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Effect of acute aerobic exercise on internet craving among college students with internet dependency: The mediating role of prefrontal cortex and executive control

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ABSTRACT

Background: The present study aimed to investigate the effects and mechanisms of acute aerobic exercise at high and moderate intensities on executive control and internet craving, and their associations in college students with internet dependency (ID)

Methods: Sixty participants with ID were randomly assigned to one of three groups: A 30-min high-intensity cycling exercise session, a 30-min moderate-intensity cycling exercise session, or no exercise. At baseline and after acute aerobic exercise treatment, self-reported internet craving was assessed immediately, and executive control in all participants was evaluated using the go/NoGo, 2-back, and more-odd shifting tasks. Brain activity in the prefrontal cortex (PFC) was measured and evaluated using functional near-infrared spectroscopy (fNIRS)

Results: The results showed different but effective reductions in internet craving, significantly improved executive control with shorter response times and higher accuracy, and increased activation in the dorsolateral prefrontal cortex (DLPFC) and the orbitofrontal lobe (OFC) after a 30-min acute aerobic exercise session at high or moderate intensity. Further correlation analysis revealed significantly close associations, either positive or negative among these variables. The serially mediated effects of inhibitory control, working memory, and cognitive flexibility were demonstrated, respectively

Conclusions: These findings suggest that performing aerobic cycling exercise alleviates internet craving in college students with ID. Such benefits may be maximized by the promoted executive control and be mediated by enhanced neurocognitive activations in the DLPFC and OFC. These exercise-enhanced improvements in cognitive and PFC functions are pivotal for reducing internet-induced craving and could have clinical benefits

1. Introduction

Over the past decades, the Internet has been increasingly integrated into our daily lives. The issue of Internet addiction (IA) has also gradually emerged as a significant public health concern. Negative consequences of IA include neglecting school or professional duties, abandoning hobbies or leisure activities, and engaging in behaviours that affect survival (Brand, 2022). Recent surveys revealed that the prevalence of IA in young university students ranged from 6 % to 35 % (Marzilli et al., 2020). According to the Interaction of Person - Affect - Cognition - Execution model (Brand et al., 2019), IA is progressive; the mechanisms involved in the early and later stages differ. In the early stages, which were the Internet dependency (ID) mentioned in other literature (Cheng et al., 2021), promoted craving and diminished executive control may contribute to engagement in addictive behaviours, and if there were no effectively control, addictive behavior would be habitual or automatic in the later stages (Brand et al., 2019). Thus, it is clinically meaningful to investigate how to prevent and cope with the promoted craving and diminished executive control among college students with ID.

Internet craving is an intense desire or urge to use Internet access (Zhou et al., 2022), similar to how substances and behaviours are craved

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in other addictions (Koob, 2021). Researchers found that engaging in exercise appropriately could reduce mental cravings. For example, in a research on methamphetamine use disorders (Li et al., 2025), the self-reported craving by Visual Analog Scales (VAS) of 32 participants was significantly reduced after a 30-min moderate intensity cycling exercise; meanwhile, quantitative evidence was found that the benefit induced by exercise may be achieved through enhancing the efficiency of conflict control. In another research on alcohol use disorder (Hallgren et al., 2021), 117 participants performed a 12-min sub-maximal fitness test on a cycle ergometer. The self-reported craving by the Desire for Alcohol Questionnaire reduced significantly for these participants, and those with higher cravings and lower cardiorespiratory fitness were most likely to benefit. Some studies claimed that high-intensity exercise helped reduce such cravings (Wang et al., 2020). Still, not all intensity levels at low, moderate, or high levels of an acute aerobic exercise were significantly associated with cravings reduction, while a moderate intensity exercise provided the maximal benefits (Haasova et al., 2014). Collectively, these studies indicated the importance of exercise participation in reducing cravings for different addictions and, importantly, implied that exercise intensity could be a key variable warranting further investigation. However, the effects of acute aerobic exercise at varying intensities on Internet craving among individuals with ID, as well as the underlying physiological mechanisms, remain unclear.

Early studies inferred that a neurocognitive process following exercise might mediate exercise effects on mental craving (Van Rensburg et al., 2012). In the cognitive process, executive control may be the key. Executive control is a congeries of complex mental processes and cognitive abilities that enable individuals to plan and achieve goals for their behaviours (Morse, 2021). As mentioned above, the association between craving and executive control contributes to the development of addictive behaviours (Brand et al., 2019), while the improved executive control accompanies the exercise-induced craving reduction. (Li et al., 2025). For the neuroprocess, cerebral oxygenation reserve and its dynamic changes in the PFC may play an important role. Koob (2021) proposed a three-stage heuristic framework that is associated with addiction, and claimed that the third stage, craving, involved dysregulations in executive control that the PFC mediates. It is worth noting that exercise can reduce craving by enhancing top-down executive control in the PFC (Engeli et al., 2021), and improvements in executive control after acute aerobic exercise were mainly observed in the PFC (Matsunaga et al., 2023).

These findings underscore the importance of neural-cognitive interactions between PFC activation and executive control in an exercise program for alleviating mental craving and promoting executive control, which may potentially trigger further changes or induce additional quantitative and qualitative adaptations in neurophysiological systems. Nevertheless, many existing studies focused on substance addiction. They were speculative, with few using quantitative methods to visually present the relationships among exercise, craving, executive control, and PFC activation in individuals with IA or ID. Functional near-infrared spectroscopy (fNIRS), one of the widely used neuroimaging technologies, offers a portable means to measure the specific role of cerebral blood dynamics during cognitive processing, especially executive control processes dependent on PFC (Rösch et al., 2021). Data from fNIRS could provide insights into whether and how interventions influence executive control by altering neural efficiency. This is important for clinical use and for developing strategies to improve executive control.

According to the Inverted-U hypothesis, moderate-intensity exercise yields the best performance. The drive theory, however, proposes a linear relationship between arousal and performance and predicts the most significant effects of high-intensity exercise. Based on the research above, we hypothesized that different intensities of acute aerobic exercise would have distinct effects on changes in Internet craving, mediated by executive control and corresponding PFC activation, among college students with ID. In addition, the alleviation of Internet-induced craving was positively associated with improvements in executive control and with enhanced mediational effects, driven by increased PFC activation following an acute aerobic exercise intervention.

2. Materials and methods

2.1. Subject recruitment

Based on a priori sample size calculation by G-power software (Faul et al., 2007), a sample of at least 54 participants was needed to provide adequate power with three groups and two tests of each group in the mixed experimental design repeated-measures analysis of variance (ANOVA) model. This calculation assumed a desired statistical test power of 0.90 and a significant level of $f = 0.25$, $\alpha = 0.05$ (Yan et al., 2025). This study initially recruited 481 college students aged 18–24 through advertising. They then underwent a screening survey using a revised edition of the Chinese Internet Addiction Scale (CIAS) to identify those with ID. The scale has 19 items that measure core symptoms and issues related to IA. A total score of 46–53 was indicated as ID (Bai & Fan, 2005). The Cronbach's α of the CIAS was 0.90.

Of 481 college students, 254 were identified as having ID and considered potential participants. The Physical Activity Rating Scale (PARS) was used to assess the physical activity levels of 254 subjects using three items. The inclusion criteria were as follow: 1) age ≥ 18 years; 2) no participation in any similar research project before this study; 3) normal vision or corrected vision and no color blindness or color weakness; 4) absence of major chronic diseases or physical problems such as cardiovascular, metabolic, renal, pulmonary diseases or doctor-diagnosed neurological or psychological disorders; 5) more than five years of exposure to the Internet; and 6) scores of the PARS was 5–42, which corresponded to a low or moderate intensity of physical exercise.

2.2. Study design

The study flowchart and participant flow are shown in Fig. 1. The study protocol was reviewed and approved by the Ethical Committee of our affiliation (No. 2024071) and was in accordance with the Declaration of Helsinki. All participants were asked to visit the laboratory and instructed to familiarize themselves with the experimental procedures and measurements. All participants voluntarily agreed to participate in the study and provided their informed consents.

This is a mixed design study. The participants were randomly assigned to one of three groups by using Excel software, with 20 participants in each group: the randomly ordered numbers 1–20 to the high intensity group (HIG), 21–40 to the moderate intensity group (MIG), and 41–60 to the no exercise or control group (NEG), respectively. Subsequently, each group completed demographic and test-related data collection as a baseline before applying interventional treatments. HIG and MIG groups performed an acute bout of aerobic cycling exercise lasting 30 min at different intensities. All groups took Internet craving measurements and neuropsychological measures of response to an intervention (with or without exercise), including inhibitory control, working memory, and cognitive flexibility, and prefrontal cortex activation, before the cycling exercise intervention (pre-test) and immediately after the exercise intervention (post-test).

2.3. Measures of internet craving

Using the visual analog scale (VAS), the valence of each individual's craving for the Internet was measured pre- and post-test. The scale used “no craving at all” and “strongest craving ever” to anchor a 100-mm line, with a score ranging from 0 (no craving at all) to 10 (strongest craving ever). This method has been used to measure mental craving in previous studies (Zhou, Finlayson, et al., 2021).

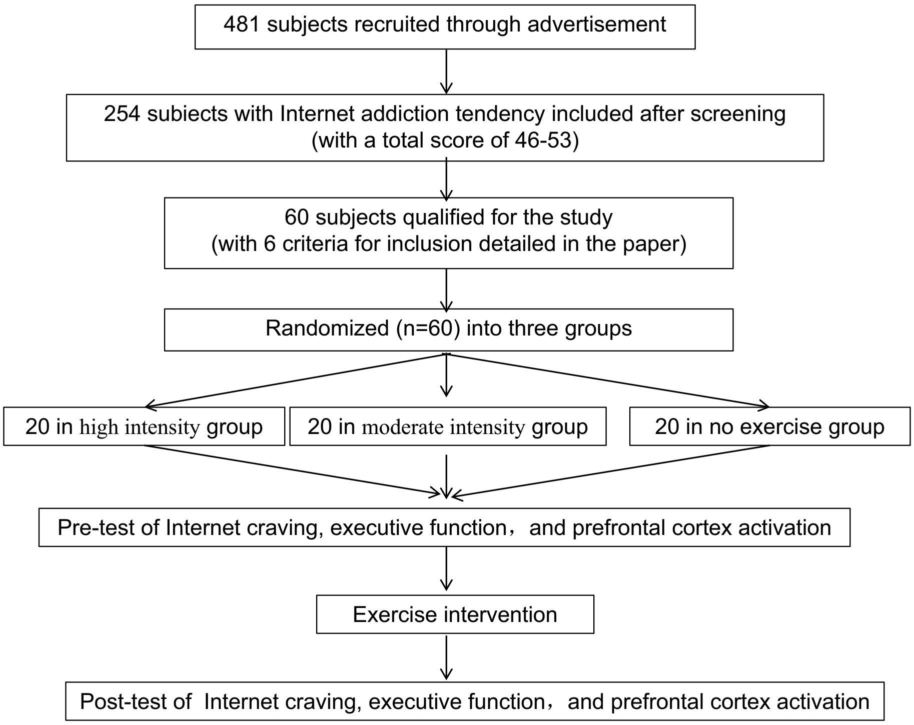


Fig. 1. Flowchart of study design. This diagram shows the flow of participants through the study.

2.4. *Tests of executive control*

The three relatively independent but interrelated components of executive control in adulthood include inhibitory control, working memory, and cognitive flexibility (Diamond, 2013). The Go/NoGo task was used to measure inhibitory control, with the accuracy of NoGo stimulation as measured variable; the 2-back task was used to measure working memory, with reaction time (RT) and accuracy as measured variable; and the More-Odd shifting task was used to measure cognitive flexibility function, with the switch cost (difference in RT and/or accuracy between the switch and nonswitch trials) as measured variable. The experiment was carried out on a computer with an Intel central processor. The display was an HP TPO1, with a resolution of 1920 × 1080 and a refresh rate of 60 Hz. The experiment tasks were programmed and run on *E*-Prime software. The distance between the eyes and the center of the screen was 57 cm.

In the Go/NoGo task, a series of stimulus characters was presented in the center of the screen, one at a time. The presentation time of each stimulus character was 400 ms, and the interval time between the stimulus characters was random, 400–700 ms. Before testing, the participants were told that “M” was a Go stimulus while “W” was a NoGo stimulus. When “M” appeared in the center of the screen, the subjects were required to press the “J” key, while when “W” appeared, they were required to do nothing. The formal test consisted of 96 Go stimuli (80 %) and 24 NoGo stimuli (20 %) and was divided into four blocks, with a 15 s rest at the end of each block.

In the 2-back task, a “+” was presented in the center of the screen, and subjects were required to gaze for 500 ms. Then, a capital letter was randomly given one at a time, and each letter's presentation time was 1000 ms. Before the test, the participants were told that if the presented number matched the second one ahead, they needed to press the “F” key. If the given number was different from the second one ahead, they should press the “J” key. A total of 62 letters were presented for the task. Since the first two numbers did not need to respond, there were actually 60 reactions to the evaluations, divided into four blocks.

In the More-Odd shifting task, a random number between 1 and 4 or 6 and 9 would be displayed in the center of the screen. When the number was black, the subjects should compare it to five and press the “F” or “J” button. When the displayed number was green, they should quickly respond whether the number was odd or even. When the task was the same as the previous one, the current task was named a non-switch trial. If the current task differed from the previous one, it was called a switch trial. The formal test consisted of 61 numbers and was divided into four blocks, but the first block was excluded from the data analysis.

2.5. *fNIRS data acquisition and processing of prefrontal cortex activation*

A 22-channel fNIRS instrument (LIGHTNIRS, Japan) was used in the present study, operating at two near-infrared wavelengths (760 and 850 nm). Optical signal variations in each channel were sampled at 13.33 Hz. Eight light source optodes and eight light detector probes were arranged in 2 rows and 8 columns, as shown in Fig. 2. The source optode and detector pairs covered the bilateral DLPFC, frontal pole cortex (FPC), and OFC. The three-dimensional information of the brain structure corresponding to each channel was identified using SPM soft and a 3D digital positioning device (FASTRAK, Polhemus, USA). The Montreal Neurological Institute (MNI) ICBM152 brain template was used to register fNIRS data to the MNI standard brain space.

2.6. *Intervention programs*

All participants in the exercise groups underwent an acute bout of steady-state aerobic exercise on a stationary bicycle ergometer (Ergoline, Germany). The exercise workloads were set manually. The bicycle power was initially set to 50 W with a revolution speed of 50 rpm. The exercise session lasted 30 min, with 5 min of warm-up and 5 min of cooldown. Based on each participant's specific physical condition, the resistance was adjusted to keep each individual's heart rate (HR) within their respective HR range responding to the exercise.

Before the exercise intervention, resting HR was measured using a Finland Polar RS400 heart rate telemeter. This HR telemeter was also used to monitor HR in real time during exercise. Participants in the HIG were required to reach 70–85 % of their maximum heart rate (HRmax), and participants in the MIG were required to reach 50–70 % of their

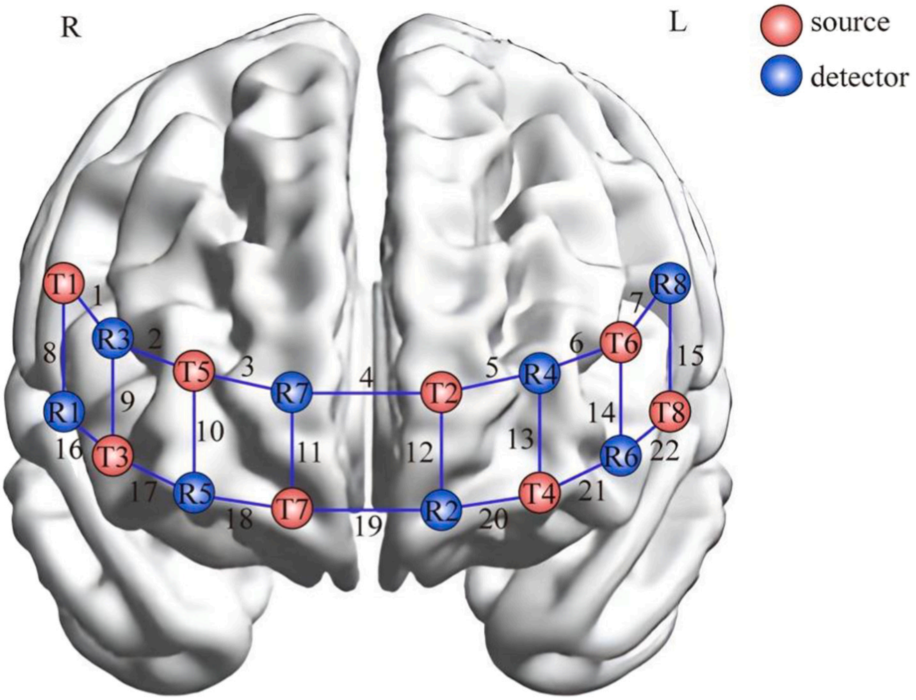


Fig. 2. The spatial profiles of 22 fNIRS channels used in the present study.

HRmax. The HRmax was calculated using the formula of 207–0.7 × age (Chu et al., 2015).

After a 5-min warm-up, each participant was asked to accelerate their exercise to reach to a steady-state HR, the preestimated target HR range corresponding to the exercise intensity, within 5 min. The subject continued the exercise and was instructed to keep the HR within the specified range for 25 min. Each participant's HR was recorded every three minutes. Participants were asked to continue cycling for 5 min as cool-down after stopping the exercise. All participants in the NEG were required to sit quietly.

2.7. *Statistical analysis*

The MATLAB-based HOMER2 toolbox preprocessed the fNIRS data. The raw data were converted into optical density and concentration changes using the modified Beer-Lambert law (Strangman et al., 2003). Motion artifacts were corrected using the Temporal Derivative Distribution Repair (TDDR) (Fishburn et al., 2019). A dual-pass Butterworth filter with a Hamming taper (0.01 and 0.5 Hz in the Go/NoGo task and More-Odd shifting task, and 0.008 and 0.2 Hz in the 2-back task) was included in a generalized linear model to remove physiological noises and signal drift (Gagnon et al., 2011). The changes in oxygenated hemoglobin concentration (HbO) of specific channels corresponding to cortical regions were averaged for further analysis (Rösch et al., 2021).

Statistical analysis was performed using IBM SPSS software. Descriptive statistics were used to summarize the Internet craving score, RT, accuracy, and HbO in three executive control tasks before and after an acute aerobic exercise intervention. Data with more than ±3 standard deviations (SD) were excluded. The Kolmogorov–Smirnov and Shapiro–Wilk tests were used to assess normality. If the distributions were normal, an ANOVA was conducted to determine whether the measured variables differed across the experimental conditions. If the normality assumption did not hold, we first normalized the distributions and then conducted ANOVA. The Harman single-factor method was used to test for common method bias. If the first factor extracted from the factor analysis accounted for 20.22 % (<40 %) of the variance, it indicated that there was no significant standard-method bias in the present study (Xiong et al., 2012). When appropriate, the Bonferroni post hoc test was used to detect significant differences between pairs of conditions. The significance level was set at $p \leq 0.05$. Data are presented as mean ± SD unless otherwise stated.

Correlations between variables were analysed using point-biserial and Pearson's correlation coefficients. A serial multiple-mediator model with three mediators for the two-condition within-participant design was tested by the SPSS MEMORE macro (model 1), respectively (Montoya & Hayes, 2017). Bootstrap resampling with 5000 repetitions was used to examine mediation effects rigorously. If the 95 % confidence interval did not include zero in the mediating effect analysis, the mediating effect was considered significant.

3. Results

3.1. *Participants' characteristics*

This study included a total sample of 60 qualified participants (male, $n = 31$; female, $n = 29$). The subject average age was 21.47 ± 1.86 years. Table 1 summarizes the participants' demographic information. There

Table 1
Initial physical characteristics of subjects (mean ± SD).

Variables	HIG	MIG	NEG	*P**
Subjects (n)	20	20	20	
Age (years)	22.05 ± 1.43	21.20 ± 2.26	21.15 ± 1.73	0.229
Gender (M/F)	11/9	8/12	12/8	0.433
Height (cm)	171.40 ± 8.86	170.10 ± 10.83	172.25 ± 9.10	0.778
Weight (kg)	65.20 ± 10.51	64.70 ± 13.74	65.60 ± 11.76	0.973
BMI (kg/m^2)	22.07 ± 2.12	22.12 ± 2.54	21.94 ± 2.29	0.968
Years of IE	7.10 ± 3.21	9.35 ± 3.36	8.75 ± 3.46	0.098
CIAS	49.90 ± 2.17	49.25 ± 2.61	50.15 ± 2.58	0.495
PARS	24.75 ± 7.36	25.55 ± 7.51	26.35 ± 6.41	0.777

Note*:* SD = standard deviation; HIG = High intensity group; MIG = Moderate Intensity group; NIG = No Exercise group; n = number of subjects; M/F = male/female; BMI = body mass index; Years of IE = Years of Internet Exposure; CIAS = Chinese Internet Addiction Scale; PARS = Physical Activity Rating Scale. *P** = Significant mean difference.

were no significant differences among the three groups on baseline characteristics.

3.2. Post-interventional changes in internet craving

A two-way repeated-measures ANOVA [3 (exercise intensity: high/moderate/no) × 2 (test time: pre-test/post-test)] was used to examine the effect of exercise intensity and test time on changes of Internet craving, executive control, and prefrontal cortex activation in the three groups, respectively. The ANOVA results for Internet craving indicated significant main effects of exercise intensity and test time, as well as a significant interaction between duration and time. As shown in Table 2, further simple effects analyses revealed that the mean Internet craving was significantly different between pre- and post-test in both exercise groups with high or moderate intensity. According to Cohen's d, however, high-intensity exercise elicited the larger effect.

3.3. Changes in executive control and PFC activation response to an acute aerobic exercise with different intensities

Table 2 presents the ANOVA results for the accuracy of the NoGo stimulus. It showed a significant main effect of test time and a significant interaction effect between the two variables. Further simple-effect analyses revealed that participants improved the accuracy of the NoGo stimulus after acute aerobic exercise at high and moderate intensities, with moderate intensity being more effective. Regarding prefrontal cortex activation, a significant interaction effect of test time × exercise intensity was found when the DLPFC and OFC activations were used as dependent variables. Furthermore, simple effects analyses revealed significant increases in DLPFC activation after acute aerobic exercise in both the HIG and MIG groups, with a larger increase in the HIG. Significantly improved OFC activation was observed only in the MIG group following acute aerobic exercise. Fig. 3 A-F displays the activation in DLPFC and OFC before and after exercise for subjects in the HIG and MIG groups.

For changes in the 2-back task's dependence variables, significant effects of test time and the interaction between test time and exercise intensity were observed when accuracy and DLPFC activation were used as dependent variables. As shown in Table 2, Cohen's d for accuracy in the MIG group was slightly higher than in the HIG group. However, the HIG group showed a higher Cohen's d for DLPFC activation than the MIG group. The results suggested that either high- or moderate-intensity acute exercise prompted positive changes in accuracy and DLPFC activation during 2-back task. Moderate-intensity exercise was more effective for accuracy, while high-intensity exercise was more effective for DLPFC activation. When using the RT as the dependent variable, analyses showed no significant main effect of exercise intensity or time-intensity interaction for activations in FPC and OFC. These results indicated that exercise intensity did not affect these variables. The activation in DLPFC before and after exercise for subjects in the HIG and MIG groups was shown in Fig. 4 A-D.

For the RT and activation in the DLPFC, FPC, and OFC during the More-Odd task, the ANOVA revealed a significant interaction between test time and exercise intensity (see Table 2). Further simple-effect analyses showed that RT and activations in DLPFC and OFC improved after acute exercise in both the HIG and MIG groups. However, improvement in FPC activation was observed only in the MIG group. Based on Cohen's d values, the shorter RT was observed in the MIG group, while greater activation in the DLPFC and OFC was observed in the HIG group. There was no significant main effect or interaction for accuracy. Fig. 5 A-J presented the activation in DLPFC, FPC, and OFC before and after exercise for subjects in the HIG and MIG groups.

3.4. Serial mediating effects of PFC activation and executive control

As shown in Table 3, across all participants with ID, analyses of Point-biserial correlation and Pearson correlation coefficient indicated significant associations between exercise-induced changes in Internet craving and measured variables as follow: 1) the DLPFC activation with response NoGo accuracy during the Go/NoGo task; 2) the DLPFC activation with response accuracy during the 2-back task; 3) the PFC activation with response RT and during the More-Odd shifting task. Therefore, we conducted a serial multiple-mediator model to evaluate further the mediational roles of inhibitory control, working memory, and cognitive flexibility, and the corresponding activations in the DLPFC, FPC, and OFC.

Table 4 shows the aforementioned correlation analysis results from the serial multiple-mediator model. For inhibitory control, NoGo stimulus accuracy and DLPFC activation had significant mediating effects on the association between exercise and Internet craving; the mediation magnitudes were 10.72 % and 63.69 %, respectively, though the serial mediating effect was not established. For working memory, the mediating effects and the serial mediating effect of DLPFC activation and accuracy were all significant. Still, there were no such effects in the activations of FPC and OFC. For cognitive flexibility, the mediating effects of activation in DLPFC, OFC, and RT were significant. Furthermore, two serial mediating-effect tests (DLPFC activation and RT; OFC activation and RT) also revealed significant changes; however, FPC activation did not mediate significantly.

4. Discussion

4.1. Influence of exercise intensity on enhancing executive control and alleviating internet craving of college students with ID

The present study found that the Internet craving scores of college students with ID were significantly reduced after acute exercise in both the HIG and the MIG groups, with high-intensity exercise eliciting a larger effect. Similar results were observed in most of the PFC activation during the three tasks. The moderate intensity, however, showed higher accuracy in the Go/NoGo and 2-back tasks and shorter RTs in the More-Odd shifting task. The effect sizes ranged from 0.5 to 2.98, with the majority falling between 0.8 and 1.5, in line with the moderate-to-large effect sizes reported by Yan et al. (2025).

While the craving and brain activation data were reported to support the predictions of drive theories (Volkow & Fowler, 2000), other researchers claimed that high-intensity aerobic exercise may be the most potent stimulator of adult neurogenesis (Jiang et al., 2024; Park et al., 2021). The behavioural data were also reported to conform to predictions of the inverted U hypothesis. According to the Inverted-U hypothesis, moderate-intensity exercise may have coincided with the optimal level of arousal, sufficient to activate the brain without depleting cognitive resources to an excessive degree (Srensen et al., 2022), thereby achieving optimal performance in executive control tasks. Nevertheless, the Inverted-U hypothesis is not a theoretical explanation; it is simply a descriptive relationship for the general situation. The motor cortex was considered being closely inter-connected with prefrontal and other brain regions (Du et al., 2019) and addictive individuals could have the less activated PFC (Solly et al., 2022). Thus, a possibility of such conditions could be, within an acceptable limitation, the higher intensity exercise, the greater activation in motor cortex and then, the more significant improvements for PFC activation. Furthermore, the PFC is also involved with drive and compulsive repetitive behaviours (Volkow & Fowler, 2000). Thus, greater PFC activation after high-intensity exercise may lead to better alleviation of craving, as shown in the present study.

Given the inconsistent results from investigations of executive control tasks and PFC activation, the neurophysiological basis may be more complex than a simple arousal model. In the perception-action cycle, the PFC was proposed to provide goal-directed feedback to motor systems but not to act independently (Chen et al., 2021). It is a key neural substrate for response selection and its associated capacity limits (Tan et al.,

Table 2
Analysed results for Internet craving score and measured variables in executive control tasks.

Variable	*Group* (N)	Pre-test Mean ± SD	Post-test Mean ± SD	Difference	F[b]	P[b]	Cohen's *d*	Result of two-way ANOVA
Internet craving score								
	HIG (*n* = 20)	7.23 ± 1.16	2.52 ± 1.12	4.71 ± 1.59	234.62	≤0.001	2.98	Time: F = 206.45, p ≤ 0.001, η_p^2=0.78;
	MIG (n = 20)	6.30 ± 1.82	3.15 ± 1.42	3.16 ± 1.40	105.27	≤0.001	2.31	Intensity: F = 7.51, *p* = 0.001, η_p^2=0.21;
	NEG(n = 20)	6.21 ± 2.01	6.42 ± 1.82	−0.21 ± 1.10	0.48	0.492		Interaction: F = 66.96, *p* ≤ 0.001, η_p^2=0.70
Go/NoGo task								
Accuracy of NoGo stimulus (%)	HIG (n = 20)	81.56 ± 13.52	87.81 ± 9.18	6.25 ± 12.82	5.47	0.023	0.50	Time: F = 9.98, *p* = 0.003, η_p^2=0.15;
	MIG (n = 20)	83.44 ± 15.87	92.50 ± 7.44	9.06 ± 13.06	11.50	0.001	0.79	Intensity: F = 2.13, *p* = 0.128, η_p^2=0.07;
	NEG (n = 20)	81.94 ± 9.37	81.25 ± 10.92	0.69 ± 9.68	0.07	0.798		Interaction: F = 3.53, *p* = 0.036, η_p^2=0.11
DLPFC[a]	HIG (n = 20)	−1.37 ± 4.66	7.57 ± 3.75	8.94 ± 6.22	42.62	≤0.001	1.56	Time: F = 53.09, p ≤ 0.001, η_p^2=0.48;
	MIG (n = 20)	1.36 ± 4.25	9.91 ± 4.22	8.55 ± 6.10	38.82	≤0.001	1.46	Intensity: F = 17.63, p ≤ 0.001, η_p^2=0.38;
	NEG (n = 20)	−0.16 ± 4.74	−0.34 ± 4.67	0.18 ± 6.09	0.02	0.898		Interaction: F = 14.11, p ≤ 0.001, η_p^2=0.33
FPC[a]	HIG (n = 20)	0.14 ± 3.62	1.03 ± 3.38					Time: F = 2.78, *p* = 0.101, η_p^2=0.05;
	MIG (n = 20)	−0.59 ± 2.61	2.50 ± 4.38					Intensity: F = 1.38, *p* = 0.261, η_p^2=0.05;
	NEG (n = 20)	−0.44 ± 4.19	−0.76 ± 6.13					Interaction: F = 1.87, *p* = 0.164, η_p^2=0.06
OFC[a]	HIG (n = 20)	0.15 ± 5.28	0.16 ± 3.49	0.01 ± 6.08	0	0.995		Time: F = 2.95, *p* = 0.091, η_p^2=0.05;
	MIG (n = 20)	−1.70 ± 3.91	2.67 ± 4.54	4.37 ± 4.48	9.38	0.003	0.67	Intensity: F = 1.09, *p* = 0.344, η_p^2=0.04;
	NEG (n = 20)	−1.31 ± 5.77	−1.44 ± 7.81	0.13 ± 8.07	0.01	0.924		Interaction: F = 3.22, *p* = 0.047, η_p^2=0.10
2-back task								
Accuracy (%)	HIG (n = 20)	84.30 ± 12.70	92.60 ± 5.35	8.30 ± 9.39	18.11	≤0.001	1.20	Time: F = 33.84, p ≤ 0.001, η_p^2=0.37;
	MIG (n = 20)	81.35 ± 12.51	91.30 ± 7.69	9.95 ± 8.67	26.03	≤0.001	1.30	Intensity: F = 0.36, *p* = 0.700, η_p^2=0.01;
	NEG (n = 20)	87.20 ± 8.56	88.60 ± 6.48	1.40 ± 8.06	0.52	0.476		Interaction: F = 5.41, *p* = 0.007, η_p^2=0.16
RT (ms)	HIG (n = 20)	848.51 ± 127.47	758.65 ± 110.68					Time: F = 26.21, p ≤ 0.001, η_p^2=0.32;
	MIG (n = 20)	850.56 ± 151.59	774.05 ± 162.91					Intensity: F = 0.03, *p* = 0.973, η_p^2≤0.01;
	NEG (n = 20)	826.51 ± 122.89	792.48 ± 88.47					Interaction: F = 1.67, *p* = 0.198, η_p^2=0.06
DLPFC[a]	HIG (n = 20)	−0.48 ± 3.97	4.08 ± 2.40	4.56 ± 3.21	28.04	≤0.001	1.53	Time: F = 15.64, p ≤ 0.001, η_p^2=0.22;
	MIG (n = 20)	0.83 ± 2.66	3.23 ± 3.77	2.40 ± 4.33	10.60	0.005	0.64	Intensity: F = 1.79, *p* = 0.176, η_p^2=0.06;
	NEG (n = 20)	1.19 ± 3.71	−0.15 ± 2.84	1.34 ± 3.38	2.41	0.109		Interaction: F = 13.20, p ≤ 0.001, η_p^2=0.32
FPC[a]	HIG (n = 20)	2.21 ± 4.39	2.40 ± 3.47					Time: F = 0.13, *p* = 0.720, η_p^2≤0.01;
	MIG (n = 20)	2.50 ± 4.86	2.01 ± 4.74					Intensity: F = 1.41, *p* = 0.253, η_p^2=0.05;
	NEG (n = 20)	1.25 ± 4.38	0.69 ± 3.05					Interaction: F = 0.09, *p* = 0.915, η_p^2≤0.01
OFC[a]	HIG (n = 20)	0.81 ± 4.79	2.89 ± 3.94					Time: F = 2.75, *p* = 0.103, η_p^2=0.05;
	MIG (n = 20)	1.43 ± 2.74	3.22 ± 4.90					Intensity: F = 0.13, *p* = 0.877, η_p^2=0.01;
	NEG (n = 20)	1.76 ± 5.05	1.95 ± 5.69					Interaction: F = 0.52, *p* = 0.599, η_p^2=0.02
More-Odd shifting task								

(*continued on next page*)

Table 2 (*continued*)

Variable	*Group* (N)	Pre-test Mean ± SD	Post-test Mean ± SD	Difference	F[b]	P[b]	Cohen's *d*	Result of two-way ANOVA
RT (ms)	HIG (n = 20)	250.51 ± 101.48	135.74 ± 62.54	114.76 ± 117.24	24.60	≤0.001	0.98	Time: F = 31.20, p ≤ 0.001, η_p^2=0.35;
	MIG (n = 20)	241.53 ± 90.20	152.18 ± 79.98	89.35 ± 72.15	14.91	≤0.001	1.25	Intensity: F = 1.45, *p* = 0.244, η_p^2=0.05;
	NEG (n = 20)	237.63 ± 110.93	217.82 ± 70.30	19.82 ± 114.78	0.73	0.395		Interaction: F = 4.51, *p* = 0.015, η_p^2=0.14
Accuracy (%)	HIG (n = 20)	1.25 ± 6.66	3.00 ± 8.18					Time: F = 0.10, *p* = 0.758, η_p^2≤0.01;
	MIG (n = 20)	6.00 ± 9.54	3.50 ± 6.51					Intensity: F = 1.43, *p* = 0.248, η_p^2=0.05;
	NEG (n = 20)	4.25 ± 6.13	3.75 ± 5.82					Interaction: F = 0.83, *p* = 0.440, η_p^2=0.03
DLPFC[a]	HIG (n = 20)	−2.01 ± 4.29	4.62 ± 3.24	6.63 ± 5.09	32.38	≤0.001	1.31	Time: F = 28.53, p ≤ 0.001, η_p^2=0.33;
	MIG (n = 20)	0.26 ± 4.79	4.46 ± 2.76	4.20 ± 5.84	12.98	0.001	0.82	Intensity: F = 5.33, *p* = 0.008, η_p^2=0.16;
	NEG (n = 20)	−0.80 ± 4.86	−0.85 ± 4.13	0.05 ± 4.64	≤0.01	0.967		Interaction: F = 8.42, p = 0.001, η_p^2=0.23
FPC [a]	HIG (n = 20)	−0.06 ± 3.70	2.69 ± 5.31	2.75 ± 7.13	3.25	0.077		Time: F = 4.12, p = 0.047, η_p^2=0.07;
	MIG (n = 20)	0.50 ± 5.14	4.40 ± 3.64	3.90 ± 6.41	6.55	0.013	0.63	Intensity: F = 3.65, *p* = 0.032, η_p^2=0.11;
	NEG (n = 20)	0.42 ± 4.55	−0.87 ± 5.18	−1.29 ± 6.90	0.72	0.401		Interaction: F = 3.20, *p* = 0.048, η_p^2=0.10
OFC[a]	HIG (n = 20)	−2.91 ± 4.91	4.69 ± 3.08	7.60 ± 6.25	29.52	≤0.001	1.45	Time: F = 36.47, p ≤ 0.001, η_p^2=0.39;
	MIG (n = 20)	−0.59 ± 5.90	4.28 ± 3.77	4.87 ± 6.35	12.14	0.001	0.78	Intensity: F = 2.39, p = 0.101, η_p^2=0.08;
	NEG (n = 20)	−1.66 ± 5.19	0.50 ± 4.87	2.16 ± 6.16	2.38	0.125		Interaction: F = 3.78, *p* = 0.029, η_p^2=0.18

Note:

[a] The changes in concentration of oxygenated hemoglobin ($\times 10^{-7}$ mmol/L).

[b] The F and *p* values were determined by simple effect analysis. Values are means±SD. A *p*-value ≤0.05 was considered to be statistically significant.

2021). That could be, the higher the intensity of an exercise, the more resources, including the PFC, might be needed to devote to these stimulus-responsive evaluation and classification (Martínez et al., 2023). Accordingly, a possible explanation of our results, showing a high intensity exercise having a better effect on PFC activation but not being the optimal choice for task performance of executive control, might be due to this high intensity exercise-induced arousal assisting and promoting sensory processes that were implicated in stimulus detection, albeit without having any effect on the executive processing.

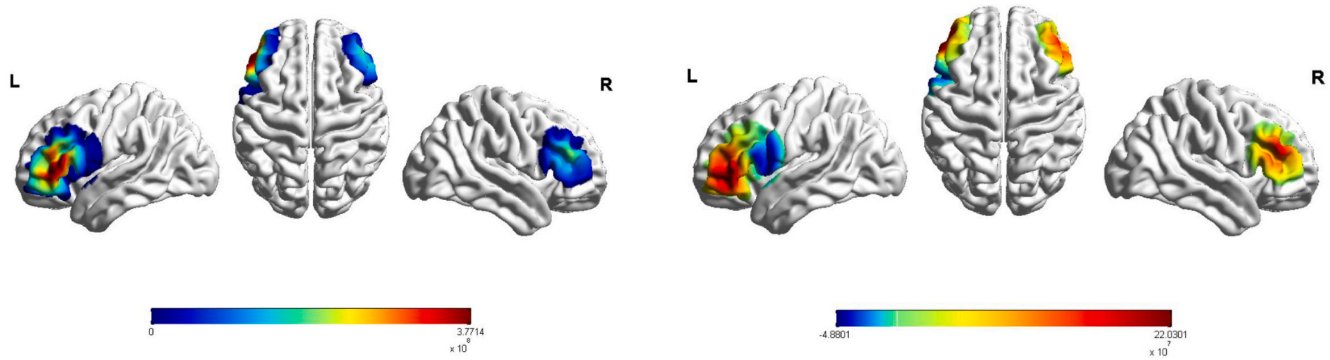
4.2. *Mediation effects of PFC activation and executive control*

In this study, we applied the three classic paradigms to explore the three components of executive control. The corresponding activation in the PFC was measured using synchronous fNIRS. The results of a serial multiple-mediator analysis suggested that acute aerobic exercise could indirectly alleviate Internet craving among college students with ID. The indirect alleviation may go through with multiple possibilities and processes that were hypothesized as follows: 1) improved DLPFC activation; 2) improved inhibitory control; 3) improved DLPFC activation, and then enhanced working memory; 4) improved DLPFC activation, and then enhanced cognitive flexibility; and 5) improved OFC activation, and then enhanced cognitive flexibility.

4.2.1. *Mediation effects of DLPFC activation and executive control*

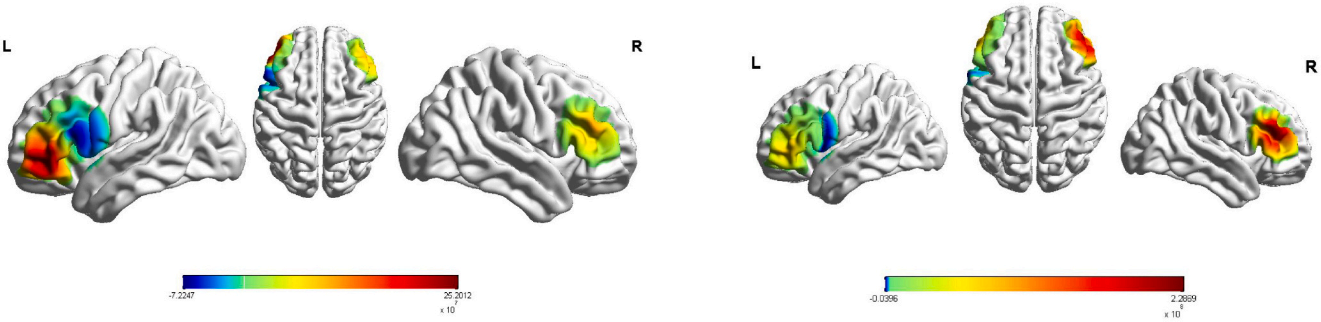
The present study added new evidence supporting the positive effects of aerobic exercise on Internet craving and DLPFC activation. The DLPFC is a core region of the executive control network and top-down regulation of emotion-related craving (Qi et al., 2022), and its targeted modulation of DLPFC activation and related functional networks correlates with craving reduction (Su et al., 2017). Anatomically, the DLPFC lies in the anterior frontal gyrus of humans and has widespread structural connectivity with the pre-supplementary motor area, supplementary motor area, and primary motor cortex (Jung et al., 2022). Given these findings from our study, the DLPFC may be activated by receiving sensorimotor signals from the motor cortex, then initiate inhibitory control, working memory, and cognitive flexibility, and finally ameliorate Internet craving. In fact, this conjecture is consistent with the reports of most previous clinical trials targeting the DLPFC that investigated its potential effectiveness for individuals with substance use disorders (Soleimani et al., 2024).

Deficits or impairments in inhibitory control may result in uncontrolled impulsive processing that has been widely observed in addictive individuals for nicotine, alcohol, cocaine, and Internet games (Batschelet et al., 2021; Lü et al., 2022; Wilczkowski et al., 2023; Zhou, Zhang, et al., 2021). The dual process model of addiction posits that the interaction between the reflective and impulsive processing systems is responsible for addictive behaviours. In contrast, the reflective processing system aids rational decision-making processes based on long-term benefits, and the impulsive processing system responds quickly to processes of physiological arousal, cravings, and cognitive biases (Chia & Zhang, 2020). Inhibitory control was reported to be mediated mainly by a right-lateralized fronto-striatal-parietal network, particularly in the DLPFC, OFC, posterior and anterior cingulate gyri, basal ganglia, and parietal structures (Stein et al., 2021). In this study, DLPFC activation and NoGo stimulus accuracy were positively correlated, though the serial multiple-mediator effect was not confirmed. One potential possibility is that the mediating effect of DLPFC activation on inhibitory control was too small to be detected. Future research should further explore the mediating roles of other parts of the fronto-striatal-parietal network that may differentially respond to various exercises at different intensities.



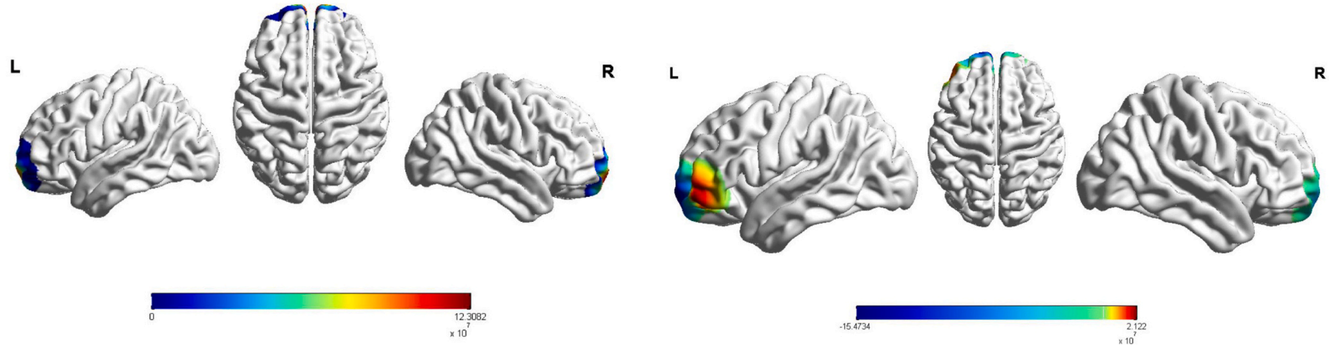
A)-DLPFC, High Intensity, Pre-test

B)-DLPFC, High Intensity, Post-test



C)-DLPFC, Moderate Intensity, Pre-test

D)-DLPFC, Moderate Intensity, Post-test



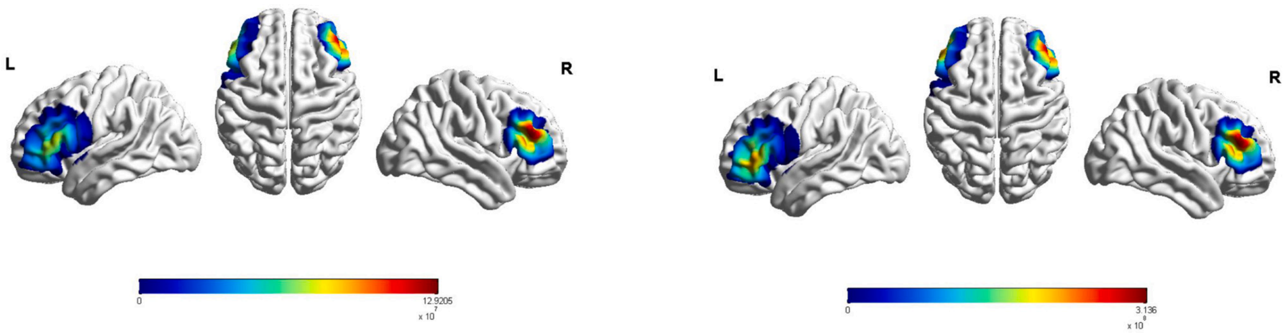
E)-OFC, Moderate Intensity, Pre-test

F)-OFC, Moderate Intensity, Post-test

Fig. 3. Activation in DLPFC and OFC for subjects in the inhibitory control testing.

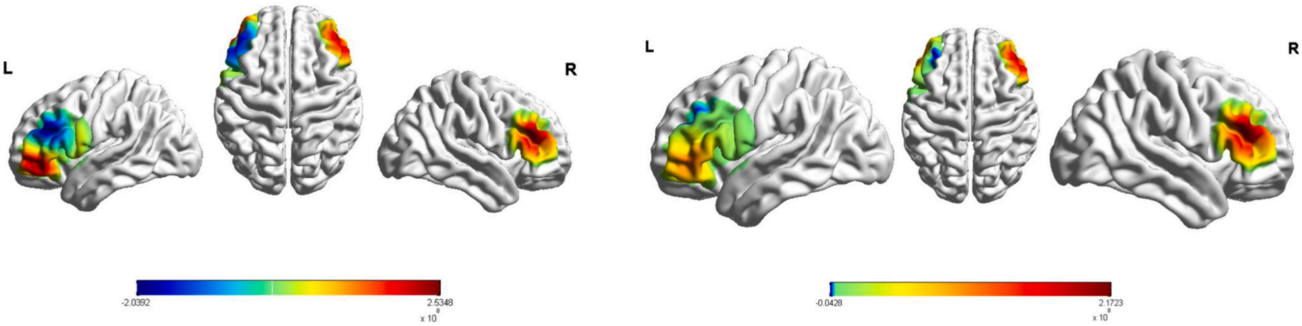
Some studies have shown that individuals with IA have deficits in working memory (Khanbabaei et al., 2022). The disability to suppress attention to addictive information and delete no-longer-relevant information from working memory to maintain the intended actions may be the essential cause for behavioural addictions (Oh et al., 2024; Zhou et al., 2016). Available experimental evidence suggests that aerobic exercise is an effective behavioural strategy for improving working memory performance (Mou et al., 2023). The DLPFC has been considered pivotal in the domain of working memory (Oh et al., 2024). In the present study, ID participants in both the HIG and MIG groups showed the enhanced working memory and DLPFC activation following acute cycling exercise. It is possible that acute exercise activates the DLPFC through anatomical and functional connections with motor-related cortex, then manipulates motor-related information rather than Internet-related information, enabling individuals with ID to focus on physical activities and gain cognitive benefits, such as reduced psychological craving. Given that working memory and other high-level cognitive processes are supported by interregional communication among many brain areas, future research is needed to identify and verify the specific functional connectivity.

Cognitive flexibility represents the ability to adapt one's thinking and behavior in responding to environmental demands (Uddin, 2021). It is multifaceted and involves a range of skills, including attention shifting, strategy updating, responding to feedback, reversal learning, exploration, and task switching (Tong et al., 2024). However, impaired cognitive flexibility can occur in people with IA and other types of behavioural addictions (Dong et al., 2014). This was the case in our study, where subjects could not shift their attention away from the Internet before exercise but experienced intense cravings for it. Fortunately, a positive impact of exercise on cognitive flexibility was found in our studies and in previous studies (Li et al., 2022; Shukla et al., 2020). Masley et al. (2009) proposed central mechanisms underlying improvements in cognitive flexibility following exercise and hypothesized that these central mechanisms were affected in the brain, particularly in the PFC. Thus, our results suggest that changes in DLPFC and OFC activation after acute cycling exercise may mediate the effect on



A)-DLPFC, High Intensity, Pre-test

B)-DLPFC, High Intensity, Post-test



C)-DLPFC, Moderate Intensity, Pre-test

D)-DLPFC, Moderate Intensity, Post-test

Fig. 4. Activation in DLPFC for subjects in the working memory testing.

cognitive flexibility and thereby alleviate Internet craving.

Regarding FPC results, significant negative correlations with Internet craving and significant positive correlations with accuracy were observed. These findings are consistent with converging evidence for the FPC as a target for neuromodulation in addiction treatment (Rolls et al., 2024; Soleimani et al., 2024). However, the mediating effect of FPC activation was not revealed. A possible explanation is that the FPC lacks direct connectivity with the premotor cortex (Rolls et al., 2024); thus, exercise may have no direct effect on the FPC.

4.2.2. *Mediation effects of OFC activation and cognitive flexibility*

It has been observed that signals occurring during craving were mainly processed by the OFC and responded to input from the DLPFC (Kroczek et al., 2016; Qi et al., 2022). The OFC has been considered a neural marker of craving and recovery in drug use disorder (Du et al., 2019; Kronberg et al., 2025), due to highlighting the OFC dysfunction in maladaptive reward processing, salience attribution, and decision-making (Knudsen & Wallis, 2022). There may be functional subdivisions within the OFC relevant to choosing among rewarding options (Wang et al., 2022) and to mediating reversal learning (Tuite et al., 2022), a form of cognitive flexibility necessary for adapting to a changing environment. OFC lesions may impair mental flexibility, and such deficits may be key to assessing and accumulating evidence to inform a rule-guided decision (Mansouri et al., 2024; Wang et al., 2022). These findings together suggest that engagement in exercise across different intensities could have differential cognitive benefits and influence Internet craving.

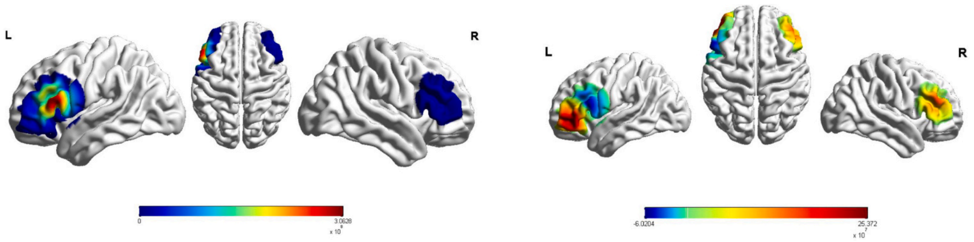
4.3. *Study limitations*

This research employed a serial multiple-mediator model to comprehensively assess the effect and potential mechanisms of acute aerobic exercise on Internet craving in individuals with Internet dependency. Notably, the study used fNIRS, which provided stronger visual evidence and a novel insight into the interplay between acute aerobic exercise and Internet craving, as well as the mediating role of exercise-enhanced prefrontal cortex and improvements in executive control.

Despite these promising findings, it is necessary to acknowledge the limitations of this study. First, acute cycling exercise elicited brief changes, while participants in this study were recruited only from a university, which may limit the generalizability of our findings. Further research should adopt randomized, controlled clinical trials with long-term follow-up, include diverse exercise forms, use larger sample sizes, and encompass more varied populations. Second, because Internet craving scores were obtained through self-report and no explicit Internet-related cues were provided, participants could be influenced by the experimental context and honestly report their feelings and perceptions, possibly decreasing the validity of these results. Future research should adopt more precise, objective methods to measure physiological indicators —such as heart rate, blood pressure, and eye movements —to assess this craving. Thirdly, anatomical or functional connections of the brain were used in some part to explain the effect of acute exercise or the mediating role of PFC activation. Due to limitations in fNIRS, however, this connectivity was not tested in the present study. Future research could employ additional approaches to provide a more direct and accurate inspection. Finally, as the speed-accuracy trade-off is prevalent in experiments measuring RT, our results may also be affected, and future research may consider a larger sample size or using more comprehensive measuring variables.

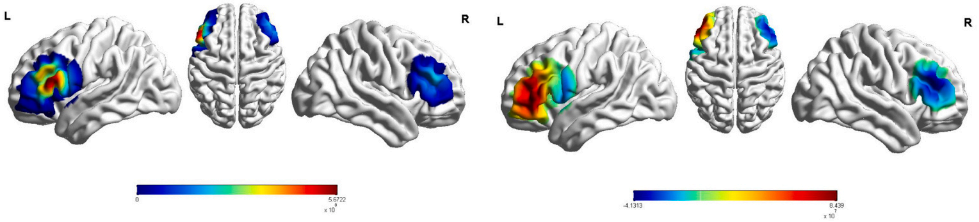
5. Conclusions

Our study demonstrated that acute aerobic cycling at varying intensities effectively reduced Internet craving among college students with ID. The findings highlighted that a 30-min session of high-intensity exercise could elicit a larger effect on Internet craving and activation in the DLPFC and OFC. In contrast, moderate-intensity exercise could have



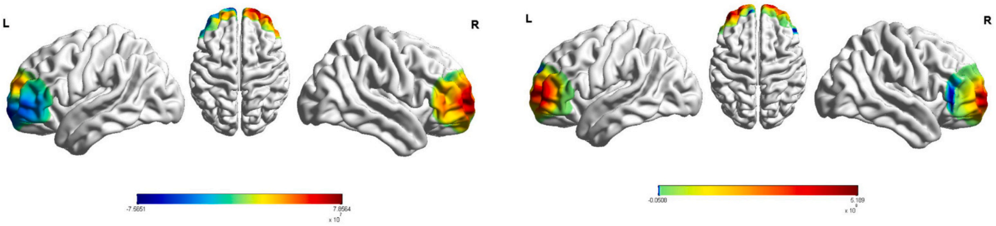
A)-DLPFC, High Intensity, Pre-test

B-DLPFC, High Intensity, Post-test



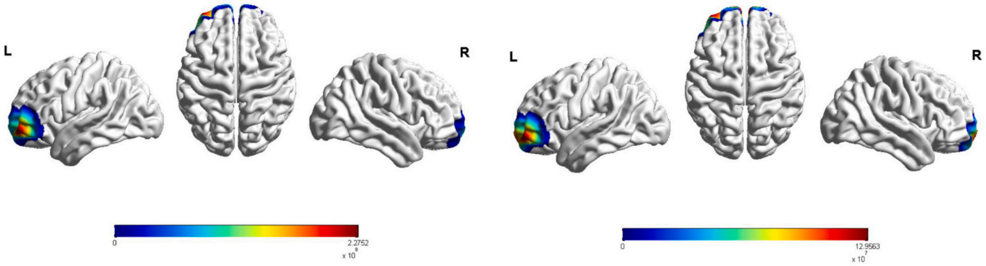
C)-DLPFC, Moderate Intensity, Pre-test

D)DLPFC, Moderate Intensity, Post-test



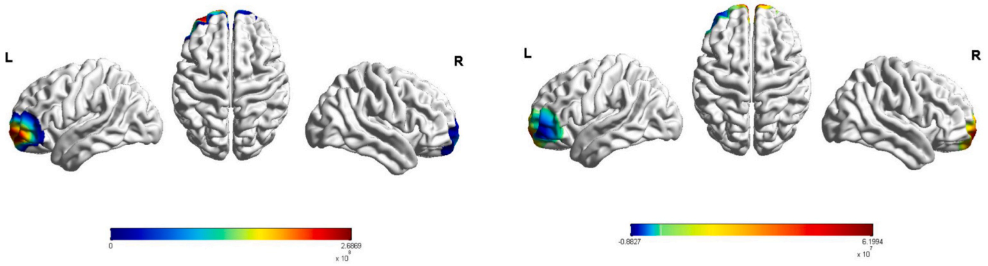
E)-FPC, Moderate Intensity, Pre-test

F)-FPC, Moderate Intensity, Post-test



G)-OFC, High Intensity, Pre-test

H)-OFC, High Intensity, Post-test



I)-OFC, Moderate Intensity, Pre-test

J)-OFC, Moderate Intensity, Post-test

Fig. 5. Activation in DLPFC, FPC and OFC for subjects in the cognitive flexibility testing.

a greater impact on executive control performance. Such exercise-induced benefits may be maximized by the promoted executive control and mediated by enhanced neurocognitive activations in the DLPFC and OFC. Importantly, the observed improvements in cognitive and PFC functions, enhanced following exercise, are pivotal in alleviating the Internet-induced craving and could have clinical benefits. The mediational role and related regulatory mechanisms underlying the functional changes and improvements induced by exercise involve enhanced executive control and increased activation in the DLPFC and OFC, with cognitive impacts on Internet craving. Based on their individual needs, college students with ID may choose to do the high- and/or moderate-intensity exercise by considering our study results: an acute high-intensity aerobic exercise can be good for reducing psychological cravings and performing a moderate-intensity aerobic exercise can be more beneficial to positive cognitive activities.

Table 3
The correlation coefficient between exercise, Internet craving, executive control, and prefrontal cortex activation.

	exercise	craving	NoGo accuracy	RT	Accuracy	RT ^{g}	Accuracy ^{g}
craving	-0.538^{**}						
NoGo accuracy	$0.205^{**\,a}$	$-0.188^{*\,a}$					
DLPFC ^{d}	$0.475^{**\,a}$	$-0.726^{**\,a}$	$0.258^{**\,a}$				
FPC ^{d}	0.144^{a}	-0.148^{a}	$0.426^{**\,a}$				
OFC ^{d}	0.131^{a}	-0.161^{a}	$0.418^{**\,a}$				
RT	$-0.254^{**\,b}$	$0.264^{**\,b}$					
Accuracy	$0.332^{**\,b}$	$-0.323^{**\,b}$					
DLPFC ^{e}	$0.260^{**\,b}$	$-0.606^{**\,b}$		-0.081^{b}	$0.212^{*\,b}$		
FPC ^{e}	-0.035^{b}	$-0.233^{*\,b}$		0.012^{b}	$0.219^{*\,b}$		
OFC ^{e}	0.148^{b}	$-0.214^{*\,b}$		0.107^{b}	$0.323^{**\,b}$		
RT ^{g}	$-0.387^{**\,c}$	$0.6644^{**\,c}$					
Accuracy ^{g}	-0.029^{c}	-0.028^{c}					
DLPFC ^{f}	$0.377^{**\,c}$	$-0.631^{**\,c}$				$-0.532^{**\,c}$	-0.083^{c}
FPC ^{f}	$0.184^{*\,c}$	$-0.234^{*\,c}$				$-0.220^{*\,c}$	-0.018^{c}
OFC ^{f}	$0.451^{**\,c}$	$-0.738^{**\,c}$				$-0.680^{**\,c}$	0.017^{c}

Note:
* $p < 0.05$.
** $p < 0.01$.
[a] The correlation in Go/NoGo task.
[b] The correlation in 2-back task.
[c] The correlation in More-Odd shifting task.
[d] The changes in oxygenated hemoglobin concentration in Go/NoGo task.
[e] The changes in oxygenated hemoglobin concentration in 2-back task.
[f] The changes in oxygenated hemoglobin concentration in More-Odd shifting task.
[g] The difference of RT or accuracy between switch trials and nonswitch trials in More-Odd shifting task.

Table 4
Mediation analysis between exercise and Internet craving with executive control and the corresponding activation in DLPFC, FPC, and OFC.

	Mediation	Proportion Mediated (%)	*β*	*p*	*LLCI*	*ULCI*
	Exercise→Internet Craving		−1.30	≤0.001	−1.61	−0.98
Go/NoGo task	Exercise→DLPFC ^{a} → Internet Craving	63.69	−1.25	0.020	−1.48	−0.25
	Exercise→NoGo Accuracy→Internet Craving	10.72	−0.33	0.031	−0.34	−0.01
	Exercise→DLPFC ^{a} → NoGo Accuracy→Internet Craving	2.71		0.746	−0.28	−0.13
2-back task	Exercise→FPC ^{a} → Internet Craving	0.93	−0.18	0.715	−0.06	0.11
	Exercise→OFC ^{a} → Internet Craving	2.85	−0.13	0.365	−0.13	0.04
	Exercise→DLPFC ^{a} → Internet Craving	20.51	−0.50	0.005	−0.45	−0.11
	Exercise→Accuracy→Internet Craving	19.04	−0.36	0.003	−0.44	−0.07
	Exercise→DLPFC ^{a} → Accuracy →Internet Craving	26.99		0.016	−0.95	−0.04
More-Odd shifting task	Exercise→DLPFC ^{a} → Internet Craving	21.28	−0.09	0.002	−0.51	−0.15
	Exercise→RT → Internet Craving	41.17	0.48	0.006	−0.48	−0.09
	Exercise→DLPFC ^{a} → RT → Internet Craving	10.10		0.026	−0.30	−0.03
	Exercise→FPC ^{a} → Internet Craving	3.24	−0.11	0.279	−0.13	0.03
	Exercise→OFC ^{a} → Internet Craving	26.06	−0.33	0.005	−0.56	−0.16
	Exercise→RT → Internet Craving	13.72	0.45	0.048	−0.37	−0.02
	Exercise→OFC ^{a} → RT → Internet Craving	15.65		0.009	−0.39	0.05

Note: The Sobel test was used to determine the *p*-values. LLCI = Lower Level of Confidence Interval; ULCI=Upper Level of Confidence Interval. [a] The changes in concentration of oxygenated hemoglobin.

CRediT authorship contribution statement

Hainan Fan: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Peng Wang:** Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Yingying Zhang:** Visualization, Investigation, Formal analysis, Data curation. **Guoyuang Huang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Formal analysis, Conceptualization. **Zhimin Nie:** Visualization, Formal analysis, Data curation. **Haize Liu:** Visualization, Formal analysis, Data curation. **Xuejing Wu:** Investigation, Data curation. **Xianzhi Jin:** Investigation, Data curation. **Zhao Xu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Data availability

All data generated or analysed during this study are included in this published article.

References

Bai, Y., & Fan, F. (2005). A study on the internet dependence of college students: The revising and applying of a measurement. *Psychological Development and Education, 2005*(04), 99–104. https://doi.org/10.16187/j.cnki.issn1001-4918.2005.04.019

Batschelet, H. M., Tschuemperlin, R. M., Moggi, F., Soravia, L. M., Koenig, T., Pfeifer, P., Roesner, S., Keller, A., & Stein, M. (2021). Neurophysiological correlates of alcohol-specific inhibition in alcohol use disorder and its association with craving and relapse. *Clinical Neurophysiology, 132*(6), 1290–1301. https://doi.org/10.1016/j.clinph.2021.02.389

Brand, M. (2022). Can internet use become addictive? *Science, 376*(6595), 798–799. https://doi.org/10.1126/science.abn4189

Brand, M., Wegmann, E., Stark, R., Müller, A., Wölfling, K., Robbins, T. W., & Potenza, M. N. (2019). The interaction of person-affect-cognition-execution (I-PACE) model for addictive be haviors: Update, generalization to addictive behaviors beyond internet-use disorders, and specification of the process character of addictive behaviors. *Neuroscience & Biobehavioral Reviews, 104*, 1–10. https://doi.org/10.1016/j.neubiorev.2019.06.032

Chen, T., Wang, H., Wang, X., Zhu, C., Zhang, L., Wang, K., & Yu, F. (2021). Transcranial direct current stimulation of the right dorsolateral prefrontal cortex improves response inhibition - sciencedirect. *International Journal of Psychophysiology, 162*, 34–39. https://doi.org/10.1016/j.ijpsycho.2021.01.014

Cheng, Y. S., Ko, H. C., Sun, C. K., & Yeh, P. Y. (2021). The relationship between delay discounting and internet addiction: A systematic review and meta-analysis. *Addictive Behaviors, 114*(19), Article 106751. https://doi.org/10.1016/j.addbeh.2020.106751

Chia, D. X. Y., & Zhang, M. W. B. (2020). A scoping review of cognitive bias in internet addiction and internet gaming disorders. *International Journal of Environmental Research and Public Health, 17*(1), 373. https://doi.org/10.3390/ijerph17010373

Chu, C. H., Alderman, B. L., Wei, G. X., & Chang, Y. K. (2015). Effects of acute aerobic exercise on motor response inhibition: An erp study using the stop-signal task. *Journal of Sport and Health Science, 4*(1), 73–81. https://doi.org/10.1016/j.jshs.2014.12.002

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Dong, G., Lin, X., Zhou, H., & Lu, Q. (2014). Cognitive flexibility in internet addicts: fMRI evidence from difficult-to-easy and easy-to-difficult switching situations. *Addictive Behaviors, 39*(3), 677–683. https://doi.org/10.1016/j.addbeh.2013.11.028

Du, X., Choa, F. S., Chiappelli, J., Wisner, K. M., Wittenberg, G., Adhikari, B., Bruce, H., Rowland, L. M., Kochunov, P., & Hong, L. E. (2019). Aberrant middle prefrontal-motor cortex connectivity mediates motor inhibitory biomarker in schizophrenia. *Biological. Psychiatry, 85*, 49–59. https://doi.org/10.1016/j.biopsych.2018.06.007

Engeli, E. J. E., Zoelch, N., Hock, A., Nordt, C., & Herdener, M. (2021). Impaired glutamate homeostasis in the nucleus accumbens in human cocaine addiction. *Molecular Psychiatry, 26*, 5277–5285. https://doi.org/10.1038/s41380-020-0828-z

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191. https://doi.org/10.3758/BF03193146

Fishburn, F. A., Ludlum, R. S., Vaidya, C. J., & Medvedev, A. V. (2019). Temporal derivative distribution repair (tddr): A motion correction method for fnirs. *Neuroimage, 184*, 171–179. https://doi.org/10.1016/j.neuroimage.2018.09.025

Gagnon, L., Perdue, K., Greve, D. N., Goldenholz, D., Kaskhedikar, G., & Boas, D. A. (2011). Improved recovery of the hemodynamic response in diffuse optical imaging using short optode separations and state-space modeling. *Neuroimage, 56*(3), 1362–1371. https://doi.org/10.1016/j.neuroimage.2011.03.001

Haasova, M., Warren, F. C., Ussher, M., Janse Van Rensburg, K., Faulkner, G., Cropley, M., … Taylor, A. (2014). The acute effects of physical activity on cigarette cravings: Exploration of potential moderators, mediators and physical activity attributes using individual participant data (ipd) meta-analyses. *Psychopharmacology, 231*(7), 1267–1275. https://doi.org/10.1007/s00213-014-3450-4

Hallgren, M., Herring, M. P., Vancampfort, D., Hoang, M. T., & Abrantes, A. M. (2021). Changes in craving following acute aerobic exercise in adults with alcohol use disorder. *Journal of Psychiatric Research, 142*(1), 243–249. https://doi.org/10.1016/j.jpsychires.2021.08.007

Jiang, H., Kimura, Y., Inoue, S., Li, C., Hatakeyama, J., Wakayama, M., Takamura, D., & Moriyama, H. (2024). Effects of different exercise modes and intensities on cognitive performance, adult hippocampal neurogenesis, and synaptic plasticity in mice. *Experimental Brain Research, 242*(7), 1709–1719. https://doi.org/10.1007/s00221-024-06854-3

Jung, J. Y., Ralph, M. A. L., & Jackson, R. L. (2022). Subregions of dlpfc display graded yet distinct structural and functional connectivity. *Journal of Neuroscience, 42*(15), 3241–3252. https://doi.org/10.1523/JNEUROSCI.1216-21.2022

Khanbabaei, S., Abdollahi, M. H., & Shahgholian, M. (2022). The predictive role of working memory and impulsivity in internet addiction, an investigation about the mediating role of time perception. *Personality and Individual Differences, 185*, Article 111280. https://doi.org/10.1016/j.paid.2021.111280

Knudsen, E. B., & Wallis, J. D. (2022). Taking stock of value in the orbitofrontal cortex. *Nature Reviews Neuroscience, 23*(7), 428–438. https://doi.org/10.1038/s41583-022-00589-2

Koob, G. F. (2021). Drug addiction: Hyperkatifeia/negative reinforcement as a framework for medications development. *Pharmacological Reviews, 73*(1), 163–201. https://doi.org/10.1124/pharmrev.120.000083

Kroczek, A. M., Häußinger, F. B., Rohe, T., Schneider, S., Plewnia, C., Batra, A., Fallgatter, A. J., & Ehlis, A. C. (2016). Effects of transcranial direct current stimulation on craving, heart-rate variability and prefrontal hemodynamics during smoking cue exposure. *Drug and Alcohol Dependence, 168*, 123–127. https://doi.org/10.1016/j.drugalcdep.2016.09.006

Kronberg, G., Ceceli, A. O., Huang, Y., Gaudreault, P., King, S. G., McClain, N., Alia-Klein, N., & Goldstein, R. Z. (2025). Shared orbitofrontal dynamics to a drug-themed movie track craving and recovery in heroin addiction. *Brain, 148*(5), 1778–1788. https://doi.org/10.1093/brain/awae369

Li, M., Jin, J., Zhai, X., Zhu, T., Zhao, X., & Wang, D. (2025). Acute aerobic exercise ameliorates craving and attentional function in individuals with methamphetamine use disorders. *Physiology & Behavior, 290*, Article 114775. https://doi.org/10.1016/j.physbeh.2024.114775

Li, X., Geng, D., Wang, S., & Sun, G. (2022). Aerobic exercises and cognitive function in post-stroke patients: A systematic review with meta-analysis. *Medicine, 101*(41), Article e31121. https://doi.org/10.1097/MD.0000000000031121

Lü, W., Wu, Q., Liu, Y., Wang, Y., Wei, Z., Li, Y., … Zhang, X. (2022). No smoking signs with strong smoking symbols induce weak cravings: An fmri and eeg study. *NeuroImage, 252*, Article 119019. https://doi.org/10.1016/j.neuroimage.2022.119019

Mansouri, F. A., Buckley, M. J., & Tanaka, K. (2024). Mapping causal links between prefrontal cortical regions and intra-individual behavioral variability. *Nature Communications, 15*(1), 140. https://doi.org/10.1038/s41467-023-44341-5

Martínez, R., Chen, C., Fan, Y. T., Wu, H. H., Du, P. S., Chen, G. Y., & Chen, C. Y. (2023). Meta-analysis of electroencephalographic correlates and cognitive performance for acute exercise-induced modulation. *Neuropsychobiology, 82*(3), 131–149. https://doi.org/10.1159/000529307

Marzilli, E., Cerniglia, L., Ballarotto, G., & Cimino, S. (2020). Internet addiction among young adult university students: The complex interplay between family functioning, impulsivity, depression, and anxiety. *International Journal of Environmental Research and Public Health, 17*(21). https://doi.org/10.3390/ijerph17218231

Masley, S., Roetzheim, R., & Gualtieri, T. (2009). Aerobic exercise enhances cognitive flexibility. *Journal of Clinical Psychology in Medical Settings, 16*(2), 186–193. https://doi.org/10.1007/s10880-009-9159-6

Matsunaga, M., Ohtsubo, Y., Ishii, K., Tsuboi, H., Suzuki, K., & Takagishi, H. (2023). Association between internet addiction, brain structure, and social capital in adolescents. *Social Neuroscience, 18*(6), 355–364. https://doi.org/10.1080/17470919.2023.2264543

Montoya, A. K., & Hayes, A. F. (2017). Two-condition within-participant statistical mediation analysis: A path-analytic framework. *Psychological Methods, 22*(1), 6–27. https://doi.org/10.1037/met0000086

Morse, S. J. (2021). Is executive control the universal acid? *Criminal Law and Philosophy, 16*(2), 299–318. https://doi.org/10.1007/s11572-021-09607-3

Mou, H., Fang, Q., Tian, S., & Qiu, F. (2023). Effects of acute exercise with different modalities on working memory in men with high and low aerobic fitness. *Physiology & Behavior, 258*, Article 114012. https://doi.org/10.1016/j.physbeh.2022.114012

Oh, H., Berrington, A., Auer, D. P., Babourina-Brooks, B., Faas, H., & Jung, J. Y. (2024). A preliminary study of dynamic neurochemical changes in the dorsolateral prefrontal cortex during working memory. *European Journal of Neuroscience, 59*(8), 2075–2086. https://doi.org/10.1111/ejn.16280

Park, S., Reinl, M., & Schott, N. (2021). Effects of acute exercise at different intensities on fine motor-cognitive dual-task performance while walking: A functional near-infrared spectroscopy study. *European Journal of Neuroscience, 54*(12), 8225–8248. https://doi.org/10.1111/ejn.15241

Qi, L., Tian, Z. H., Yue, Y., Guan, S., Tang, L., & Dong, G. (2022). Effects of acute exercise on craving and cortical hemodynamics under drug-cue exposure in ma-dependent individuals. *Neuroscience Letters, 781*, Article 136672. https://doi.org/10.1016/j.neulet.2022.136672

Rolls, E. T., Deco, G., Huang, C. C., & Feng, J. (2024). The connectivity of the human frontal pole cortex, and a theory of its involvement in exploit versus explore. *Cerebral Cortex, 34*(1). https://doi.org/10.1093/cercor/bhad416

Rösch, S. A., Schmidt, R., Lührs, M., Ehlis, A. C., Hesse, S., & Hilbert, A. (2021). Evidence of fnirs-based prefrontal cortex hypoactivity in obesity and binge-eating disorder. *Brain Sciences, 11*(1). https://doi.org/10.3390/brainsci11010019

Shukla, D., Al-Shamil, Z., Belfry, G., & Heath, M. (2020). A single bout of moderate intensity exercise improves cognitive flexibility: Evidence from task-switching. *Experimental Brain Research, 238*(10), 2333–2346. https://doi.org/10.1007/s00221-020-05885-w

Soleimani, G., Joutsa, J., Moussawi, K., Siddiqi, S. H., Kuplicki, R., Bikson, M., … Ekhtiari, H. (2024). Converging evidence for frontopolar cortex as a target for neuromodulation in addiction treatment. *American Journal of Psychiatry, 181*(2), 100–114. https://doi.org/10.1176/appi.ajp.20221022

Solly, J. E., Hook, R. W., Grant, J. E., Cortese, S., & Chamberlain, S. R. (2022). Structural gray matter differences in problematic usage of the internet: A systematic review and meta-analysis. *Molecular Psychiatry, 27*, 1000–1009. https://doi.org/10.1038/s41380-021-01315-7

Srensen, L. K. A., Bohté, S. M., Slagter, H. A., & Scholte, H. S. (2022). Arousal state affects perceptual decision-making by modulating hierarchical sensory processing in a large-scale visual system model. *PLoS Computational Biology, 18*(4), Article e1009976. https://doi.org/10.1371/journal.pcbi.1009976

Stein, M., Steiner, L., Fey, W., Conring, F., Rieger, K., Federspiel, A., & Moggi, F. (2021). Alcohol-related context modulates neural correlates of inhibitory control in alcohol dependent patients: Preliminary data from an fmri study using an alcohol-related go/nogo-task. *Behavioural Brain Research, 398*, Article 112973. https://doi.org/10.1016/j.bbr.2020.112973

Strangman, G., Franceschini, M. A., & Boas, D. A. (2003). Factors affecting the accuracy of near-infrared spectroscopy concentration calculations for focal changes in oxygenation parameters. *Neuroimage, 18*(4), 865–879. https://doi.org/10.1016/S1053-8119(03)00021-1

Su, H., Zhong, N., Gan, H., Wang, J., Han, H., Chen, T., … Zhao, M. (2017). High frequency repetitive transcranial magnetic stimulation of the left dorsolateral prefrontal cortex for methamphetamine use disorders: A randomised clinical trial. *Drug and Alcohol Dependence, 175*, 84–91. https://doi.org/10.1016/j.drugalcdep.2017.01.037

Tan, S. J., Filmer, H. L., & Dux, P. E. (2021). Age-related differences in the role of the prefrontal cortex in sensory-motor training gains: A tdcs study. *Neuropsychologia, 158*, Article 107891. https://doi.org/10.1016/j.neuropsychologia.2021.107891

Tong, K., Fu, X., Hoo, N. P., Mun, L. K., Vassiliu, C., Langley, C., Sahakian, B. J., & Leong, V. (2024). The development of cognitive flexibility and its implications for mental health disorders. *Psychological Medicine, 54*(12), 1–7. https://doi.org/10.1017/S0033291724001508

Tuite, K., Girotti, M., & Morilak, D. (2022). Activation of the central medial thalamic afferent to the orbitofrontal cortex contributes to successful reversal learning. *FASEB Journal, 36*. https://doi.org/10.1096/fasebj.2022.36.S1.R2678

Uddin, L. Q. (2021). Cognitive and behavioural flexibility: Neural mechanisms and clinical considerations. *Nature Reviews Neuroscience, 22*(3), 167–179. https://doi.org/10.1038/s41583-021-00428-w

Van Rensburg, K. J., Taylor, A., Benattayallah, A., & Hodgson, T. (2012). The effects of exercise on cigarette cravings and brain activation in response to smoking-related images. *Psychopharmacology, 221*(4), 659–666. https://doi.org/10.1007/s00213-011-2610-z

Volkow, N. D., & Fowler, J. S. (2000). Addiction, a disease of compulsion and drive: Involvement of the orbitofrontal cortex. *Cerebral, Cortex(3)*, 318–325. https://doi.org/10.1093/cercor/10.3.318

Wang, D., Zhu, T., Chen, J., Lu, Y., Zhou, C., & Chang, Y. K. (2020). Acute aerobic exercise ameliorates cravings and inhibitory control in heroin addicts: Evidence from event-related potentials and frequency bands. *Frontiers in Psychology, 11*, Article 561590. https://doi.org/10.3389/fpsyg.2020.561590

Wang, M. Z., Hayden, B. Y., & Heilbronner, S. R. (2022). A structural and functional subdivision in central orbitofrontal cortex. *Nature Communications, 13*(1), 3623. https://doi.org/10.1038/s41467-022-31273-9

Wilczkowski, M., Karwowska, K., Kielbinski, M., Zajda, K., Pradel, K., Drwiga, G., Rajfur, Z., Blasiak, T., Przewlocki, R., & Solecki, W. B. (2023). Recruitment of inhibitory neuronal pathways regulating dopaminergic activity for the control of cocaine seeking. *European Journal of Neuroscience, 58*(12), 4487–4501. https://doi.org/10.1111/ejn.15885

Xiong, H., Zhang, J., Ye, B., Zheng, X., & Sun, P. (2012). Common method variance effects and the models of statistical approaches for controlling it. *Advances in Psychological Science, 20*(5), 757–769. https://doi.org/10.3724/sp.j.1042.2012.00757

Yan, Y., Qin, X., Liu, L., Zhang, W., & Li, B. (2025). Effects of exercise interventions on internet addiction among college students: A systematic review and meta-analysis of randomized controlled trials. *Addictive Behaviors, 160*, Article 108159. https://doi.org/10.1016/j.addbeh.2024.108159

Zhou, W., Zhang, Z., Yang, B., Zheng, H., Dong, G., & Dong, G. (2021). Sex difference in neural responses to gaming cues in internet gaming disorder: Implications for why males are more vulnerable to cue-induced cravings than females. *Neuroscience Letters, 760*, Article 136001. https://doi.org/10.1016/j.neulet.2021.136001

Zhou, W. R., Wang, Y. M., Wang, M., Wang, Z. L., Zheng, H., Wang, M. J., Potenza, M. N., & Dong, G. H. (2022). Connectome-based prediction of craving for gaming in internet gaming disorder. *Addiction Biology, 27*(1), Article e13076. https://doi.org/10.1111/adb.13076

Zhou, Y. U., Finlayson, G., Liu, X., Zhou, Q., & Zhou, C. (2021). Effects of acute dance and aerobic exercise on drug craving and food reward in women with methamphetamine dependence. *Medicine Science in Sports Exercise, 53*(11), 2245–2253. https://doi.org/10.1249/MSS.0000000000002723

Zhou, Z., Zhou, H., & Zhu, H. (2016). Working memory, executive function and impulsivity in internet-addictive disorders: A comparison with pathological gambling. *Acta Neuropsychiatrica, 28*(02), 92–100. https://doi.org/10.1017/neu.2015.54