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RESEARCH ARTICLE

The impaired visual working memory of overweight and its intervention via six-week Tabata training: behavioral and event-related potential evidence

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Abstract

Overweight individuals often experience impairments in executive function, particularly working memory. Physical exercise has been shown to mitigate such cognitive decline and modulate brain activities. This study aimed to investigate whether a six-week high-intensity interval (HIIT) Tabata exercise could improve working memory performance in overweight individuals and explore the associated neural mechanisms. To achieve this aim, two experiments were conducted. In Experiment 1, 20 overweight (Body Mass Index, BMI≥24) and 20 health-weight university students completed the n-back task ($n=0\sim2$) to assess working memory. Results confirmed that overweight participants exhibited lower accuracy (ACC) in the 2-back task compared with health-weight participants. Accordingly, in Experiment 2, another 40 overweight university students were randomly assigned into the training group (six-week HIIT Tabata) or control group (no physical exercise). All the participants performed the 2-back task with EEG recording at two points: before and after the six-week intervention (pre-test vs. post-test). Results showed that compared to pre-test, the training group showed higher accuracy at the post-test, whereas no such change was observed in the control group. Moreover, ERP results revealed a reduction in post-test P2 amplitude in the training group. Overall, this study demonstrates that being overweight negatively impacts working memory, while a six-week HIIT Tabata intervention may help alleviate these deficits, possibly through more efficient neural resource utilization.

Keywords Overweight · Working memory · Physical activity · HIIT · Event-related potentials

Introduction

Overweight and obesity pose risks to both physical and mental health. Modern lifestyle and dietary changes have led to a rapid increase in these conditions. As for 2022, approximately 2.5 billion adults worldwide reported body mass index (BMI) over 25 kg/m^2, and were classified as overweight. Among them, 890 million individuals met the criteria for obesity with a BMI greater than 30 kg/m^2 (World Health Organization, 2024). Overweight individuals face an increased susceptibility to physical issues including cardiovascular disease (Ortega et al. 2016), type-2 diabetes, and musculoskeletal disorders (Wearing et al. 2006). And they are also more likely to experience mental disorders such as depression and anxiety (Herhaus et al. 2020; Moradi et al. 2021; Zhao et al. 2009).

Beyond these physical and mental health risks, researchers have highlighted the impact of overweight on brain

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activities (Kroll et al. 2020; Zhang et al. 2023) and cognitive functions (Prickett et al. 2015; Yang et al. 2018). Structure and functional brain changes have also been reported, particularly reduction of orbitofrontal cortex (OFC) volume, which is linked to disinhibited eating and working memory deficits (Maayan et al. 2011). Additionally, obesity has been associated with impaired dopaminergic pathways that modulate reward sensitivity and cognitive control, further contributing to executive dysfunction (Volkow et al. 2011). And overweight individuals often demonstrated deficits in high-order cognitive function, including cognitive flexibility (the ability to adjust new demands, rules or priorities, and switch between tasks, Delgado-Rico et al. 2012), inhibition control (the ability to suppress unrelated stimuli and dominant response, Reyes et al. 2015) and working memory (Ross et al. 2015; Yau et al. 2014). Importantly, poorer executive function has been linked to more frequent consumption of high-fat food, stressing its role in dietary self-regulation (Hall 2012). These findings emphasize the urgent need to develop appropriate intervention to address cognitive impairments associated with overweight and obesity.

As an important subcomponent of executive function (Baddeley 2012), working memory (WM) plays a central role in self-regulation, which is closely associated with eating behaviors and body weight management (Houben et al. 2016; Teixeira et al. 2015). By maintaining goals recruited from long-term memory, WM enables individuals to resist temptations and inhibit prepotent responses, thereby supporting goal-directed rather than habitual actions (Amodio et al. 2008; Hofmann et al. 2012). WM also supports other aspects of self-regulation, such as emotion regulation (Pan et al. 2022; Zelazo and Cunningham 2007), and underpins other high-order cognitive function, including inhibition control (Best and Miller 2010; Gathercole et al. 2008; Unsworth et al. 2015). Moreover, WM is involved in reward association learning (Collins and Frank 2012), a process closely linked to the development and maintenance of maladaptive behaviors, including binge eating (Schaefer et al. 2023; Schag et al. 2013). Deficits in WM are therefore particularly relevant to overweight and obesity, as they undermine self-regulation in eating behaviors. Indeed, lower WM performance is associated with greater loss-of-control eating (Tan and Lumeng 2018), reduced fruit and vegetable intake (Allom and Mullan 2014), and more consumption of energy-dense food (Dassen et al. 2018; Whitelock et al. 2018). Importantly, the improvement of WM through computerized training, has been shown to effectively modify eating behaviors, including reduced disordered eating thoughts, decreased emotional eating, and less food intake in obese population (Dassen et al. 2018; Houben et al. 2016). These findings suggest that intervention targeting WM would enhance self-regulation and support healthier lifestyle choices particularly in individuals with overweight and obesity.

In addition to cognitive training, physical exercise also shows potential in improving working memory in population with overweight and obesity, due to overlapping neural substrates supporting executive function (Marvel et al. 2019; Padilla et al. 2014; Russo et al. 2017; Zhao et al. 2023). Motor and cognitive development are closely linked, as children with cerebellar or prefrontal damage show both motor and cognitive deficits (Best and Miller 2010; Diamond 2000). Neuroimaging studies indicate that the dorsolateral prefrontal cortex (DLPFC), premotor and parietal regions are co-activated during tasks requiring motor planning and cognitive control (Andersen and Cui 2009; Miller and Cohen 2001; Sweeney et al. 2007). Supporting this link, behavioral evidence shows that individuals engaging in regular exercise performed better in working memory tasks compared to irregular exercisers (Yuan et al. 2023). And the intervention studies found that acute aerobic exercise could effectively improve individual's performance in WM tasks (Pontifex et al. 2009). Specifically, higher accuracy and shorter reaction time were observed after the short-time high-intensity interval training (HIIT) in individuals with overweight (Zheng et al. 2022). Neurophysiological findings further support these behavioral effects. A single bout of exercise accompanied by positive music increases the activation of dorsolateral prefrontal cortex (DLPFC), leading to improved executive performance on the Stroop task (Suwabe et al. 2021). And activating motor regions during a working memory task by the transcranial magnetic stimulation (TMS) facilitated individual's behavioral performance in WM tasks (Cona et al. 2017; Liao et al. 2014). Beyond direct neural mechanisms, emerging evidence suggests that exercise may also modulate cognitive function via systemic pathways such as the microbiota–gut–brain axis (Kang and Wang 2024). Collectively, these findings consistently support the idea that physical exercise can effectively enhance working memory.

Recently, HIIT has garnered considerable research interest due to its significant benefits for physical health. Its primary appeal lies in achieving high energy expenditure and cardiorespiratory loads within a condensed timeframe by alternating short bursts of intense exercise with brief recovery periods. Compared with traditional aerobic training, HIIT requires shorter training duration while eliciting comparable physiological adaptations (Gibala et al. 2012). Given that improved cardiorespiratory fitness has been associated with more effective cognitive functioning (Barnes et al. 2003), researchers have begun to explore whether HIIT may also benefit cognition. However, the evidence remains mixed. Some studies reported improvements in executive function following HIIT intervention in older adults and young adults with higher baseline cognitive abilities (Buchheit and Laursen 2013; Liu et al. 2023). In contrast, Chua et al. (2020) found no enhancement on children's memory. Moreover, a recent meta-analysis suggested that the intervention duration may moderate cognitive outcomes of HIIT (Liu et al. 2024).

To address these inconsistencies, the present study examined the effects of a six-week HIIT intervention on working memory (WM) in individuals with overweight. We first aimed to confirm the effect of overweight on WM using 0–2 back task, ensuring that the task difficulty was appropriate to detect performance differences. We then conducted a six-week Tabata training program, a popular form of HIIT, and assessed behavioral performance and brain activities before and after the invention to investigate its impact on WM and the underlying neural mechanism. Based on previous studies (Syan et al. 2019; Yang et al. 2018), we expected that overweight individuals to show poorer performance on the n-back task compared to health-weight individuals. Furthermore, we hypothesized that the Tabata training would improve WM performance, reflected by increased ACC or/and reduced RT at post-test relative to pre-test.

The current study applied event-related potentials (ERPs) due to their high temporal resolution for capturing WM processes. Specifically, the early P2, peaking approximately 150–275 ms post-stimulus, is distributed over the frontal-central and parietal-occipital regions (e.g., Dieterich et al. 2016; Getzmann et al. 2018; Kanske et al. 2011a). This component was more pronounced in response to task-related stimuli than task-irrelevant ones (Potts 2004), reflecting attention allocation and early information processing (Shalchy et al. 2020; Staub et al. 2014). Reduced P2 amplitudes have been linked to lower WM performance (Mercado et al. 2022). The subsequent N2 component occurring around 250–300 ms post-stimulus, are mostly prominent over the frontal and posterior regions (Correa et al. 2006; Hou et al. 2024). It is considered closely related to cognitive control and inhibition processes (Amodio et al. 2008; Folstein and Van Petten 2008), typically showing larger amplitudes for irrelevant versus relevant stimuli in WM tasks (Brydges et al. 2014; Lintas et al. 2021). Finally, the P3, a commonly studied ERP component in WM studies, peaks between 250ms and 500ms post-stimulus onset over the central-parietal region (Daffner et al. 2011; Fields 2023). It is considered an index of attention resources and memory updating, with greater amplitudes observed in individuals with higher WM capacity (Brouwer et al. 2012; Carretié et al. 2013; Klawohn et al. 2022; Pergher et al. 2019). According to these findings, we hypothesize that after six-week Tabata training, overweight individuals would exhibit improved WM performance, accompanied by enhanced ERP responses, specifically increased amplitudes of P2, N2, and P3.

Transparency and openness

We reported how we determined our sample sizes, all data exclusions and measures in the present study. These, along with our data, research materials and codebook, have been made publicly available on the Open Science Framework (OSF) and can be access at https://osf.io/ubcja/.This study was not preregistered.

Experiment 1

Method

Participants

A priori sample size estimation was conducted using G-power 3.1 (Faul et al. 2007), with an medium effect size f of 0.25 (Cohen 1988), significant level α as 0.05, group as 2, number of measures as 3. The required sample size was estimated to be 28. To ensure sufficient power, 66 undergraduate students (13 males, 53 females) from local university were recruited by online advertisement. Specifically, 32 participants (7 males, 25 females; M_{age} = 20.41, SD_{age} = 2.20) with BMI≥24 were included in the overweight group (OW group), and other 34 participants (6 males, 28 females; M_{age}= 20.53, SD_{age} = 1.86) with BMI below 24 were included in the health-weight group (HW group). All the participants are right-handed with normal or corrected-normal vision. They were physically healthy with no history of mental illness, neurological disorders, cardiovascular diseases, or other relevant medical conditions. Additionally, they did not have hereditary obesity or obesity induced by hormone medications. Before the formal experiment, all participants were provided with informed consents. This study was approved by the ethical committee of human research in local university.

Behavioral procedures

The n-back (n=0, 1, 2) working memory paradigm was used in this study due to its suitability for assessing the higher order cognitive processing, rather than social cognition or emotion processing (Owen et al. 2005). In Experiment 1, n-back tasks were conducted to examine the group difference in working memory with increasing task difficulties progressively. The sequence of the three-level tasks was counterbalanced. Each condition comprised 40+n trials (i.e., 40, 41, and 42 trials, respectively), including 20 targets. Participants were instructed to respond from trial $n+1$, yielding 120 recorded trials in total. The stimuli comprised eight capital letters (A, B, H, K, M, P, S, T), which

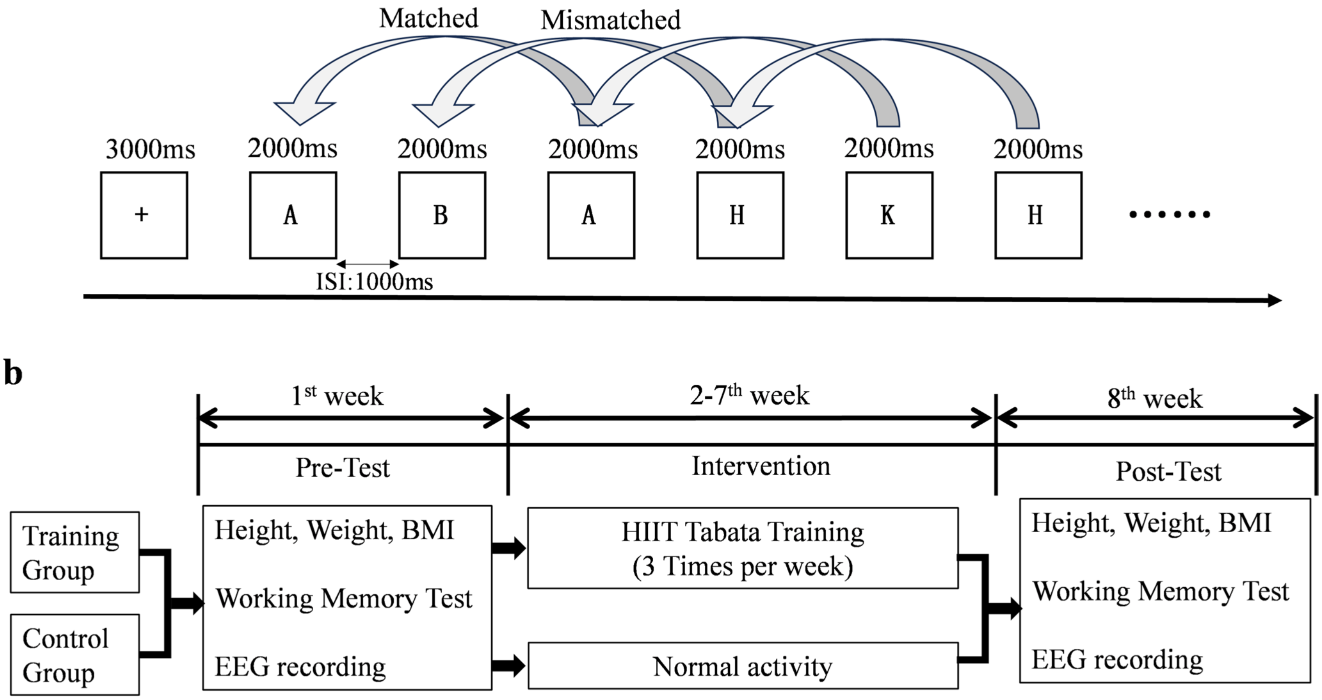

Fig. 1 **a** Illustration of the 2-back task; **b** Flow chat of the intervention procedure in Experiment 2. ISI = interstimulus interval

were presented one by one. Participants were instructed to indicate whether the current stimulus matched the target letter by pressing the "F" key with their left index finger for a match and the "J" key with their right index finger for a mismatch.

Specifically, in the 0-back condition, the target letter was provided at the start of the task following a 3000-ms fixation. In the 1-back and 2-back conditions, participants were required to determine whether the current stimulus is matched the one present one or two trials prior, respectively. Before each condition, a short practice session (10 + n trials) was administered to ensure participants fully understood the task rules and achieved at least 70% accuracy. A 2-minute rest was provided between tasks. Figure 1a illustrates the procedure of 2-back task. Trials with RT exceeding ± 3SD from each participant's mean were excluded from RT analysis. Participants with overall accuracy below 50% would be excluded from analyses; however, no one was excluded.

Statistics

Statistics analyses were performed using SPSS 21. Group difference in demographics variables were analyzed by the two-tailed independent *t*-test or *chi*-square test. For behavioral outcomes, the Shapiro–Wilk test was first used to assess normality. As the accuracy data did not meet the normality assumption, nonparametric Mann–Whitney U tests were performed to compare accuracy between groups across n-back tasks. Response time was analyzed using a mixed-model ANOVA with group (OW vs. HW) as the between-subject factor and task difficulty (0-back, 1-back, 2-back) as the within-subject factor. The Greenhouse-Geisser correction was applied when the assumption of sphericity was violated. Post hoc comparisons were conducted with Bonferroni-Holm correction when significant main or interaction effects were observed. The significant level was at 0.05 and partial η square (η_p^2) was also reported as a measure of effect size for ANOVA results.

Table 1 Demographic characteristics of participants in experiment 1

	HW Group *N* = 34	OW Group *N* = 32	t/χ^2	*p*
Sex(male/female)	6/28	7/25	0.19	0.76
Age (SD)	20.53(1.86)	20.41(2.20)	0.25	0.81
BMI(SD)	20.05(2.15)	28.09(4.07)	−10.12	< 0.001

HW-health weight, OW-overweight; SD-standard deviation

Results

Demographic data

No significant differences in age or sex were observed between the OW group and HW group (see Table 1). And participants in OW group had significantly higher body mass index (BMI; 28.09 ± 4.07) than the HW group (20.05 ± 2.15; $t(64) = 10.12$, $p < .001$, 95% CI = [6.45, 9.63]).

ACC

Mann-Whitney U tests revealed a significant group difference in the 2-back task, with participants in the OW group (0.84±0.11) showing lower ACC than those in the HW group (0.89±0.08, $z = -2.48$, $p=.03$; see Fig. 2a). No significant differences were observed in the 0-back (OW group: 0.98±0.03, HW group: 0.98±0.03; $z = -1.00$, $p=.64$) or 1-back tasks (OW group: 0.97±0.02, HW group: 0.97±0.03; $z = -0.07$, $p=.95$).

RT

The results of mixed-model ANOVA on RT showed a significant main effect of task difficulty, $F\ (2, 128)=388.136$, $p<.001$, $\eta_p^2=0.86$, indicating that participants responded more slowly as task difficulty increased. There was no significant main effect of group, $F\ (1,64)=2.15$, $p=.15$, $\eta_p^2=0.03$, or group and task difficulty interaction, $F\ (2, 128)=0.57$, $p<.49$, $\eta_p^2<0.01$ (see Fig. 2b).

Discussion

Consistent with previous research (Alarcón et al. 2016; Hsu et al. 2015), Experiment 1 confirmed that overweight impairs working memory performance, as overweight participants showed lower accuracy on 2-back task compared to health-weight individuals. However, we did not observe the significant group differences in 0-back and 1-back tasks, likely due to a ceiling effect. Based on these findings, the 2-back task was chosen for Experiment 2 to assess participants' working memory before and after the exercise intervention, to explore the effect of HIIT training.

Experiment 2

In Experiment 2, we aimed to further investigate whether six weeks of high-intensity interval training could elevate the working memory deficits in overweight individuals, and

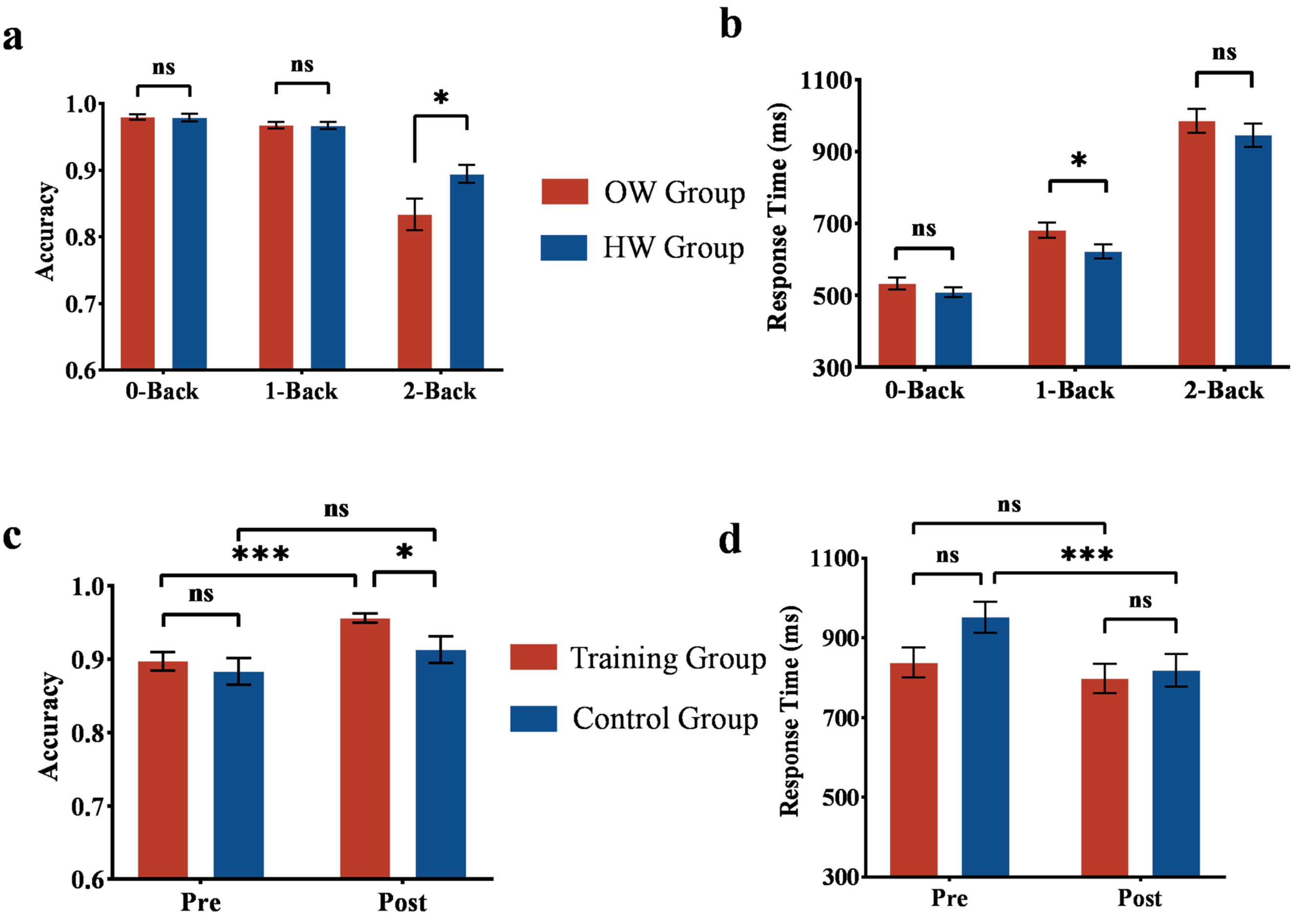

Fig. 2 The behavioral performance of participants in Experiment 1 and Experiment 2. Accuracy (**a**) and response time (**b**) on the N-back task in Experiment 1 for the health-weight and overweight groups; accuracy (**c**) and response time (**d**) in Experiment 2 for the training and control groups at per- and post-test. OW: overweight, HW: health-weight. *ns*: non-significance, * $p<.05$, *** $p<.001$. Erro bars indicate standard error of the mean (SEM)

Table 2 Demographic characteristics of participants in experiment 2

	Control Group *N* = 19	Training Group *N* = 18	t/χ^2	*p*
Sex (male/female)	4/15	4/14	0.07	0.93
Age (SD)	19.95(1.54)	19.89(1.78)	0.11	0.92
BMI-Pre (SD)	27.86(4.76)	27.27(3.21)	0.30	0.77
BMI-Post (SD)	27.66(4.80)	25.78(2.87)	1.43	0.16

SD-standard deviant

to explore the underlying neural mechanisms using EEG technology.

Method

Participants

Thirty-nine university students with BMI over 24 who did not participate in Experiment 1, were recruited through an online advertisement titled "Explore the effect of six-week Tabata training on weight loss". Other exclusion criteria were same as Experiment 1. The sample size was determined based on a meta-analysis on acute aerobic exercise improving working memory(Moreau and Chou 2019), with an effect size (f) of 0.34, α level of 0.05, and statistical power (1-β) of 0.80 to detect a significant interaction between group (Training Group vs. Control Group) and time (Pre-training vs. Post-Training). After recruitment, participants were randomly assigned to groups by a computer-generated numbering system: individuals with odd numbers were allocated to the training group (*N* = 20; 4 males, 16 females; M_{age} = 20.20, SD_{age} = 2.33), and those with even numbers were allocated to the control group (*N* = 19; 4 males, 15 females; M_{age} = 19.95, SD_{age} = 1.54). Two participants in training group did not complete the post-testing, so data from 37 participants were included in the final analysis (see Table 2).

Experimental procedure

All participants visited the laboratory twice, once before and once after the six-week Tabata training. During both visits, they performed the 2-back task while EEG was recorded. In the 2-back task, stimuli (eight capital letters same with Experiment 1) were presented consecutively for 2 s, with a 1 s blank screen inserted between stimuli. Participants were instructed to respond starting from the third stimulus: if the current letter matched the letter presented two trails prior, they pressed "F"; if not, they pressed "J". To maintain randomness and participants' attention, an equal ratio of matching and mismatching stimuli (1:1) was presented in a random order. A total of 122 trials were included, with 60 target stimuli. As in Experiment 1, trials with RT exceeding ± 3SD from each participant's mean were excluded. All subjects achieved an overall accuracy above 50% and were included for analysis.

Table 3 Six-week Tabata training program

	Action Name	Duration	Intensity	Times
Basic Stage (1 ~ 3 weeks)	On-the-spot jump with overhead press	20s	75%~85%	2
	Touch the ground with hands + horse stance jump	20s	75%~85%	2
	Side step lunge + squat	20s	75%~85%	2
	Lateral kick jump	20s	75%~85%	2
Improvement Stage (4 ~ 6 weeks)	Mountaineering race	20s	85%~95%	1
	Touch-ground running	20s	85%~95%	1
	Upward Jump + Backward Run	20s	85%~95%	1
	Left and right jumping steps + running with high legs in place	20s	85%~95%	1
	Squat jump with a body twist	20s	85%~95%	1
	Opposite hand to foot touch	20s	85%~95%	1
	Lean-back leg kick-up	20s	85%~95%	1
	Burpee	20s	85%~95%	1

For the participants in the training group, they completed Tabata training three times per week for six weeks. Each session consisted of three rounds, with 8 exercises per round. Each exercise was performed for 20 s, followed by a 10-second rest. A 1-minute rest was given between rounds. Each training session lasted 14 min, excluding warm-up and cool-down periods. Specifically, 1–3 weeks were the basic phase and 4 ~ 6 weeks were the improvement phase. The improvement phase included more intense motor movements compared to the basic phase. More details are shown in Table 3; Fig. 1b.

Additionally, all participants were instructed to take daily photos of their meals and share them with the experimenter through the WeChat app. Participants were instructed to maintain a balanced diet that included a mix of protein and vegetables, and to avoid consuming high-calorie foods or beverages after 8 p.m. Smoking and alcohol consumption were not allowed throughout the study. Also, participants were advised to follow a consistent sleep routine, ensuring at least seven hours of sleep per night and avoiding staying up late. Non-experimental physical activities were strictly controlled to ensure all participants only engaged in the prescribed training program during the specific time.

EEG recording and analysis

Continuous EEG recordings were performed by 64-electrode head cap (Brain Products) according to the standard international 10–20 system (sample rate: 500 Hz; band-pass: 0.01–100 Hz; notch filter: 50 Hz). The ground electrode was placed on the medial-frontal line between FPz and Fz, and FCz was selected as the online reference. All the electrode impedance was kept below 5kΩ.

Offline EEG pre-processing was conducted with MATLAB (vision 2019b), EEGLAB toolbox v2021.0, and Fieldtrip v20210330. Firstly, the continuous EEG was filtered offline using basic FIR filter with a 0.1–30 Hz bandpass implemented in EEGLAB. Nonbrain electrodes were removed and artifactual channel were rejected using the clean_raw data plugin in EEGLAB. The data was then re-referenced to the average activity of bilateral mastoids (TP9, TP10). Independent Component Analysis (ICA) was implemented to detect eye blinks, horizontal and vertical eye movements, and these components were removed by visual inspection.

The pre-processed data was segmented into epochs from 200 ms pre-stimulus to 800 ms post-stimulus onset. Only epochs with correct responses were included. After baseline correction using the pre-stimulus interval (−200 ms), epochs containing artifacts with peak-to-peak deflection exceeding ± 85μV was rejected (remaining epochs: Training Group-Pre:105.44 ± 8.12; Training Group-Post:105.83 ± 17.80; Control Group-Pre:98.33 ± 18.00; Control Group-Post:100.50 ± 15.76). The number of epochs used for ERP averaging was similar across the four conditions, $F(3,70) = 1.15$, $p = .33$.

Based on previous studies (Shalchy et al. 2020) and the visual inspection of the grand-averaged ERP waveforms, the time windows for ERP components were identified as follows: N1 (160 to 190ms), P2 (210 to 240ms), N2 (280 to 380 ms), P3 (390 to 450 ms), at the midline sites from frontal to parietal sites (Fz, Cz, Pz). Three-way repeated-measures ANOVAs were conducted for each ERP component of interest, with group (control group and training group) as a between-subjects factor, and time (pre-training and post-training) and electrode (Fz, Cz and Pz) as within-subjective factors. The other statistical details were same as those in Experiment 1.

Results

Demographic data

As showed in Table 2, there was no significant difference between control and training groups in sex, age, pre-training and post-training BMI ($ps > 0.05$).

Behavioral results

ACC

In the training group, a Wilcoxon signed-rank test revealed that ACC significantly increased from pre-test (0.898 ± 0.051) to post-test (0.957 ± 0.026; $z = 3.62$. $p < .001$). In contrast, the control group did not show such a significant change between pre-test (0.882 ± 0.083) and post-test (0.909 ± 0.082; $z = 1.72$, $p = .09$; see Fig. 2c). More importantly, Mann–Whitney U tests showed no significant difference between the two groups at pre-test ($z = 0.18$, $p = .86$), suggesting comparable performances at baseline; whereas, in the post-test, the training group exhibited significantly higher ACC compared to control group ($z = 2.21$, $p = .03$).

RT

The ANOVA revealed a significant main effect of time, F (1, 35) = 18.22, $p < .001$, $\eta_p^2 = 0.34$, with overall faster responses in the post-test (809.02 ± 27.94 ms) than the pre-test (897.94 ± 27.55 ms; see Fig. 2d). Additionally, the interaction between group and time was significant, $F(1, 35) = 4.79$, $p = .035$, $\eta_p^2 = 0.12$. Simple effect analysis showed that the control group showed a significant decrease in RT after six weeks (pre: 952.96 ± 179.98 ms, post: 818.46 ± 187.76 ms; $p < .001$, 95% CI [75.501, 193.492]), whereas, the training group showed no significant change (pre: 842.91 ± 153.25 ms, post: 799.57 ± 148.70 ms; $p = .16$, 95% CI [−17.271, 103.953]). However, there was no significant group difference either at pre-test ($p = .06$, 95% CI [−1.82, 221.91]) or post-test ($p = .74$, 95% CI [−94.56, 132.35]). The main effect of group was not significant, F (1, 35) = 1.57, $p = .22$, $\eta_p^2 = 0.04$.

ERP results

As shown in Fig. 3a-c, N1, P2, N2 and P3 components were observed in the 2-back task across groups and times. Correspondingly, Fig. 3d presents the averaged topographical distributions of these ERP components within their respective time windows.

N1 (160–190ms)

For the N1, there was only a significant main effect of Electrode in both amplitude and latency, suggesting that the largest N1 amplitude was observed at Cz, followed by Fz, with the smallest amplitude at Pz (Cz > Fz: $p = .03$, Cz > Pz: $p < .001$; Fz > Pz: $p < .001$), but earliest observed at Pz, and latest at Fz. Other main effects and interactions were not significant, except the interaction between Group and Electrode (see Tables 4 and 5).

P2 (210–240ms)

The ANOVA analysis revealed a marginally significant Group × Time × Electrode interaction, $F(2, 70) = 2.97$, $p = .058$, $\eta_p^2 = 0.08$. Post hoc tests indicated that at the Pz site, the training group showed a significant reduction in P2 amplitude following the six-week training (4.02 ± 0.91μV) compared to the pre-test (5.55 ± 0.98μV; $p = .002$, 95% CI [0.59, 2.46]), while no significant difference was observed in the control group (pre: 4.62 ± 0.95μV, post: 4.05 ± 0.88μV;

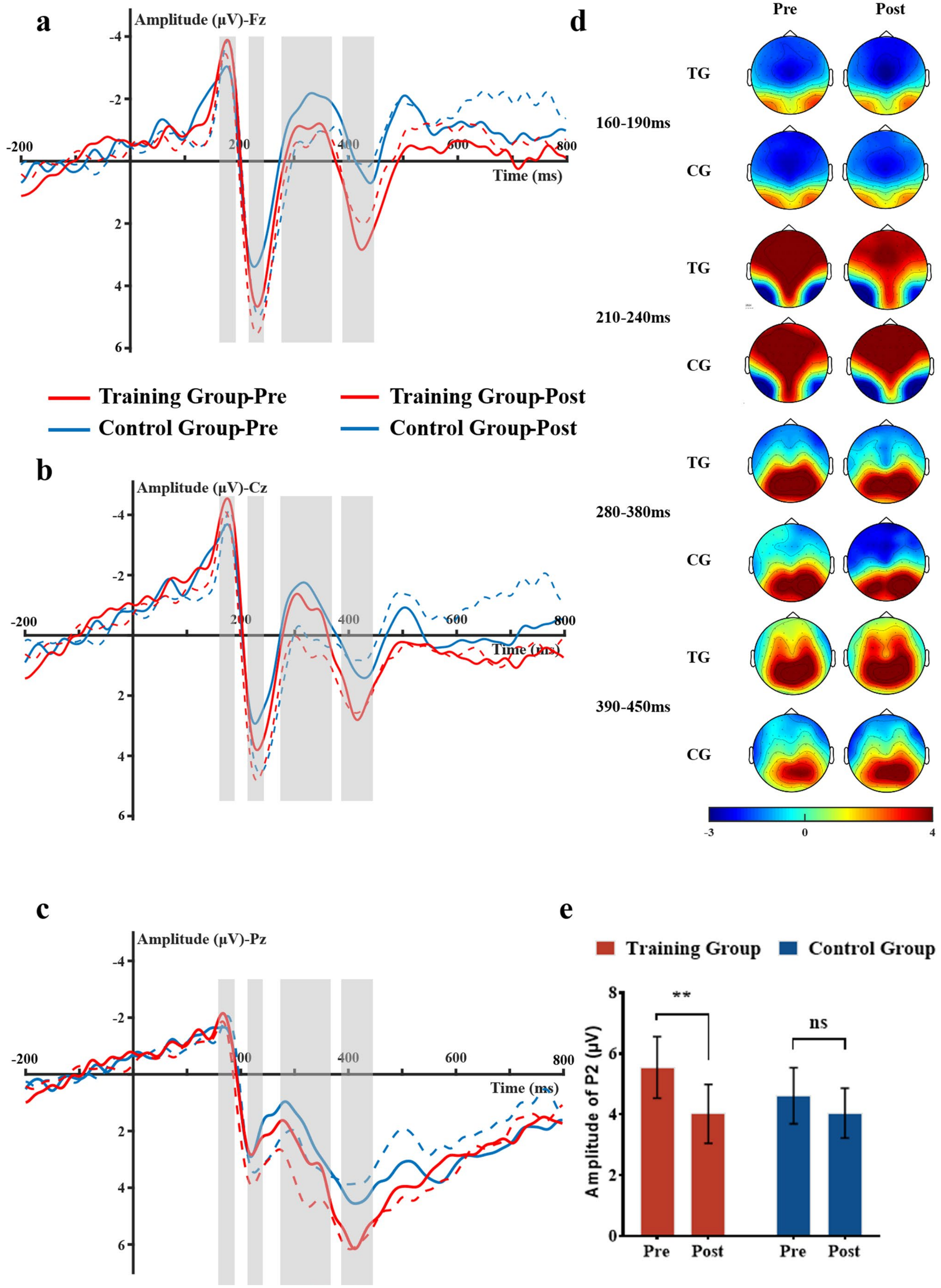
a
Amplitude (μV)-Fz
-4
-2
-200
200
400
600
800
Time (ms)
2
4
6
Training Group-Pre
Training Group-Post
Control Group-Pre
Control Group-Post
b
Amplitude (μV)-Cz
-4
-2
-200
200
400
600
800
Time (ms)
2
4
6
c
Amplitude (μV)-Pz
-4
-2
-200
200
400
600
800
Time (ms)
2
4
6
d
Pre
Post
TG
160-190ms
CG
TG
210-240ms
CG
TG
280-380ms
CG
TG
390-450ms
CG
-3
0
4
e
Training Group
Control Group
Amplitude of P2 (μV)
8
6
4
2
0
**
ns
Pre
Post
Pre
Post

Fig. 3 **a–c** the ERP waveforms as a function of group and time; **d** the topographies of ERP components across groups and times; **e** P2 amplitudes at Pz site across groups and time. Grey rectangles indicate the time windows for ERP components: N1(160–190 ms), P2 (210–240 ms), N2 (280–380 ms), and P3 (390–450 ms). Error bar = SEM. ** $p<.01$, ns = non significance

$p=.21$, 95% CI [−0.34, 1.48]; see Fig. 3e). Regarding P2 latency, a significant main effect of electrode was found, F (2, 70) = 6.23, $p=.006$, $\eta_p^2=0.15$, indicating that the P2 peaked earlier at Fz and Cz sites compared to the Pz site.

N2 (280–380ms)

For the N2 amplitude, the three-way interaction between Group × Time × Electrode was significant. However, further analysis did not show any significant Group × Time interactions at Fz, Cz or Pz site, Fs(1,35) = [1.59, 0.13], ps > 0.22. The main effect of Time and Electrode was significant. Participants in both training and control group exhibited increased negativities in N2 in the post-test (−2.06 ± 0.68μV) compared to the pre-training (−0.82 ± 0.67μV). And the largest N2 was observed at Cz site (−3.17 ± 0.71μV), followed by Fz (−2.50 ± 0.76 μV; $p=.026$), with smallest at Pz (1.35 ± 0.53μV; ps < 0.001). For the latency, only the main effect of Electrode was significant, with N2 peaking earlier at Pz and Cz sites than Fz (ps < 0.05).

P3 (390–450ms)

A significant main effect of electrode was observed for both the amplitude and latency of P3, Fs (2,70) < 63.43, ps < 0.001, with the largest P3 amplitude and the earliest peak occurring at the Pz site. No other effects reached statistical significance.

Discussion

Overweight and obesity are major risk factors for physical and mental health, and have been linked to impairments in the high-order cognition. The present study examined the impact of being overweight on working memory and further explored the effects and underlying neural mechanisms of a six-week HIIT program using behavioral and ERP measures. Experiment 1 revealed that overweight individuals performed worse than health-weight peers on the 2-back task as evidenced by lower accuracy, confirming deficits in working memory. Study 2 found a behavioral performance increased after the HIIT intervention, as reflected by increased accuracy in training group at post-test, accompanied by the reduced parietal P2 amplitude. However, the amplitudes of N1, N2 and P3 did not change significantly. Together, these findings highlight working memory as a key domain affected by overweight and provide preliminary support for long-term HIIT as a potential intervention to mitigate cognitive deficits in this population.

Consistent with prior studies (e.g., Alarcón et al. 2016; Coppin et al. 2014), individuals with overweight exhibited lower accuracy on the working memory task compared to the health weights. This aligns with previous evidence that executive functions, including working memory, are impaired by overweight and obesity (Favieri et al. 2019; Yang et al. 2018). Similar deficits have also been reported in children and adolescents with overweight and obesity, who performed worse on cognitive tasks such as list sorting task and digit span task (Goldschmidt et al. 2018; Li et al. 2008; Liang et al. 2014). One possible mechanism underlying these impairments is obesity-related chronic inflammation, which disrupts the prefrontal networks supporting working memory and other cognitive process (Castanon et al. 2015; Lowe et al. 2019; Yang et al. 2020). Importantly, the relationship between overweight and working memory seems to be bidirectional. The reduced working memory capacity undermines individuals' ability to maintain health-related goals and resist restraint, thereby contributing to unhealthy eating behaviours; while greater obesity has been shown to predict worse subsequent working memory, creating a vicious cycle that links cognitive impairments and weight gain over time (Best and Miller 2010; Dohle et al. 2018). Supporting this notion, individuals with better working memory performance showed more fruit and vegetable intake (Allom and Mullan 2014), and successful dietary restrain has been found to partly depend on working memory capacity (Augustijn et al. 2018).Together with our findings, these results highlight the central role of working memory in the regulation of eating behaviours and suggest that impairments in this cognitive function may contribute both to the onset and maintenance of overweight and obesity. Therefore, identifying effective interventions to improve it becomes particularly important, which was the focus of our second study examining the effect of the long-term HIIT intervention.

Supporting our hypothesis, overweight individuals who participated in the six-week HIIT training showed enhanced working memory performance, as indicated by an increased accuracy in the 2-back task. These findings aligned with several reports that high-intensity exercise enhances executive functions (Álvarez-Bueno et al. 2017; Crova et al. 2014; Liu et al. 2020). Noticeably, executive function is a multi-faceted concept, which includes working memory, inhibition, and cognitive flexibility (Diamond 2013; Hofmann et al. 2012). Meta-analyses suggest that the effects of exercise may differ across these subdomains. For instance, Verburgh et al. (2013) reported that chronic physical exercise significantly improved inhibition but not working memory. Similarly, Xue et al. (Xue et al. 2019) found enhanced inhibitory control rather than working memory following long-term exercise interventions. Currently, only limited number of

Table 4 Three-way mixed-measures ANOVA results for group (Training group, control group), Time (pre-test, post-test), and Electrodes (Fz, Cz, Pz) for the amplitude of N1, P2, N2, and P3

	N1 (160-190ms)			P2 (210-240ms)			N2 (280-380ms)			P3 (390-450ms)		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Group	0.37	0.55	0.01	0.16	0.69	<0.01	0.70	0.41	0.02	0.99	0.33	0.03
Time	0.21	0.65	<0.01	8.04	0.008	0.19	6.30	0.017	0.15	2.33	0.14	0.06
Electrode	44.41,	<0.001	0.56	3.12	0.076	0.082	62.25	<0.001	0.64	43.72	<0.001	0.56
Group × Time	1.33	0.26	0.04	<0.01	0.94	<0.01	0.24	0.63	<0.01	0.02	0.90	<0.01
Group × Electrode	0.35	0.60	<0.01	0.11	0.79	<0.01	1.48	0.24	0.05	0.12	0.85	<0.01
Time × Electrode	0.60	0.51	0.02	0.72	0.49	0.02	1.69	0.20	0.05	0.95	0.37	0.03
Group × Time × Electrode	0.07	0.89	<0.01	2.97	0.058	0.08	3.53	0.041	0.09	2.89	0.078	0.08

studies have investigated the effects of high-intensity exercise on the performance of working memory in individuals with overweight or obesity. Russo et al. (2017) found that the performance of digit memory test was improved after high-intensity exercise in adults with overweight or obesity. Similarly, Mora-Gonzalez et al. (2019) found that only for obese children with high-intensity exercise, there is a positive association between physical activity and the response accuracy in working memory task (the delayed non-match-to-sample task). Besides, although no group differences were observed at either pre-test or post-test in Experiment 2, the control group exhibited faster response times after six weeks. Such changes in RT may be attributable to practice effects rather than reflecting genuine cognitive improvements, especially given the lack of accompanying changes in accuracy or ERP measures.

Unexpected, ERP results revealed a reduction in parietal P2 amplitude following HIIT, while N1, N2 and P3 remained unchanged. The P2 component is typically linked to the early visual processing and allocation of attention resource (Chapman et al. 2015; Kanske et al. 2011b; Potts 2004).The decreased parietal P2 observed here may indicate that less attentional effort was required to achieve comparable or even better behavioral performance, reflecting more efficient utilization of neural resources (Grabner et al. 2004; Neubauer and Fink 2009). Similar reduction in cortical activity has been documented in athletes during sport-related information processing (Babiloni et al. 2010; Li and Smith 2021) and in young relative to older adults when processing task-irrelevant stimuli (Guerrero et al. 2022; Reuter-Lorenz and Cappell 2008; Vallesi et al. 2009). The decreased P2 amplitude in overweight individuals after HIIT training may suggest more economical neural activation.

Moreover, P2 is generally observed at both frontal-central and parietal sites (Carretié 2014; Kanske et al. 2011a; Yuan et al. 2007), which seems to reflect distinct processes: the former mainly linked to top-down cognitive control, while the latter to bottom-up visual information processing (Clark et al. 2001; Kanske et al. 2011b). Previous studies show that acute exercise often increases frontal-central P2 via heightened arousal and enhanced inhibitory control (Crova et al. 2014; Lambourne and Tomporowski 2010; Zhou and Qin 2019). In contrast, participants in the present study performed the working memory task in resting state, one day after all training completion, which may explain the absence of frontal-central P2 enhancement. Instead, the reduction in parietal P2 may suggest long-term HIIT does not act primarily through arousal-related mechanisms but rather by fostering more economical neural processing. (Polich 2007).

Consistent with this interpretation, no significant changes were found in N2 and P3 amplitudes, components often sensitive to arousal, as reflected in most cognitive and emotion

Table 5 Three-way mixed-measures ANOVA results for group (Training group, control group), Time (pre-test, post-test), and Electrodes (Fz, Cz, Pz) for the latency of N1, P2, N2, and P3

	N1 (160-190ms)			P2(210-240ms)			N2(280-380ms)			P3(390-450ms)		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Group	1.06	0.31	0.03	<0.01	0.93	<0.01	0.26	0.61	<0.01	2.33	0.14	0.06
Time	0.38	0.54	0.01	3.71	0.06	0.10	0.81	0.37	0.02	1.57	0.22	0.04
Electrode	24.83	<0.001	0.42	6.12	0.013	0.15	6.23	0.006	0.15	9.72	0.001	0.22
Group × Time	0.74	0.40	0.02	1.18	0.28	0.03	0.89	0.35	0.03	0.01	0.91	<0.01
Group × Electrode	5.24	0.02	0.13	0.14	0.76	<0.01	1.86	0.17	0.05	0.53	0.54	0.02
Time × Electrode	0.23	0.74	<0.01	1.55	0.22	0.04	0.79	0.45	0.02	3.27	0.044	0.09
Group × Time × Electrode	1.04	0.35	0.03	0.23	0.76	<0.01	0.59	0.54	0.02	0.45	0.64	0.01

related studies (Kissler et al. 2009; Rozenkrants and Polich 2008).Taken together, these findings suggest that, unlike acute exercise which produces transient arousal-driven benefits, long-term HIIT may promote sustained improvements in working memory by optimizing attentional resource utilization. This indicates a possible shift from short-term arousal effects to longer-lasting efficiency-oriented neural adaptations, though future longitudinal studies are warranted to confirm this mechanism. Notably, although a reduction in parietal P2 was observed in the present study, the marginal interaction between intervention and time indicates that further research is needed to confirm this finding.

Several limitations should be acknowledged. First, the present study did not include an active control group, which makes it difficult to fully rule out placebo or expectancy effects. Future studies should consider incorporating an active control condition (e.g., light exercise or alternative training) to better isolate the specific effects of HIIT. Second, although prior meta-analytic evidence suggests that chronic physical activity may yield more enduring benefits than acute exercise (Rathore and Lom 2017), the absence of a high-intensity acute exercise comparison group in our design limits the ability to directly disentangle the neural mechanisms of acute versus chronic exercise. Third, while our sample size met the requirements for statistical power, it was relatively small and restricted to overweight university students, which may constrain the generalizability of our findings. Future research should recruit larger and more diverse samples, including populations such as obese children or adolescents, to test the robustness and external validity of the results. Fourth, participants' compliance with lifestyle instructions (e.g., avoiding additional exercise and maintaining diet) was monitored through self-reports, which may be subject to bias. More objective measures, such as wearable activity trackers or digital dietary logs, should be employed in future studies to improve the accuracy of adherence assessment. Finally, cognitive and neural outcomes were assessed only once after the six-week intervention, leaving the long-term sustainability of the observed benefits unclear. Incorporating multiple follow-up assessments would provide stronger evidence regarding the durability of HIIT-induced improvements.

In sum, the present findings suggest that overweight is associated with working memory deficits and that long-term HIIT may attribute to improvements at both the behavioral and neural level. By pointing to behavioral gains alongside early neural adaptations, this study provides preliminary support for long-term HIIT as a potential approach to mitigate obesity-related cognitive deficits, while underscoring the need for future research to examine its cognitive benefits.

Author contributions Author Contributions: X. Yan and D. Fu had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of data analysis. Concept and design: D. Fu, Q. He, T. Wu, M. Xiao, J. Yuan, X. Yan. Acquisition, analysis, or interpretation of data: X. Wang, M. Xiao, J. Yuan, X. Yan. Draft of the manuscript: D. Fu, J. Yuan, X. Yan. Critical revision of the manuscript for important intellectual content: J. Yuan, X. Yan. Statistical analysis: D. Fu, X. Yan. Obtained Funding: J. Yuan, X. Yan. Supervision: J. Yuan, X. Yan.

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Data availability We reported how we determined our sample sizes, all data exclusions and measures in the present study. These, along with our data, research materials and codebook, have been made publicly available on the Open Science Framework (OSF) and can be access at https://osf.io/ubcja/.This study was not preregistered.

Declarations

Competing interests The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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