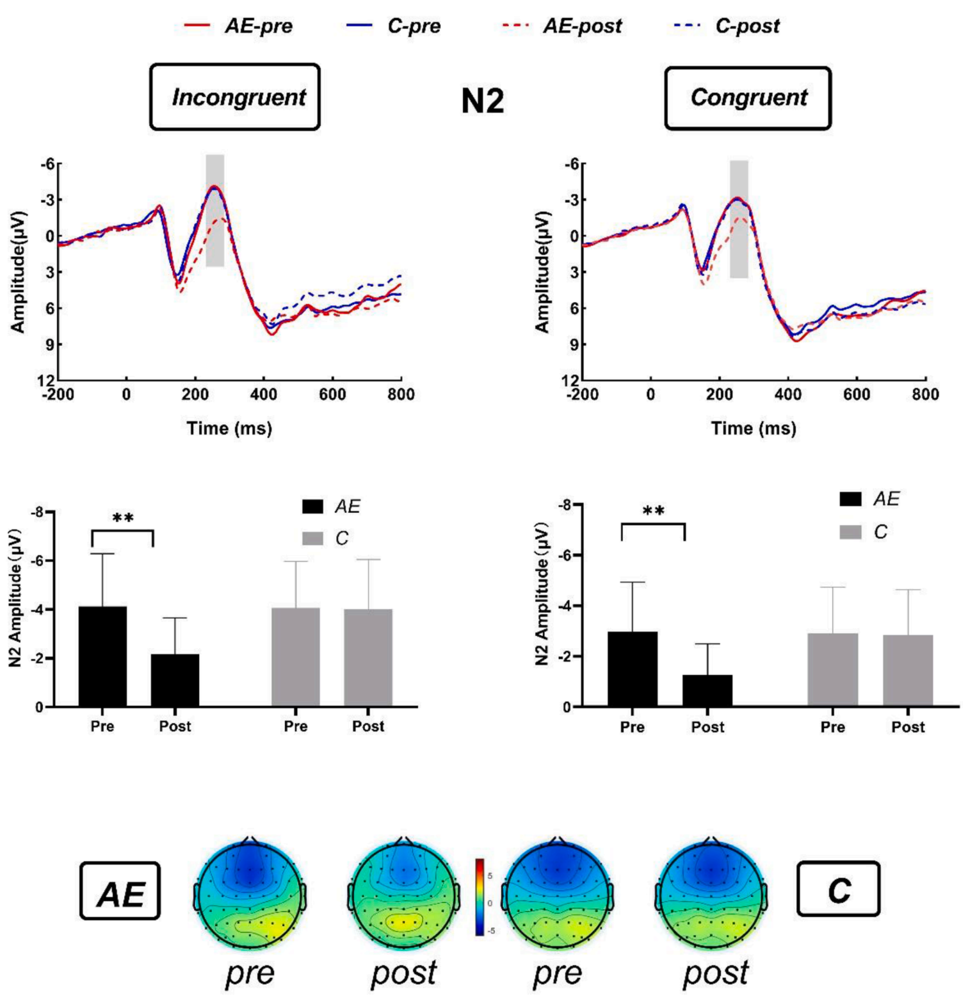


**Fig. 2. N2 wave results for the flanker task.** ERP waveforms at Fz and FCz sites for the aerobic exercise (AE) and control (C) groups during the congruent and incongruent conditions of the Flanker task, at pretest and posttest. N2 topographic maps for the aerobic exercise and control groups at pretest and posttest. N2 amplitude results (230–280 ms) at anterior and posterior sites in the intervention and control groups. ****$p < 0.01$.**

Flanker task, alongside the ERP waveforms for both groups at pre-test and post-test.

N2 amplitude (computed as the mean amplitude across Fz and FCz) was analyzed using a three-way mixed ANOVA with group (Intervention, Control) as the between-subjects factor, and time (Pre-test, Post-test) and task type (Congruent, Incongruent) as within-subjects factors. The three-way interaction was not significant, F(1, 38)= 3.56, p= .067, $\eta^2$= .086. However, there was a significant Group × Testing Phase interaction, F(1, 38)= 22.82, $p$ < .001, $\eta^2$= .375. The main effect of task type was also significant, F(1, 38)= 235.60, $p$ < .001, $\eta^2$= .861, with incongruent trials eliciting larger (more negative) N2 amplitudes than congruent trials.

Given the significant Group × Time interaction, and to clarify whether the pattern differed by task condition, separate 2 (Group) × 2 (Testing Phase) ANOVAs were conducted for the incongruent and congruent conditions. A Bonferroni-adjusted alpha level of .025 (.05/2) was applied.

For the incongruent condition, the Group × Time interaction remained significant, F(1, 38)= 38.00, $p$ < .001, $\eta^2$= .384. Pairwise comparisons revealed that the intervention group showed a significant reduction in N2 amplitude from pre-test (M= –4.13 μV, SD= 2.15) to post-test (M= –2.17 μV, SD= 1.48), t(19)= 9.08, $p$ < .001, Cohen's d= 2.03. No significant change was observed in the control group (pre: M= –4.06 μV, SD= 1.92; post: M= –4.00 μV, SD= 2.03, p= .926).

For the congruent condition, the Group × Time interaction also remained significant, F(1, 38)= 17.33, $p$ < .001, $\eta^2$= .313. The intervention group again showed a significant reduction in N2 amplitude from pre-test (M= –2.97 μV, SD= 2.07) to post-test (M= –1.26 μV, SD= 1.23), t(19)= 7.48, $p$ < .001, Cohen's d= 1.67. No significant change was found in the control group (pre: M= –2.91 μV, SD= 1.81; post: M= –2.84 μV, SD= 1.80, p= .924)

### 3.3.2. P3 amplitude

Fig. 3 displays the topographic maps of the P3 wave from the Flanker task, as well as the ERP waveforms for each group before and after the intervention.

P3 amplitude (computed as the mean amplitude across CPz and Pz) was analyzed using a three-way mixed ANOVA with group (Intervention, Control) as the between-subjects factor, and time (Pre-test, Post-test) and task type (Congruent, Incongruent) as within-subjects factors. The three-way interaction was not significant, F(1, 38)= .74, p= .394, $\eta^2$= .019. However, there was a significant Group × Time interaction, F(1, 38)= 10.51, p= .002, $\eta^2$= .217. The main effect of task type was also significant, F(1, 38)= 102.85, $p$ < .001, $\eta^2$= .730, with congruent trials eliciting larger (more positive) P3 amplitudes than incongruent trials.

Given the significant Group × Time interaction, and to clarify whether the pattern differed by task condition, separate 2 (Group) × 2 (Testing Phase) ANOVAs were conducted for the incongruent and congruent conditions. A Bonferroni-adjusted alpha level of .025 (.05/2)

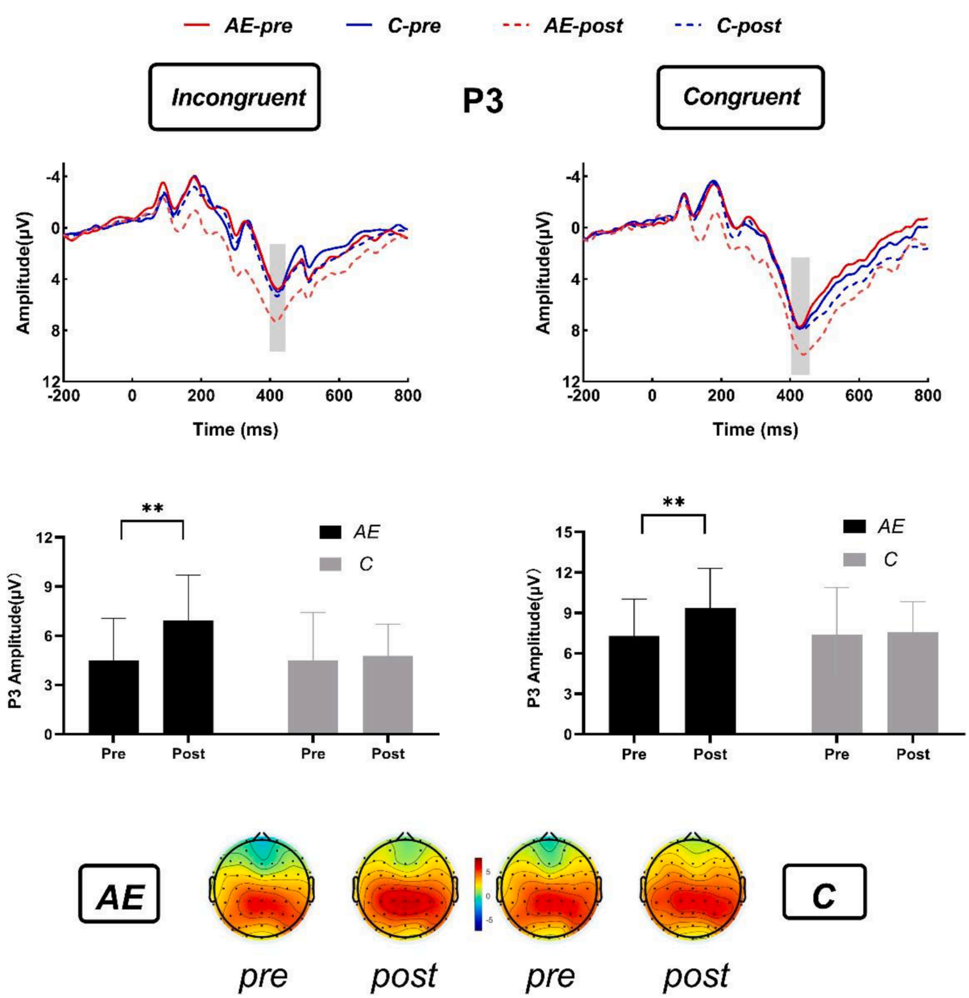


**Fig. 3. P3 wave results from the flanker task.** (a) ERP waveforms at CPz, and Pz sites for the intervention and control groups during the congruent and incongruent conditions of the Flanker task, at pre-test and post-test.(b) P3 topographic maps for the congruent and incongruent conditions.(c) P3 amplitude results (400–500 ms) at anterior and posterior sites in the intervention and control groups. **$p$ < 0.01.**

was applied.

For the incongruent condition, the Group × Time interaction remained significant, $F(1, 38)= 12.39$, $p= .001$, $\eta^2= .246$. Pairwise comparisons revealed that the intervention group showed a significant augmentation in P3 amplitude from pre-test (M= 4.50 μV, SD= 2.57) to post-test (M= 6.95 μV, SD= 2.75), $t(19)= 7.18$, $p < .001$, Cohen's d= 1.60. No significant change was observed in the control group (pre: M= 4.51 μV, SD= 2.92; post: M= 4.77 μV, SD= 1.92, p= .546).

For the congruent condition, the Group × Time interaction also remained significant, $F(1, 38)= 6.72$, $p= .013$, $\eta^2= .150$. The intervention group again showed a significant increase in P3 amplitude from pre-test (M= 7.30 μV, SD= 2.73) to post-test (M= 9.38 μV, SD= 2.94), $t(19)= 5.25$, $p < .001$, Cohen's d= 1.17. No significant change was found in the control group (pre: M= 7.40 μV, SD= 3.48; post: M= 7.58 μV, SD= 2.24, p= .731).

## 4. Discussion

Our study investigated whether 30 min of moderate-intensity acute aerobic exercise could reduce test anxiety and improve inhibitory control in individuals with high test anxiety (HTA). The findings indicate that acute moderate-intensity aerobic exercise effectively alleviated inhibitory control deficits and test anxiety symptoms in HTA individuals. Specifically, after 30 min of moderate-intensity aerobic exercise, HTA individuals reported a significant reduction in self-rated test anxiety and demonstrated improved inhibitory control, evidenced by a significant reduction in reaction times on the Flanker task compared to the control group. Additionally, post-intervention results showed a significant decrease in N2 amplitude and a significant increase in P3 amplitude.

Consistent with previous research, our behavioral results indicate that HTA participants exhibited longer reaction times and lower accuracy rates during the incongruent condition of the Flanker task compared to the congruent condition, demonstrating a typical "Flanker effect." This effect occurs because the incongruent condition requires greater inhibitory control to manage potential errors caused by distractors [49,63]. Importantly, beyond a significant reduction in reaction times for both congruent and incongruent trials on the Flanker task compared to the control group after the 30 min moderate-intensity aerobic exercise session, the HTA intervention group also demonstrated a significant decrease in the Flanker conflict effect, indicating reduced interference cost. Because the conflict effect directly indexes the ability to suppress distractor-driven response tendencies [64,65], its attenuation provides compelling behavioral evidence that acute aerobic exercise improved inhibitory control in HTA individuals. The general RT improvement observed in both conditions is consistent with previous studies showing that acute exercise positively impacts both congruent and incongruent conditions in inhibitory control tasks [66–72]. The general improvement in cognitive performance post-exercise may be attributed to mediating factors such as the level of neural activation [73,50], blood acidosis or the accumulation of metabolic waste, and/or the involvement of different metabolic systems [74], or changes in fluid functions [75]. Another possible explanation is that the reticular activation process leads to more efficient bottom-up processing in both central and peripheral sensory and motor systems following exercise, resulting in shorter reaction times [76,77].

Notably, we did not observe significant improvements in accuracy following the exercise intervention, which could be due to a ceiling effect since participants achieved over 90% accuracy on the relatively simple version of the Flanker task used in this study. According to the Processing Efficiency Theory proposed by Eysenck et al. [78], test anxiety primarily impairs processing efficiency (i.e., reaction speed) rather than performance effectiveness (i.e., response accuracy). Therefore, HTA individuals may show deficits in reaction speed but not in accuracy. Wei et al. [24] also found that HTA individuals exhibited differences in reaction speed but not in accuracy compared to those with low test anxiety, suggesting limited room for improvement in accuracy following exercise intervention. The significant improvement in reaction time post-intervention, while maintaining similar accuracy levels to baseline, further supports that the reduction in reaction time was not due to a speed-accuracy trade-off but was indeed a result of the acute exercise intervention.

In this study, the HTA intervention group demonstrated a significant reduction in N2 amplitude across both congruent and incongruent conditions following a 30 min aerobic exercise session compared to the control group. The N2 component is associated with the detection of response conflict, mismatch between stimuli and mental templates, and early-stage cognitive control involved in response inhibition [40,59]. Previous studies on healthy participants have shown mixed results, with some reporting no significant changes in N2 amplitude after acute exercise [79,80], while others observed a reduction in N2 amplitude [81]. Notably, the downregulation of N2 amplitude post-exercise has often been found in populations with pre-existing deficits in inhibitory control, a characteristic commonly observed in individuals with high test anxiety [24,82,83]. Our findings align with these results, This reduction in N2 amplitude suggests that acute aerobic exercise allows HTA individuals to monitor conflicts more effectively while using fewer attentional resources, improving response inhibition. Additionally, the observed alleviation of anxiety in the HTA group likely plays a critical role in reducing cognitive load during conflict conditions. Anxiety often depletes cognitive resources through increased self-focused attention and intrusive thoughts, which hinder task performance [84]. By mitigating anxiety, exercise likely frees cognitive resources, enabling more efficient conflict processing and task engagement.

When examining the P3 component, we observed smaller P3 amplitudes under the congruent condition compared to the incongruent condition during the Flanker task, replicating earlier findings [85–89]. This reduction in P3 amplitude likely reflects the increased cognitive conflict and task difficulty experienced by participants during incongruent trials. Consistent with prior research [85,86,88], our study found that acute moderate-intensity exercise led to an increase in P3 amplitude in HTA individuals, particularly under conditions requiring inhibitory processing. The observed increase in P3 amplitude suggests that acute exercise enhances the allocation of neural resources to task-relevant stimuli [90].Interestingly, the enhancement in P3 amplitude post-exercise was not limited to the incongruent condition; similar increases were observed in the congruent condition. This indicates that acute exercise may improve the allocation of attentional resources in HTA individuals across both basic and inhibition-demanding tasks. The electrophysiological responses observed, particularly in the P3 component, are thought to be influenced by neurotransmitter systems such as dopamine (DA), with ERP responses during cognitive tasks potentially reflecting these changes. The P3 component is most likely generated by cortical cells and involves the dopaminergic neurotransmitter system [25]. According to Pogarell et al. [91], the striatal DA system can influence P3 amplitude. Therefore, acute moderate-intensity exercise may modulate DA system activity, enhancing the neurophysiological processes underlying stimulus encoding and response generation, which is reflected in the observed changes in P3 amplitude.

Overall, the present findings demonstrate that 30 min of moderate-intensity aerobic exercise significantly enhances inhibitory control in individuals with high test anxiety (HTA), as evidenced by both behavioral and electrophysiological measures. The concurrent reduction in N2 amplitude and increase in P3 amplitude suggest a rebalancing of cognitive control processes. The reduction in N2 amplitude reflects a decreased reliance on conflict detection mechanisms, while the increase in P3 amplitude indicates enhanced top-down attentional regulation and improved allocation of cognitive resources. These changes are consistent with neurochemical mechanisms induced by acute exercise, such as elevated levels of dopamine, norepinephrine, and serotonin, which are known to enhance prefrontal cortex activity and cognitive control [71,92,93]. Furthermore, the reduction in cortisol levels following exercise may mitigate hyperactivation of the amygdala, promoting a calmer emotional state and contributing to improved cognitive efficiency [94].

In addition to these neurophysiological effects, the emotional improvements observed in HTA individuals, particularly reductions in anxiety levels, appear to play a critical role in alleviating the cognitive and neural burden associated with conflict processing. High anxiety is frequently associated with increased self-focused attention and intrusive thoughts, which deplete cognitive resources and interfere with task performance [84]. By reducing anxiety, exercise likely facilitates a more efficient allocation of attentional resources, minimizing the interference caused by anxiety-related thoughts. This effect is particularly important for HTA individuals, whose heightened anxiety often results in excessive monitoring and overactivation of conflict detection systems. Exercise-induced increases in norepinephrine, dopamine, and serotonin are also known to improve mood and stress regulation, further enhancing prefrontal cortex function and emotional control [25,93].

Taken together, these findings suggest that acute moderate-intensity aerobic exercise facilitates a more efficient neural and cognitive strategy for managing demanding tasks, particularly those requiring response inhibition and attentional control. The observed electrophysiological changes, including reduced N2 amplitude and enhanced P3 amplitude, underscore the potential of exercise-induced neurochemical modulation in improving both emotional regulation and cognitive performance. This highlights the potential of moderate-intensity aerobic exercise as an effective intervention for mitigating test anxiety and improving cognitive function in high-stakes contexts.

The study primarily focused on intervening in the inhibitory control function of individuals with test anxiety. Based on the conclusions of Gass and Curiel [95], it is suggested that deficits across multiple executive function domains may provide a more reliable etiology for test anxiety. Rather, given that exercise may influence several executive components in parallel, it is important that future studies assess the effects of interventions across multiple executive processes instead of focusing exclusively on a single domain such as inhibitory control. A broader investigation of how various executive functions relate to test anxiety may provide a more complete understanding of its cognitive mechanisms and help inform the development of more comprehensive intervention strategies.

However, this study has certain limitations regarding the selection of participants, as it primarily involved a sample of university students, which was relatively easy to access. It is important to note that the prevalence of test anxiety is generally higher among middle and high school students than among university students [3]. Relying solely on university students may reduce the ecological validity of the exercise intervention effects. Future research should consider extending the application of exercise interventions to high-test-anxiety students in secondary education settings. Additionally, in this study, test anxiety was induced through instructional prompts that simulated an evaluative situation, which may not fully replicate real-world evaluative environments. Subsequent studies should explore the effects of interventions on test anxiety and inhibitory control in authentic evaluative contexts.

Although numerous studies have reported impaired inhibitory control among individuals with high test anxiety [23,24,96], the present study did not include a low-anxiety comparison group. Therefore, we cannot determine whether our participants exhibited baseline deficits relative to normative levels. The observed improvements should be interpreted as within-group changes rather than remediation of a quantified deficit. Future work should incorporate low-anxiety control groups to directly evaluate deficit magnitude and normalization effects.

Additionally, socioeconomic status (SES) was not assessed in this study. Although all participants were drawn from the same university population—thereby reducing some SES-related variability—SES remains an uncontrolled background factor and should be considered in future research as it may influence both exercise responses and cognitive performance.

This study showed that a single session of moderate-intensity aerobic exercise could significantly reduce test anxiety in individuals with high test anxiety (HTA). However, the reduction was modest, with TAS scores remaining above 20 post-intervention, still within the high test anxiety range. This highlights the limitation of relying solely on a single-session intervention for addressing persistent anxiety.Future research should explore whether long-term exercise interventions can reduce test anxiety to moderate or low levels. Additionally, combining exercise with other psychological interventions, such as mindfulness or cognitive-behavioral therapy, may enhance effectiveness and provide more sustainable outcomes.

This study represents the first investigation into the effects of acute aerobic exercise on inhibitory control in individuals with test anxiety, utilizing both behavioral and electrophysiological measures. The findings offer robust evidence that 30 min of moderate-intensity acute aerobic exercise exerts a beneficial impact on test anxiety, as evidenced by reductions in self-reported test anxiety and significant enhancements in inhibitory control among HTA individuals.

## Data availability statement

The data that support the findings of this study are available from the corresponding author, [Renlai Zhou], upon reasonable request.

## CRediT authorship contribution statement

**Lingfeng Wu:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Renlai Zhou:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

## Competing interests

None.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.physbeh.2026.115250.

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