Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Transcutaneous Acupoint Electrical Stimulation Ameliorates Working Memory Impairment in Nap-deprived Interns: The Mediating Role of Augmented Brain-Heart Interaction

Jieyi Fan
Fourth Military Medical University
Liang Wang
Fourth Military Medical University
Ze Lv
Fourth Military Medical University
Chengfei Li
Fourth Military Medical University
Yikai Pan
Fourth Military Medical University
Yuan Wang
Fourth Military Medical University
Shuhan Li
Fourth Military Medical University
Yongchun Wang
Fourth Military Medical University
Yuan Gao
Fourth Military Medical University
Xiqing Sun
sunxiqingfmmu@163.com
Fourth Military Medical University

Research Article

Keywords: Transcutaneous acupoint electrical stimulation, Working Memory, Heart rate variability, Prefrontal brain activity

Posted Date: February 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8925154/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background

Working memory (WM) decrement due to circadian dips and sleep restriction is a prevalent issue among interns, potentially impacting clinical decision-making. Non-invasive neuromodulation techniques, such as transcutaneous electrical acupoint stimulation (TEAS), offer a promising approach to mitigate cognitive fatigue. This study investigates the efficacy and underlying neurophysiological mechanism of TEAS at the Yintang (EX-HN3) acupoint in counteracting WM impairment induced by nap deprivation.

Methods

We enrolled 90 interns with habitual napping behavior, who were randomly assigned to one of three groups: normal control group (NC), nap deprivation group (ND), and nap deprivation group receiving TEAS intervention (ND+TEAS). Cognitive performance was assessed using a 3-back WM task at baseline (12:00) and post-intervention (15:00). Concurrently, prefrontal cerebral hemodynamics and autonomic nervous system activity were monitored via functional near-infrared spectroscopy (fNIRS) and heart rate variability (HRV), respectively. Subjective cognitive load was evaluated using the NASA-Task Load Index (NASA-TLX).

Results

Compared to the NC group, the ND group exhibited significant deterioration in WM accuracy and speed, accompanied by reduced prefrontal cortex (PFC) activation and attenuated parasympathetic activity (reflected by decreased HRV high-frequency power). The ND+TEAS group demonstrated a reversal of these effects, showing superior WM performance, enhanced PFC oxygenation, and increased vagally-mediated HRV indices relative to the ND group. Crucially, mediation analysis revealed that the improvement in WM performance following TEAS was mediated by its effect on augmenting PFC activation, which in turn was associated with increased parasympathetic tone.

Conclusions

TEAS at the Yintang acupoint effectively alleviates nap deprivation-induced WM impairment. The mechanism appears to involve the enhancement of parasympathetic nervous activity and the subsequent facilitation of prefrontal cortical function. These findings provide novel experimental evidence for the brain-heart interaction as a pathway for cognitive enhancement and position TEAS as a viable, non-invasive strategy to bolster cognitive resilience in populations susceptible to circadian fatigue, such as clinical staff.

1. Introduction

Working memory (WM), a core component of executive function, is essential for clinical reasoning, decision-making, and procedural execution in high-stakes medical environments[1, 2]. For interns and other healthcare professionals, acute cognitive fatigue and WM decrement are prevalent challenges, often stemming from circadian rhythm disruptions, sleep restriction, and irregular shift patterns[3]. These impairments not only affect individual well-being but also pose potential risks to patient safety[4]. Therefore, identifying safe and effective strategies to bolster cognitive resilience in this population is of paramount clinical importance.

Daytime napping is a widespread behavior adopted as a countermeasure against fatigue[5, 6]. Among habitual nappers, the forced deprivation of a regular nap has been established as a valid experimental model to induce transient cognitive

fatigue and WM deficits[6, 7], mirroring the cognitive challenges faced by medical staff after night shifts or during prolonged duty hours[8]. Such deprivation leads to measurable declines in cognitive performance, particularly in tasks requiring sustained attention and WM[3, 7].

The autonomic nervous system (ANS), which regulates involuntary physiological functions such as heart rate, consists of the parasympathetic (relaxation-promoting) and sympathetic (arousal-promoting) branches. The dynamic balance between these two branches governs cardiac regulation. Heart rate variability (HRV) serves as a key non-invasive marker of this autonomic balance, reflecting an individual's capacity for self-regulation and physiological adaptability [9, 10]. Higher HRV is generally associated with protective effects for cognitive function, whereas lower HRV is correlated with cognitive decline [11, 12]. Autonomic dysfunction has been observed in individuals with mild cognitive impairment, suggesting a link between cognitive impairment and abnormal autonomic regulation [13]. It also represents an early manifestation of neurodegenerative diseases, including Alzheimer's disease and Parkinson's disease [14, 15]. The HF-HRV is associated with performance in cognitive tasks such as cognitive inhibitory control and executive function[16, 17]. Additionally, in cognitive fatigue research, HF-HRV can predict cognitive task performance [12]. Thus, high HRV and increased HF reflect a flexible and adaptive physiological system that promotes homeostasis. Conversely, low HRV and diminished HF indicate a system less adept at adapting to external stressors[18–20].

The function of ANS is under the control of the central autonomic network (CAN)[21, 22]. A central component of the CAN is the medial prefrontal cortex (mPFC), which plays a critical role in exerting top-down cognitive control over autonomic and emotional processes[12, 23]. The CAN modulates autonomic function through key brainstem nuclei: the dorsal motor nucleus of vagus nerve mediates parasympathetic output, while the caudal ventrolateral medulla regulates sympathetic tone. The sympathetic pathway is activated in response to homeostatic challenges from external stressors[24]. Mirroring ANS dysfunction, impairment of the CAN is also linked to cardiac diseases and cognitive decline [25–27]. The activation of CAN recruits higher-order cognitive regions integral to cognition, emotion, and autonomic control[22, 28]. Functional near-infrared spectroscopy (fNIRS) studies indicate that reduced oxy-hemoglobin (HbO) concentration in the dorsolateral prefrontal cortex (DLPFC) directly reflects diminished neural activity, correlating with cognitive decline[29]. Furthermore, weakened prefrontal network connectivity is associated with deficits in specific cognitive domains[30]. Cognitive performance concurrently influences both autonomic and central nervous system function. Research on brain-heart interactions and their functional coupling is essential for understanding the physiological manifestations of homeostatic changes[31, 32]. Functional brain-heart coupling refers to the dynamic coordination between neural and cardiac activity, reflecting their functional interdependence[33].

Transcutaneous electrical acupoint stimulation (TEAS) is a non-invasive neuromodulation technique shown to enhance cognitive function. Owing to its minimal invasiveness and favorable safety profile, TEAS is particularly suitable for modulating cognitive function in the general population. A 4-week randomized controlled trial (RCT) demonstrated that TEAS improved attention and executive function in children aged 6–12 with ADHD[34]. Furthermore, an RCT in patients with schizophrenia found that adjunctive TEAS improved working memory (WM) and information processing speed compared to pharmacotherapy alone[35]. Notably, the Yintang (EX-HN3) acupoint, located on the forehead, is strategically positioned over the frontal lobe and is traditionally used for mental calming and cognitive enhancement[36]. A growing body of evidence suggests that TEAS can also modulate ANS activity, promoting parasympathetic tone[37–39]. However, a critical knowledge gap remains: whether and how TEAS can acutely mitigate WM impairment induced by a common stressor like nap deprivation in interns, and whether its cognitive benefits are mediated through the restoration of brain-heart interaction.

To address the above-mentioned knowledge gaps, the study investigates the acute effects of TEAS after deprivation of daytime napping on WM (measured via the 3-back task), cortical hemodynamics (measured by fNIRS), and the ANS (measured via HRV). Our primary aims were to 1) investigate among young habital nappers how nomal daytime napping and TEAS affect 3-back task performance, and the ANS following deprivation of daytime napping, and 2) examine the

relationships between TEAS-induced changes in WM, cortical hemodynamics, and HRV. we hypothesized that TEAS after deprivation of daytime napping would enhance WM and cortical hemodynamics. We also hypothesized that interrupting the nap deprivation with TEAS would increase HRV, reflecting a flexible and adaptive physiological system. Furthermore, we predicted that TEAS would yield benefits for both behavioral and neurobiological outcomes. Additionally, we hypothesized that improvements in WM and ANS would be mediated by changes in cortical hemodynamics.

2. Materials and Methods

2.1 Study population

A total of 95 interns from the Fourth Military Medical University First Affiliated Hospital were recruited as participants. The interns refrained from consuming any medications or beverages affecting neurological function and avoided high-intensity physical exercise for 48 hours prior to testing. All participants maintained their regular diet and daily routines and were right-handed. Before the formal experiment commenced, all interns completed the Pittsburgh Sleep Quality Index (PSQI) questionnaire to evaluate their fatigue status and sleep conditions over the preceding two weeks. Individuals who reported recent sleep disturbances or significant fatigue were excluded. Only interns with a consistent habit of daytime napping were included. The study protocol was approved by the Ethics Committee of the Fourth Military Medical University, and written informed consent was obtained from all participants prior to their enrollment.

As part of a screening procedure to assess habitual napping patterns, the interns completed sleep diaries for a minimum of one week, during which they were also required to record whether they had taken a daytime nap. Individuals were classified as habitual nappers if they reported napping at least once per week, whereas non-habitual nappers were defined as those who napped less than once per week. To account for inter-individual variability in the total number of diary days completed, napping frequency was expressed as the proportion of daytime napping relative to the total number of diary days. Consequently, habitual nappers were operationally defined as individuals who took at least one nap per week. Among habitual nappers, the mean reported nap frequency was two times per week (range: 1–6 times per week). The most frequently reported nap duration was 31–60 min. The predominant nap timing occurred between 12:00 PM and 14:00 PM (noon–early afternoon). After excluding one participant with incorrectly filled or incomplete sleep diaries and four participants who had missing data across the tasks, our final sample consisted of 90 participants (mean age ± SD:22.12 ± 0.87 years).

Interns were randomly assigned to three groups: nap deprivation group (ND), normal control group (NC), and nap deprivation group receiving TEAS intervention (ND+TEAS). Each group underwent 3-back task, HRV, fNIRS, and NASA Task Load Index (NASA-TLX) at 12:00 and 15:00. In ND, interns refrained from napping. They remained in the laboratory engaging in relaxed, sedentary activities, such as reading or listening to music, and avoided vigorous exercise. NC maintained their habitual napping schedule. ND+TEAS received a daily 30-minute TEAS for six consecutive days. On the seventh (test) day, they refrained from napping and instead remained in the laboratory engaging in light, sedentary activities. Additionally, on the test day, a continuous 30-minute TEAS was administered beginning at 14:30. To examine the impact of TEAS on HRV and its association with cognitive performance, electrocardiogram (ECG) recordings were obtained from participants during the 3-back task (See Fig. 1).

NC: normal control group; ND: nap deprivation group; ND+TEAS: nap deprivation group receiving TEAS intervention

2.2 Subjective assessment

The NASA-TLX is a subjective scale originally developed by the National Aeronautics and Space Administration (NASA) for aerospace applications. It is now the most widely used multidimensional instrument for assessing subjective cognitive load [40, 41]. The NASA-TLX assesses six dimensions: mental demand (MD), physical demand (PD), temporal demand (TD), performance (Fr), effort (Ef), and frustration (Pe). Each dimension is rated on a scale from 0 to 20[40].

2.3 Cognitive task

The 3-back task required participants to recall the spatial locations of sequentially presented blue squares. Participants were instructed to indicate whether the location of the current blue square matched the location of the square presented two trials back. The task comprised five blocks. A 10-second rest period, signaled by an on-screen "Rest" prompt, separated each block. The total task duration was 8 minutes. Each target stimulus (a blue square) was displayed for 500 ms, followed by a 1000 ms blank inter-stimulus interval, resulting in a stimulus onset asynchrony (SOA) of 1500 ms [42, 43] (See Fig. 2). Prior to the main task, participants read on-screen instructions. Following a self-reported understanding of the rules, participants completed a practice block. The practice required completing three sets of 16 trials each. Participants were required to achieve an accuracy rate (ACC) greater than 80% in each set before advancing to the main task. During the main task, no performance feedback was provided. The stimulus presentation order was pseudorandomized across participants.

2.4 fNIRS measurement

Prefrontal cortical activity was measured using an OctaMon functional near-infrared spectroscopy (fNIRS) system (Artinis Medical Systems, Netherlands). The system employed a wireless 8-channel configuration with a source-detector separation of 3.5 cm to measure concentration changes in oxygenated (HbO) and deoxygenated (HHb) hemoglobin in the PFC microcirculation. Each channel used dual wavelengths (756 and 856 nm) and sampled at 25 Hz. Data were collected using Oxysoft software (version 3.0.52, Artinis Medical Systems). Optodes were positioned bilaterally on the forehead according to the international 10–20 system, targeting Brodmann’s areas 9 and 10 (dorsolateral and anterior prefrontal cortex) (See Fig. 3).

The raw fNIRS data were preprocessed using the NIRS-KIT-main toolkit in MATLAB 2023a. Initially, the Data Preparation module converted .nirs files to .mat files. Subsequently, the HbO values and their corresponding time points were extracted from the .mat file. Following this, the Preprocessing module was employed for detrending. Variations in instrument sensitivity and participants' physiological conditions during the experiment may introduce trends that could affect the study results. By applying a linear regression model to eliminate these trends, alterations in the signals of interest can be observed more distinctly in the analysis. During the experiment, participants' body movements may introduce motion artifacts into the data. Motion correction can effectively reduce these artifacts, thereby enhancing data quality. We utilize the Temporal Derivative Distribution Repair (TDDR) method to correct motion artifacts. By constraining the frequency range to 0.01 Hz to 0.08 Hz, the filter effectively removes frequency components outside this interval, thereby reducing high-frequency noise and low-frequency drift. This process enhances the sensitivity of the signals of interest. A third-order Butterworth bandpass filter is employed for this filtering. The filtered data is subsequently converted to changes in HbO concentration using the modified Beer-Lambert law. Following this, the general linear model (GLM) is applied to derive beta values. Previous research has established that HbO is the most sensitive indicator of changes in experimental paradigm stimuli[44–46].Therefore, this study selects the beta value of HbO as a metric for evaluating brain activity, specifically focusing on the activation level of the prefrontal cortex, where elevated beta values signify increased activation in this region.

2.5 TEAS treatment

Participants were randomly assigned to three groups: NC, ND and ND+TEAS. TEAS was conducted daily using small (1.5 cm) cutaneous electrode pads placed at the Yintang (GV29) point. The Yintang acupoint is situated at the inner end of the eyebrows, specifically at the midpoint where the inner ends of both eyebrows converge. The electrical stimulation was delivered at the maximum tolerable current intensity, ensuring that no muscle contractions or discomfort occurred. The parameters were configured to a dense-sparse wave with a frequency of 50 Hz, utilizing the Hwato electronic acupuncture treatment instrument (Model No. SDZ-II; Suzhou Medical Appliances, Suzhou, China).

2.7 Heart rate variability (HRV)

All participants were instructed to wear an Equivital EQ02 + LifeMonitor (Equivital, Cambridge, UK) while performing cognitive tests and undergoing TEAS treatment [47]. The Equivital LifeMonitor is a vest-like wearable device that continuously measures ECG, heart rate (HR), and heart rate variability (HRV) through two channels using three electrodes. It features a sensor electronic module that resides in a cradle on the side of the LifeMonitor. The EQ02 monitoring system comprises LifeMonitor straps of various sizes, one LM 100 LifeMonitor sensor electronic module (SEM), a Bluetooth USB dongle for laptop connectivity, and Equivital Manager software, which is utilized to configure SEMs and to export and download data. In this study, SEMs were set to real-time monitoring mode. Data were stored simultaneously in the SEMs and the laptop. A LifeMonitor belt of appropriate size secured the SEM to each participant's body. Prior to skin contact, the textile-based electrodes were moistened with water. The SEMs were recharged for approximately 1 hour following a 12-hour recording period. At the conclusion of the study, the SEM data were transferred to the Equivital Manager software, where time- and date-stamped ECG readings, inter-beat intervals, and summarized vital sign data were extracted and exported for analysis.

2.8 Statistical analysis

The data from this study were analyzed statistically using SPSS 25. Initially, descriptive statistical analyses were performed on subjective scale data, behavioral data, physiological data, and near-infrared spectroscopy (NIRS) data. A repeated measures ANOVA was conducted for all subjective and objective evaluation results across ND, NC, and ND+TEAS), with time (12:00, 15:00) and group as factors. Different intervention types were treated as within-subject factors, and all post-hoc multiple comparisons were adjusted using the Bonferroni method. The effect size was reported using partial η^2 based on the results of the analysis of variance.

We employed the SPSS PROCESS macro v4. for mediation analysis. Our mediation models included three sets of variables: the predictor of working memory performance (X), autonomic nervous system activity (Y), and a mediator represented by a specific fNIRS measure (M). The fNIRS measures acting as mediators were determined as the mean β values observed in fNIRS channels showing group-by-time interaction effects. A parallel mediation model was used to explore the direct impact of working memory performance (measured through RTs) on autonomic nervous system function (assessed as HRV-HFnu), as well as the indirect influence mediated by the fNIRS parameters: β values of Ch3, Ch6, and Ch8. We analyzed the mediation between the outcome and the mediator, assessing both the direct effect of X and the indirect (mediation) effect of X through β values on Y. A visual representation of the complete model is depicted in Figure S1. All regression coefficients were reported as standardized coefficients, with effects deemed significant at $p < 0.05$. Bootstrapped confidence intervals (5,000 runs) were used to determine the significance of indirect effects.

3. Results

3.1Baseline characteristics

Table 1 summarizes the descriptive statistics and nap parameters were observed among three group (See Table 1).

Table 1
Baseline characteristics of three groups

		NC	ND	ND+TEAS
Demographics	Number of Participants	30	30	30
	Age (years)	24.78 ± 1.98	23.65 ± 1.37	24.12 ± 1.05
	Education (years)	17.43 ± 2.01	16.39 ± 1.87	17.96 ± 1.99
Daytime napping characteristics	time in bed (TIB)	66.18 ± 4.39		64.29 ± 5.22
	total sleep time (TST)	58.12 ± 3.26		
	bedtime	12:50 – 13:00	12:45 – 13:00	12:50 – 13:00
	wake time	14:00–14:10	14:00–14:10	14:00–14:10

Normal control group (NC), Nap deprivation group (ND) and Nap deprivation group receiving TEAS intervention (ND+TEAS).

3.2 The effect of different interventions on NASA-TLX scale scores

A two-factor repeated-measures ANOVA of NASA-TLX scale scores indicated significant differences in MD, Pe, and Ef. The interaction effect between testing time point and intervention condition on MD was not significant ($F_{[1, 88]} = 2.08$, $p = 0.13$, *partial* $\eta^2 = 0.05$), neither was the main effect of testing time point ($F_{[1, 88]} = 3.09$, $p = 0.08$, *partial* $\eta^2 = 0.04$). However, the main effect of intervention condition was significant ($F_{[1,88]} = 7.25$, $p < 0.001$, *partial* $\eta^2 = 0.15$). Post-hoc comparisons revealed no significant differences among the three groups at baseline (12:00, $p = 0.87$). Following TEAS, MD scores were significantly lower than those in the ND (15:00, $p = 0.02$). Moreover, MD scores after normal napping were significantly lower than those after non-nap (15:00, $p < 0.001$)

Table 2
The results of repeated measures ANOVA for NASA-TLX score across three groups at 12:00 and 15:00

Measures		NC		ND		ND+TEAS		F	*p*	partial η^2
		12:00	15:00	12:00	15:00	12:00	15:00			
MD	Mean ± SD	9.71 ± 4.46	9.45 ± 3.67	10.21 ± 4.05	13.42 ± 3.91	10.53 ± 4.15	9.67 ± 4.62			
PD	Mean ± SD	5.75 ± 2.74	5.34 ± 2.83	5.68 ± 2.25	7.03 ± 3.26	5.57 ± 2.29	5.49 ± 2.93			
	group*time	-	-	-	-	-	-	1.39	0.26	0.03
	time	-	-	-	-	-	-	0.59	0.45	0.01
	group	-	-	-	-	-	-	1.74	0.18	0.04
TD	Mean ± SD	10.50 ± 4.41	9.80 ± 2.95	10.37 ± 5.06	10.9 ± 4.48	11.98 ± 2.66	10.85 ± 5.34			
	group*time	-	-	-	-	-	-	0.73	0.49	0.02
	time	-	-	-	-	-	-	0.29	0.59	0.003
	group	-	-	-	-	-	-	1.34	0.71	0.03-
Pe	Mean ± SD	14.22 ± 3.68	14.47 ± 2.40	13.95 ± 1.79	14.01 ± 2.60	13.12 ± 2.61	12.42 ± 1.64			
	group*time	-	-	-	-	-	-	0.26	0.77	0.01
	time	-	-	-	-	-	-	0.83	0.37	0.01
	group	-	-	-	-	-	-	5.95	0.004	0.12
Ef	Mean ± SD	14.37 ± 3.85	12.99 ± 3.77	13.03 ± 3.79	13.41 ± 2.71	14.70 ± 2.69	12.41 ± 6.25			
	group*time	-	-	-	-	-	-	3.56	0.03	0.08
	time	-	-	-	-	-	-	0.09	0.76	0.001
	group	-	-	-	-	-	-	0.20	0.82	0.01
Fr	Mean ± SD	6.96 ± 2.85	7.06 ± 2.68	7.43 ± 3.20	9.85 ± 2.41	7.29 ± 3.44	6.12 ± 2.59	0.70	0.50	0.02
	group*time	-	-	-	-	-	-	1.18	0.28	0.01
	time	-	-	-	-	-	-	0.78	0.46	0.02
	group	-	-	-	-	-	-			

Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Frustration (Fr), Effort (Ef), and Performance (Pe).

The main effect of the intervention condition on Pe was significant ($F_{[1, 88]} = 5.95, p = 0.004$, partial $\eta^2 = 0.12$). In contrast, neither the interaction effect between testing time point and intervention condition ($F_{[1, 88]} = 0.26, p = 0.77$, partial $\eta^2 = 0.01$) nor the main effect of testing time point ($F_{[1, 88]} = 0.83, p = 0.37$, partial $\eta^2 = 0.01$) reached significance. Post-hoc comparisons revealed no significant differences among the three groups at baseline (12:00, $p = 0.12$). Following TEAS, Pe scores were significantly lower than those in the ND group (15:00, $p = 0.02$). However, no significant difference was found between the normal napping and non-nap (15:00, $p = 0.07$).

The interaction effect between testing time point and intervention condition on was significant ($F_{[1, 88]} = 3.56$, $p = 0.03$, partial $\eta^2 = 0.07$). In contrast, the main effects of testing time point ($F_{[1, 88]} = 0.09$, $p = 0.76$, partial $\eta^2=0.001$) and intervention condition ($F_{[1, 88]} = 0.20$, $p = 0.82$, partial $\eta^2 =0.005$) were not statistically significant. Following TEAS, post-intervention scores were significantly lower than baseline scores (12:00 vs. 15:00, $p = 0.03$). No statistically significant differences were observed for PD, TD, or Fr (all $ps > 0.05$) (See Table 2 and Fig. 4).

3.3The effect of different interventions on cognitive performance

An analysis was conducted on the mean reaction times (mean RTs) and ACC of the 3-back task to explore the impact of TEAS on WM. A two-factor repeated-measures analysis of variance (ANOVA) was utilized, with time (12:00 and 15:00) as the within-subject factor and intervention groups (NC, ND and ND+TEAS) as the between-subject factor (See Table 3 and Fig. 5). Post hoc multiple comparisons were carried out using the Bonferroni method for correction. The outcomes of the two-factor repeated-measures ANOVA for mean RTs on the 3-back test revealed that the main effect of time was not statistically significant ($F_{[1, 88]} = 0.06$, $p = 0.80$, partial $\eta^2 = 0.001$). However, a significant interaction effect between time and intervention condition was observed ($F_{[1, 88]} = 11.96$, $p < 0.001$, partial $\eta^2 = 0.24$), along with a significant main effect of the test time point ($F_{[1, 88]} = 6.87$, $p = 0.002$, partial $\eta^2 = 0.15$).

Post hoc multiple comparisons indicated no significant variances in baseline RTs at 12:00 among the different intervention groups ($p = 0.99$). By 15:00, the average RT for the 3-back task following TEAS was notably shorter than that following nap deprivation ($p = 0.002$). Similarly, post a regular nap session, the average RT for the normal control group was significantly shorter than that for the ND group at 15:00 ($p = 0.011$). Furthermore, in comparison to the baseline at 12:00, the 30-minute TEAS significantly enhanced the average RT for the 3-back task ($p = 0.004$). Conversely, following a regular nap, there was no significant enhancement in the average RT ($p = 0.08$). In ND, the average RT for the 3-back task at 15:00 was significantly prolonged compared to the baseline ($p < 0.001$).

The results indicated a significant interaction between time and intervention condition on 3-back task ACC ($F_{[1, 88]} = 31.57$, $p < 0.001$, partial $\eta^2 = 0.52$). A significant main effect was observed for the intervention group ($F_{[1, 88]} = 4.38$, $p = 0.02$, partial $\eta^2 = 0.13$), while the main effect of time was not significant ($F_{[1, 88]} = 0.03$, $p = 0.87$, partial $\eta^2 =0.001$). Post hoc comparisons revealed no significant differences in ACC at the 12:00 baseline level among intervention groups (12:00, $p = 0.07$). However, *following TEA, the ACC of the 3-back task was significantly higher compared to ND (15:00, $p < 0.001$), and the ACC of NC was significantly higher than that of ND (15:00, $p < 0.001$).*

Compared to the baseline measurement at 12:00, the 30-minute TEAS significantly enhanced ACC on the 3-back task (12:00 vs. 15:00, $p = 0.003$). Furthermore, ACC following the nap also exhibited a significant improvement (12:00 vs. 15:00, $p < 0.001$). In contrast, participants in ND demonstrated a significantly lower ACC in completing the 3-back test at 15:00 compared to the baseline level (12:00 vs. 15:00, $p < 0.001$).

Table 3
The results of repeated measures ANOVA for behavioral performance in the 3-back task across three groups at 12:00 and 15:00

Measures		NC		ND		ND+TEAS		F	*p*	partial η^2
		12:00	15:00	12:00	15:00	12:00	15:00			
Mean RTs(ms)	Mean ± SD	783.49 ± 411.21	651.44 ± 323.18	790.53 ± 252.53	1079.40 ± 411.31	795.58 ± 226.33	607.03 ± 227.75			
	group*time	-	-	-	-	-	-	11.96	< 0.001	0.24
	time	-	-	-	-	-	-	0.06	0.80	0.001
	group	-	-	-	-	-	-	0.06	0.80	0.001
Accuracy	Mean ± SD	0.83 ± 0.13	0.93 ± 0.10	0.81 ± 0.08	0.69 ± 0.11	0.84 ± 0.07	0.96 ± 0.08			
	group*time	-	-	-	-	-	-	31.57	< 0.001	0.52
	time	-	-	-	-	-	-	0.03	0.87	0.001
	group	-	-	-	-	-	-	4.3	0.02	0.13

Normal control group (NC), Nap deprivation group (ND) and Nap deprivation group receiving TEAS intervention (ND+TEAS).

3.4The effect of different interventions on HRV

The statistical analysis of HFnu revealed a significant interaction between test time point and intervention condition ($F_{[1, 88]} = 3.31$, $p = 0.04$, partial $\eta^2 = 0.10$). The main effect of the intervention condition was not significant ($F_{[1, 88]} = 1.31$, $p = 0.28$, partial $\eta^2 = 0.04$), and the main effect of the time was not significant ($F_{[1, 88]} = 0.004$, $p = 0.95$, partial $\eta^2 = 0.001$). Post hoc comparisons indicated no significant differences in ACC at the baseline level of 12:00 among NC, ND, and ND+TEAS (12:00, $p = 0.07$). However, HFnu following TEAS was significantly higher than that of the non-nap (15:00, $p = 0.047$). HFnu following the nap also exhibited a significant improvement (15:00, $p = 0.04$). Additionally, participants in ND demonstrated a significantly lower HFnu in completing the 3-back task at 15:00 compared to the baseline level (12:00 vs. 15:00, $p = 0.04$). There were no significant interactions between test time point and intervention condition or interactions between test time point and intervention condition observed in LFnu, RMSSD, and LF/HF ($ps \geq 0.05$) (See Table 4 and Fig. 6).

Z-score normalization (standardization) was applied to the data, transforming it to have a mean of zero and a standard deviation of one. All continuous numerical features of HRV underwent standardization using Z-score normalization to address the issue of varying scales among variables (See Table 4 and Fig. 6A). Specifically, each feature had its mean value (μ) from the training set subtracted and was then divided by the corresponding standard deviation (σ) from the same set. This normalization ensured that each feature had a mean of zero and a standard deviation of one, facilitating the convergence of our model and preventing features with larger scales from dominating the learning process.

Table 4
The results of repeated measures ANOVA for HRV in the 3-back task across three groups at 12:00 and 15:00

Measures		NC		ND		ND+TEAS		F	*p*	partial η^2
		12:00	15:00	12:00	15:00	12:00	15:00			
LFnu-3-back test	Mean ± SD	47.50 ± 19.85	52.70 ± 21.11	45.20 ± 23.21	44.20 ± 23.33	54.24 ± 17.71	43.26 ± 18.30			
	group*time	-	-	-	-	-	-	0.14	0.87	0.01
	time	-	-	-	-	-	-	0.33	0.57	0.01
	group	-	-	-	-	-	-	0.27	0.77	0.01
HFnu-3-back test	Mean ± SD	52.60 ± 19.78	55.94 ± 16.23	53.31 ± 15.54	42.36 ± 22.57	50.62 ± 17.67	57.68 ± 19.69			
	group*time	-	-	-	-	-	-	3.31	0.04	0.10
	time	-	-	-	-	-	-	0.004	0.95	0.001
	group	-	-	-	-	-	-	1.31	0.28	0.04
RMSSD-3-back test	Mean ± SD	37.05 ± 23.36	27.06 ± 11.27	34.23 ± 17.92	25.01 ± 14.16	32.21 ± 14.02	36.68 ± 13.69			
	group*time	-	-	-	-	-	-	2.67	0.08	0.08
	time	-	-	-	-	-	-	2.98	0.09	0.05
	group	-	-	-	-	-	-	0.83	0.44	0.03
LF/HF-3-back test	Mean ± SD	1.63 ± 2.21	0.93 ± 0.74	1.00 ± 0.83	1.34 ± 1.38	1.16 ± 1.87	1.09 ± 0.60			
	group*time	-	-	-	-	-	-	0.82	0.45	0.03
	time	-	-	-	-	-	-	1.65	0.99	0.001
	group	-	-	-	-	-	-	0.26	0.77	0.01

Normal control group (NC), Nap deprivation group (ND) and Nap deprivation group receiving TEAS intervention (ND+TEAS).

3.5 The effect of different interventions on fNIRS brain activation

This study utilized a two-way repeated-measures analysis of variance (ANOVA) to examine the impact of TEAS on cerebral activity indicators while performing 3-back task after non-nap. Variations in β values among three groups during 3-back task were assessed. To evaluate task-state activation levels indicative of the prefrontal cortex (PFC), individual two-way repeated-measures ANOVA were conducted on each of the eight channels. The interaction effect outcomes for each channel are detailed in Table 6 and Fig. 7.

For the Ch3, the interaction effect between the intervention condition and time was significant ($F_{[1, 88]} = 4.51$, $p = 0.014$, *partial* $\eta^2 = 0.11$). In contrast, neither the main effect of time ($F_{[1, 88]} = 0.18$, $p = 0.67$, *partial* $\eta^2 = 0.002$) nor the main effect of the intervention condition ($F_{[1, 88]} = 0.05$, $p = 0.96$, *partial* $\eta^2=0.001$) reached significance. Post-hoc multiple comparisons indicated a significant difference in β values during the 3-back task after 30 minutes of TEAS when compared to the baseline at 12:00 (12:00 vs. 15:00, $p = 0.02$). However, no significant difference was observed after one hour of normal

napping (12:00 vs. 15:00, $p = 0.20$). Additionally, without any intervention following nap deprivation, β values did not show a significant difference (12:00 vs. 15:00, $p = 0.17$).

The interaction effect between intervention condition and test time point was significant for the Ch6 ($F_{[1, 88]} = 7.41$, $p < 0.001$, partial $\eta^2 = 0.17$). Neither the main effect of time ($F_{[1, 88]} = 0.29$, $p = 0.59$, partial $\eta^2 = 0.004$) nor the main effect of intervention condition ($F_{[1, 88]} = 0.25$, $p = 0.78$, partial $\eta^2 = 0.007$) reached significance. Post-hoc multiple comparisons revealed a significant difference in β values during the 3-back task after 30 minute TEAS compared to the baseline at 12:00 (12:00 vs. 15:00, $p = 0.004$). However, no significant difference was observed after one hour of normal nap (12:00 vs. 15:00, $p = 0.09$). Furthermore, without any intervention following nap deprivation, β values exhibited no significant difference (12:00 vs. 15:00, $p = 0.09$).

The interaction effect between intervention condition and time was significant for the Ch8 ($F_{[1, 88]} = 6.40$, $p = 0.003$, partial $\eta^2 = 0.15$). However, the main effects of time ($F_{[1, 88]} = 0.25$, $p = 0.62$, partial $\eta^2 = 0.003$) and intervention condition ($F_{[1, 88]} = 0.001$, $p = 0.99$, partial $\eta^2 = 0.001$) were not significant. Post-hoc multiple comparisons revealed a significant difference in β values during the 3-back task after 30 minutes TEAS compared to the baseline at 12:00 (12:00 vs. 15:00, $p = 0.007$). Conversely, no significant difference was observed after one hour of normal nap (12:00 vs. 15:00, $p = 0.10$). Additionally, without any intervention following nap deprivation, β values exhibited no significant difference (12:00 vs. 15:00, $p = 0.12$).

For hemodynamic response in HbO (i.e., β value), there were no significant interactions between test time point and intervention condition or interactions between test time point and intervention condition observed ($ps \geq 0.05$) (See Table 5).

Table 5
The results of repeated measures ANOVA for β values in the 3-back task across three groups at 12:00 and 15:00

Channel		NC		ND		ND+TEAS		F	*p*	partial η^2
		12:00	15:00	12:00	15:00	12:00	15:00			
Ch1	Mean ± SD	0.18 ± 0.07	0.14 ± 0.01	0.15 ± 0.12	0.13 ± 0.01	0.17 ± 1.55	0.19 ± 1.60			
	group*time	-	-	-	-	-	-	1.62	0.20	0.04
	time	-	-	-	-	-	-	1.45	0.23	0.02
	group	-	-	-	-	-	-	0.61	0.55	0.02
Ch2	Mean ± SD	0.14 ± 0.09	0.18 ± 0.01	0.18 ± 0.13	0.18 ± 0.01	0.13 ± 1.56	0.17 ± 1.55			
	group*time	-	-	-	-	-	-	2.43	0.10	0.06
	time	-	-	-	-	-	-	2.12	0.14	0.03
	group	-	-	-	-	-	-	1.37	0.26	0.04
Ch3	Mean ± SD	0.15 ± 0.06	0.21 ± 0.01	0.20 ± 0.15	0.21 ± 0.01	0.26 ± 1.55	0.31 ± 1.54			
	group*time	-	-	-	-	-	-	4.51	0.014	0.11
	time	-	-	-	-	-	-	0.18	0.67	0.002
	group	-	-	-	-	-	-	0.05	0.96	0.001
Ch4	Mean ± SD	0.18 ± 0.07	0.16 ± 0.01	0.20 ± 0.11	0.16 ± 0.01	0.19 ± 1.54	0.18 ± 1.56			
	group*time	-	-	-	-	-	-	1.89	0.16	0.05
	time	-	-	-	-	-	-	1.72	0.19	0.02
	group	-	-	-	-	-	-	1.11	0.33	0.03
Ch5	Mean ± SD	0.08 ± 0.08	0.17 ± 0.01	0.11 ± 0.01	0.17 ± 0.01	0.14 ± 1.58	0.26 ± 1.56			
	group*time	-	-	-	-	-	-	2.81	0.07	0.07
	time	-	-	-	-	-	-	0.11	0.74	0.002
	group	-	-	-	-	-	-	0.15	0.86	0.004
Ch6	Mean ± SD	0.27 ± 0.06	0.18 ± 0.01	0.28 ± 0.08	0.18 ± 0.01	0.41 ± 1.49	0.27 ± 1.55			
	group*time	-	-	-	-	-	-	7.409	< 0.001	0.17
	time	-	-	-	-	-	-	0.29	0.59	0.004
	group	-	-	-	-	-	-	0.25	0.78	0.01
Ch7	Mean ± SD	0.18 ± 0.16	0.22 ± 0.01	0.14 ± 0.07	0.12 ± 0.01	0.13 ± 1.53	0.17 ± 1.53			
	group*time	-	-	-	-	-	-	2.67	0.08	0.07

Channel		NC		ND		ND+TEAS		F	*p*	partial η^2
		12:00	15:00	12:00	15:00	12:00	15:00			
	time	-	-	-	-	-	-	2.48	0.12	0.03
	group	-	-	-	-	-	-	1.19	0.31	0.03
Ch8	Mean ± SD	0.22 ± 0.06	0.21 ± 0.01	0.21 ± 0.09	0.21 ± 0.01	0.32 ± 1.53	0.31 ± 1.54			
	group*time	-	-	-	-	-	-	6.403	0.003	0.15
	time	-	-	-	-	-	-	0.25	0.62	0.003
	group	-	-	-	-	-	-	0.001	0.99	0.001

Normal control group (NC), Nap deprivation group (ND) and Nap deprivation group receiving TEAS intervention (ND+TEAS).

3.6 Mediation Effects of the fNIRS Measures

The mediation model indicated a significant relationship between WM performance and autonomic nervous system activity (*c = -0.17, p < 0.001*), with the direct effect of WM performance being significant but smaller than the total effect (*c′ = -0.12, p < 0.01*), leading to shorter reaction times with higher HFnu during the 3-back task. An indirect effect was observed for the β values of Ch6 in the mediation model, showing that better WM performance was linked to a larger β value (*a = -0.01, p = 0.045*). Additionally, the fNIRS parameter associated with WM performance correlated with higher HFnu (*b = 8.72, p = 0.0101*). These findings suggest that following TEAS, improved WM performance, along with higher vagus nerve activity, mediated HRV by enhancing the β value of Ch6. However, the β values of Ch3 (*b = -0.28, p = 0.72*) and Ch8 (*b = -2.18, p = 0.26*) did not exhibit a significant mediation effect (See Fig. 8).

4. Discussion

The findings supported our hypotheses that TEAS applied at the Yintang acupoint enhanced the ANS and measures of WM and that these effects were mediated by improvements in cortical hemodynamics in interns. Compared to those who were deprived of daytime napping, those who received TEAS showed significant improvement in WM performance. We also noted significant increases in the ANS (i.e., HRV) and cortical activation in regions associated with WM. Moreover, the mediation analysis suggested that changes in HRV (i.e., HF) may influence performance via alterations in cortical oxygenation activation during a 3-back task. These findings advance our understanding of TEAS as a neuromodulatory tool and underscore the critical role of brain-heart interaction in cognitive resilience.

4.1 Influence of TEAS on WM

In terms of behavioral data, the results showed that among interns, TEAS led to significant improvements in a 3-back task, as evidenced by shorter RT and higher ACC. The findings support and extend prior research emphasizing that TEAS benefits WM, which is essential for attention and processing speed, reasoning and problem-solving, and verbal learning and language[28]. Moreover, our study adds to previous research by suggesting that TEAS resulted in more pronounced improvements in WM following non-nap compared to participants without napping. Notably, recent research indicates that the practical implementation of TEAS has been explored and confirmed as feasible for cognitive dysfunction associated with neurodegenerative diseases, such as mild cognitive impairment (MCI) and Alzheimer's disease (AD)[34, 48, 49]. However, research on its potential for cognitive enhancement in healthy participants remains insufficient[50]. Furthermore, participants exhibited slower RT and lower ACC without habitual napping, underscoring the negative consequences of the

absence of a nap on cognitive function. These findings corroborate the existing literature demonstrating the protective effects of moderate daytime napping on cognitive performance [6, 51]. Overall, our results underscore the significant impact of TEAS on multiple aspects of executive performance and highlight the potential advantages of integrating TEAS into practical settings characterized by mental fatigue (e.g., daytime nap deprivation) to alleviate the detrimental consequences of prolonged wakefulness on cognitive function.

4.2 Influence of TEAS on autonomic nervous system

Our research suggests that engaging in TEAS following non-nap led to significant increases in parasympathetic nervous activity, as indicated by variations in HFnu. Nap deprivation was associated with a decrease in parasympathetic nervous activity (HFnu). These findings support the notion that TEAS can enhance vagal tone and improve cognitive regulation capabilities. The results align with the existing literature demonstrating the correlation between an elevated parasympathetic nervous system and enhanced cognitive control, emotional regulation, and health maintenance [10]. Our study further demonstrated that participants without napping showed a significant decrease in HFnu, accompanied by increased sympathetic activity. Previous research has shown that during cognitive tasks performed under sleep deprivation, participants exhibit reduced HRV-HF, diminished vagus nerve, and heightened sympathetic activity [52]. These alterations reflect compensatory mechanisms aimed at maintaining cognitive performance, accompanied by increased sympathetic nervous system activity[53]. This perspective is supported by prominent heart-centered theories such as the Neurovisceral Integration Model and Polyvagal Theory[54, 55]. However, several studies have reported conflicting results, indicating activation of the parasympathetic system following sleep deprivation. This discrepancy may stem from individual attempts to maintain wakefulness, which could lead to reduce in HFnu, resulting in sympathetic activation and an elevation in LFnu[56].

Notably, the TEAS condition resulted in greater changes in HRV than the daytime napping condition. This finding indicates that under the physiological context of sympathetic hyperactivation and ANS imbalance induced by nap deprivation, the parasympathetic regulatory response to TEAS becomes more pronounced. This observation aligns with the theory of compensatory autonomic regulation, which proposes that neuromodulatory interventions can elicit a heightened physiological compensatory response when basal autonomic homeostasis is compromised[57, 58]. Nap deprivation disrupts autonomic function, manifesting as persistent sympathetic hyperactivation and parasympathetic suppression. Within this altered autonomic milieu, TEAS may amplify neuromodulatory effects via a threshold-lowering effect[59]. To preserve homeostasis, the organism mounts a stronger compensatory parasympathetic activation in response to identical stimulation[60, 61]. This mechanism reflects the individual adaptive capacity to enhance parasympathetic tone when autonomic equilibrium is perturbed, consistent with evidence that neuromodulation strategies (e.g., TEAS and taVNS) can restore autonomic balance by reinforcing vagal activity under conditions of sympathetic dominance[62, 63].

4.3 Influence of TEAS on Cortical Hemodynamics

Compared with nap deprivation, TEAS was associated with enhanced cortical activation, particularly in the PFC, specifically in the DLPFC and orbitofrontal cortex (OFC) regions during a 3-back task, which correlates with improved WM, indicating a significant relationship between brain activity and cognitive performance. This suggests that TEAS may enhance neural efficiency, enabling better cognitive performance in the absence of daytime napping. Previous studies have emphasized that TEAS influences the PFC involved in WM by modulating hippocampal synaptic plasticity[34]. fNIRS findings showed that TEAS led to significant activation of the DLPFC and OFC. Elevated β-values reflect enhanced neural efficiency and motivational integration after TEAS under deprivation of napping. Specifically, the activation of the DLPFC indicates increased resource allocation for WM maintenance and manipulation[64, 65], while OFC engagement may support outcome valuation and error monitoring to optimize behavioral adaptation[66]. Critically, TEAS may augment cortico-subcortical circuits (e.g., prefrontal-striatal pathways), thereby strengthening the DLPFC-OFC synergy for efficient executive control[65]. These hemodynamic changes serve as biomarkers for cognitive improvement, as evidenced by the

correlation between β-value increases and clinical recovery in memory-related disorders[67, 68]. Stimulation of the Yintang (EX-HN3) acupoint may modify the interaction between the DLPFC and OFC to impact WM [69].

4.4 The Association Between Acute Physical Exercise-Induced Changes in Retinal Microvasculature, Cortical Hemodynamics, and Cognitive Performance

The results of the mediation analysis indicated that the association between HRV and RT was partially mediated by PFC activation. In the present study, HRV, which plays a pivotal role in cognitive enhancement, was used as an independent variable, specifically referring to changes during the 3-back task, while PFC activation was selected as a mediator, serving as a key intermediary that transmits the influence of the ANS on cognitive performance[70, 71].PFC activation acts as an indicator of neural activity and functional connectivity, demonstrating the capacity of the brain to allocate resources and coordinate activity across cortical regions. Our observation that changes in cortical hemodynamics mediate the relationship between ANS and cognitive performance.

PFC activation is directly involved in WM and cognitive control processes. The dlPFC and OFC are robustly activated during a 3-back task, and their activity levels are closely associated with improvements in RT. During the 3-back task, PFC activation significantly enhances the ACC and speed of cognitive performance. Increased dlPFC activation is negatively correlated with faster RT, indicating that this region shortens RT by optimizing conflict monitoring and decision-making processes[72–74]. Moreover, fluctuations in PFC activation account for interindividual differences in cognitive performance. This indicates that reduced dlPFC activity is linked to greater RT variability, consistent with a decline in the stability of cognitive control[75, 76]. Hence, the PFC likely acts as a mediator, integrating autonomic inputs, such as HRV, to adjust cognitive resource allocation and thereby modulate behavioral performance.

These findings suggest that HRV changes indirectly regulate RT by influencing prefrontal neural activity. HRV reflects vagal tone and physiological arousal, whereas the prefrontal cortex (e.g., dlPFC and OFC) serves as a key hub connecting autonomic states with higher-order cognition. In studies combining HRV monitoring and fMRI, higher HRV predicts enhanced prefrontal activation, which in turn translates into faster RT during affect-attention control tasks[77, 78]. This suggests that increased HRV, reflecting better autonomic regulation, optimizes cognitive performance by augmenting prefrontal resources, such as conflict detection or response inhibition[79, 80]. This mechanism is particularly prominent in the 3-back task. HRV fluctuations lead to acceleration or delay in RT through corresponding changes in the PFC (e.g., dlPFC) activity[72, 78].

Conclusion

The research demonstrates that TEAS significantly enhances WM in the context of non-nap among interns, who routinely face circadian disruption, sleep restriction, and cognitive overload. The acute cognitive fatigue induced in our model mirrors the mental state often encountered during extended duties. Our results propose TEAS as a practical, non-invasive, and time-efficient intervention that could be deployed to rapidly bolster cognitive readiness and mitigate fatigue-related errors in clinical settings. This intervention regulates specific neural activities in the prefrontal cortex, leading to substantial improvements in cognitive behavioral performance. Additionally, it promotes a dynamic balance between the sympathetic and vagus nerves, enhances HRV, and increases adaptive capacity to external environmental changes. High vagus nerve-mediated HRV indicates the predominance of parasympathetic regulation over cardiac function, characterized by strong neuro-visceral integration, a more adaptable autonomic nervous system, and a tighter coupling between brain and heart. This neuro-visceral integration optimizes resource allocation in the prefrontal cortex, facilitating rapid adaptation to task demands. Importantly, these findings affirm that TEAS is an effective intervention for enhancing WM and mitigating mental fatigue, providing a foundation for targeted interventions that address both the brain's functional changes underlying cognitive performance and individual differences in autonomic nervous regulation.

Abbreviations

ACC, accuracy

AD, Alzheimer's disease

DLPFC, dorsolateral prefrontal cortex

fNIRS, functional near-infrared spectroscopy

HbO, oxygenated hemoglobin

HRV, heart rate variability

MCI, mild cognitive impairment

mPFC, medial prefrontal cortex

NASA-TLX, NASA task load index

OFC, orbitofrontal cortex

PFC, prefrontal cortex

PSQI, pittsburg sleep quality index

RT, reaction time

TEAS, transcutaneous electrical acupoint stimulation

WM, working memory

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of the Fourth Military Medical University (Ethical number: KY20243597-1), and written informed consent was obtained from all participants prior to their enrollment.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Funding

The study was funded by Equipment Technology Foundation Project (145BZB2100101353X), National Natural Science Foundation of China (No. 82570613), Innovation Capacity Support Program of Shaanxi Province (No. 2025JC-GXPT-036), China National Postdoctoral Program for Innovative Talents and Medical Science (No. BX20250458) and Technology R&D Program (2025JSKY18).

Conflict of Interest

The authors declare no conflict of interest.

Authors' contributions

Conceptualization, X.S. and G.Y.; methodology, Z.L.; software, L.W.; validation, J.F., Y.W. and C.L.; formal analysis, J.F.; investigation, Y.W.; resources, Y.P. and Y.W.; data curation, S.L.; writing—original draft preparation, J.F.; writing—review and editing, L.W.; visualization, Y.W.; supervision, Y.G.; project administration, X.S. and Y.G.; funding acquisition, X.S. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

We thank the participants for their involvement in the study as well as the researchers involved in coordinating data collection for this project.

References

1. Maguire T, Furness T, Olasoji M, Willetts G, Levett-Jones T: Investigating the Suitability of

the Forensic Mental Health Nursing Clinical Reasoning Cycle for Nurses Working in Generalist Mental Health Settings. *International journal of mental health nursing* 2025, 34(1):e13481.

2. Mouchabac S, Conejero I, Lakhlifi C, Msellek I, Malandain L, Adrien V, Ferreri F, Millet B, Bonnot

O, Bourla A *et al*: Improving clinical decision-making in psychiatry: implementation of digital phenotyping could mitigate the influence of patient's and practitioner's individual cognitive biases. *Dialogues in clinical neuroscience* 2021, 23(1):52-61.

3. Li J, Cao Y, Ou S, Jiang T, Wang L, Ma N: The effect of total sleep deprivation on working

memory: evidence from diffusion model. *Sleep* 2024, 47(2).

4. Ayres-de-Campos D: A wider agreement is needed on basic intrapartum concepts.

American journal of obstetrics and gynecology 2023, 228(5s):S994-s996.

5. Souabni M, Hammouda O, Romdhani M, Trabelsi K, Ammar A, Driss T: Benefits of Daytime

Napping Opportunity on Physical and Cognitive Performances in Physically Active Participants: A Systematic Review. *Sports medicine (Auckland, NZ)* 2021, 51(10):2115-2146.

6. Mesas AE, Núñez de Arenas-Arroyo S, Martinez-Vizcaino V, Garrido-Miguel M, Fernández-

Rodríguez R, Bizzozero-Peroni B, Torres-Costoso AI: Is daytime napping an effective strategy to improve sport-related cognitive and physical performance and reduce fatigue? A systematic review and meta-analysis of randomised controlled trials. *British journal of sports medicine* 2023, 57(7):417-426.

7. Stepan ME, Altmann EM, Fenn KM: Slow-wave sleep during a brief nap is related to reduced

cognitive deficits during sleep deprivation. *Sleep* 2021, 44(11).

8. Pessiglione M, Blain B, Wiehler A, Naik S: Origins and consequences of cognitive fatigue.

Trends in cognitive sciences 2025, 29(8):730-749.

9. Laborde S, Mosley E, Ueberholz L: Enhancing cardiac vagal activity: Factors of interest for sport psychology. *Progress in brain research* 2018, 240:71-92.

10. Thayer JF, Lane RD: Claude Bernard and the heart-brain connection: further elaboration of a model of neurovisceral integration. *Neuroscience and biobehavioral reviews* 2009, 33(2):81-88.

11. Zhou J, Huebner G, Liu KY, Ucci M: Heart rate variability, electrodermal activity and cognition in adults: Association with short-term indoor PM2.5 exposure in a real-world intervention study. *Environmental research* 2024, 263(Pt 3):120245.

12. Liu KY, Elliott T, Knowles M, Howard R: Heart rate variability in relation to cognition and behavior in neurodegenerative diseases: A systematic review and meta-analysis. *Ageing research reviews* 2022, 73:101539.

13. Jandackova VK, Scholes S, Britton A, Steptoe A: Midlife heart rate variability and cognitive decline: A large longitudinal cohort study. *International journal of clinical and health psychology : IJCHP* 2024, 24(4):100518.

14. Mather M: Autonomic dysfunction in neurodegenerative disease. *Nature reviews Neuroscience* 2025, 26(5):276-292.

15. Horsager J, Knudsen K, Sommerauer M: Clinical and imaging evidence of brain-first and body-first Parkinson's disease. *Neurobiology of disease* 2022, 164:105626.

16.Lazaridi M, Panagiotaropoulou G, Covanis P, Karantinos T, Aggelopoulos E, Klein C, Smyrnis N: Brain-Heart Link in Schizophrenia: Cognitive Inhibitory Control Deficit in Patients Is Specifically Related to Parasympathetic Dysregulation. *Schizophrenia bulletin* 2022,48(5):1155-1163.

17.Lee KFA, Chan E, Car J, Gan WS, Christopoulos G: Lowering the Sampling Rate: Heart Rate Response during Cognitive Fatigue. *Biosensors* 2022, 12(5).

18.Khan MS, Javaid SS, Mentz RJ, Lindenfeld J, Wu HT, Prochaska JH, Johansen JB, Wild PS, Linz D, Dinh W *et al*: Heart rate variability in patients with cardiovascular diseases. *Progress in cardiovascular diseases* 2025, 91:67-79.

19.Li L, Hu D, Zhang W, Cui L, Jia X, Yang D, Liu S, Deng F, Liu J, Guo X: Effect of short-term exposure to particulate air pollution on heart rate variability in normal-weight and obese

adults. *Environmental health : a global access science source* 2021, 20(1):29.

20.Lee Y, Walsh RJ, Fong MWM, Sykora M, Doering MM, Wong AWK: Heart rate variability as a biomarker of functional outcomes in persons with acquired brain injury: Systematic review and meta-analysis. *Neuroscience and biobehavioral reviews* 2021, 131:737-754.

21.Lohman T, Kapoor A, Engstrom AC, Shenasa F, Alitin JPM, Gaubert A, Rodgers KE, Bradford D, Mather M, Han SD *et al*: Central autonomic network dysfunction and plasma Alzheimer's disease biomarkers in older adults. *Alzheimer's research & therapy* 2024, 16(1):124.

22.Faingold CL: Lethal Interactions of neuronal networks in epilepsy mediated by both synaptic and volume transmission indicate approaches to prevention. *Progress in neurobiology* 2025, 249:102770.

23.Hintiryan H, Zhu M, Zhao P, Zhang M, Barry J, Nanda S, Rudd M, Wong A, Miller S, Gou L *et al*: Neural networks of the mouse visceromotor cortex. *Nature* 2025.

24.Shah AJ, Wittbrodt MT, Bremner JD, Vaccarino V: Cardiovascular pathophysiology from the cardioneural perspective and its clinical applications. *Trends in cardiovascular medicine* 2022, 32(3):172-177.

25.Yeater TD, Cruz CJ, Cruz-Almeida Y, Allen KD: Autonomic Nervous System Dysregulation and Osteoarthritis Pain: Mechanisms, Measurement, and Future Outlook. *Current rheumatology reports* 2022, 24(6):175-183.

26.Zhang H, Chen WJ, Chao YG, Su N, Robba C, Czosnyka M, Smielewski P, Czosnyka Z, He W, Hu X *et al*: Neurogenic organ dysfunction syndrome after acute brain injury. *Military Medical Research* 2025, 12(1):77.

27.De la Cruz F, Teed AR, Lapidus RC, Upshaw V, Schumann A, Paulus MP, Bär KJ, Khalsa SS: Central Autonomic Network Alterations in Anorexia Nervosa Following Peripheral Adrenergic Stimulation. *Biological psychiatry Cognitive neuroscience and neuroimaging* 2023, 8(7):720-730.

28.Ferraro S, Klugah-Brown B, Tench CR, Bazinet V, Bore MC, Nigri A, Demichelis G, Bruzzone MG, Palermo S, Zhao W *et al*: The central autonomic system revisited - Convergent evidence for a regulatory role of the insular and midcingulate cortex from neuroimaging meta-analyses. *Neuroscience and biobehavioral reviews* 2022, 142:104915.

29.Osei GN, Bockarie A, Akpalu A, Adueming PO, Antwi MH, Appiah F, Kpelle L, Donkor DM, Simpong DL: Diagnostic potential of near-infrared spectroscopy in mild cognitive impairment SD and neurodegenerative disorders: Implications for resource-limited settings. *Alzheimer's & dementia : the journal of the Alzheimer's Association* 2025, 21(10):e70769.
30.Lü Y, Chen M, Zhang W, Yu W: Biomarkers. *Alzheimer's & dementia : the journal of the Alzheimer's Association* 2025, 21 Suppl 2(Suppl 2):e101537.
31.Ziegler KA, Engelhardt S, Carnevale D, McAlpine CS, Guzik TJ, Dimmeler S, Swirski FK: Neural Mechanisms in Cardiovascular Health and Disease. *Circulation research* 2025, 136(11):1233-1261.
32.Ding F, Jia S, Xin X, Li S, Liu C, Guo Z, Liu Q, Ma X, Wei C, Wang X: Imbalance, compensation, and rigidity in brain functional connectivity and microstates among older adults with cognitive impairment. *Journal of neuroengineering and rehabilitation* 2025, 22(1):255.
33.Hu Y, Qiu Y, Chen Y, Wang Y, Dai Y, Xu Q, Zhou Y: Neurovascular coupling alterations related to cognitive impairment in cerebral small vessel disease: A multiscale brain network perspective. *Progress in neuro-psychopharmacology & biological psychiatry* 2025, 138:111311.
34.Zhuo L, Zhao X, Zhai Y, Zhao B, Tian L, Zhang Y, Wang X, Zhang T, Gan X, Yang C *et al*: Transcutaneous electrical acupoint stimulation for children with attention-deficit/hyperactivity disorder: a randomized clinical trial. *Translational psychiatry* 2022, 12(1):165.
35.Li Q, Gong Y, Cui Y, Cheng C, Wang Y, Huang G, Gu W, Meng B, Wang M, Wu D *et al*: Efficacy of transcutaneous electrical acupoint stimulation for patients with first-episode schizophrenia: An 8-week, preliminary, randomized controlled trial. *Psychiatry research* 2023, 325:115255.
36.Cai M, Park HR, Yang EJ: Electroacupuncture modulates glutamate neurotransmission to alleviate PTSD-like behaviors in a PTSD animal model. *Translational psychiatry* 2023, 13(1):357.
37.Liu S, Wang Z, Su Y, Qi L, Yang W, Fu M, Jing X, Wang Y, Ma Q: A neuroanatomical basis for electroacupuncture to drive the vagal-adrenal axis. *Nature* 2021, 598(7882):641-645.
38.Oh JY, Lee H, Jang SY, Kim H, Park G, Serikov A, Jang JH, Kim J, Yang S, Sa M *et al*: Central Role of Hypothalamic Circuits for Acupuncture's Anti-Parkinsonian Effects. *Advanced science*

(Weinheim, Baden-Wurttemberg, Germany) 2024, 11(43):e2403245.

39.Wang J, Zhang Q, Yao L, He T, Chen X, Su Y, Sun S, Fan M, Yan J, Wang T *et al*: Modulating activity of PVN neurons prevents atrial fibrillation induced circulation dysfunction by electroacupuncture at BL15. *Chinese medicine* 2023, 18(1):135.

40.Hernandez R, Roll SC, Jin H, Schneider S, Pyatak EA: Validation of the National Aeronautics and Space Administration Task Load Index (NASA-TLX) adapted for the whole day repeated measures context. *Ergonomics* 2022, 65(7):960-975.

41.Said S, Gozdzik M, Roche TR, Braun J, Rössler J, Kaserer A, Spahn DR, Nöthiger CB, Tscholl DW: Validation of the Raw National Aeronautics and Space Administration Task Load Index (NASA-TLX) Questionnaire to Assess Perceived Workload in Patient Monitoring Tasks: Pooled Analysis Study Using Mixed Models. *Journal of medical Internet research* 2020, 22(9):e19472.

42.Asgher U, Khan MJ, Asif Nizami MH, Khalil K, Ahmad R, Ayaz Y, Naseer N: Motor Training Using Mental Workload (MWL) With an Assistive Soft Exoskeleton System: A Functional Near-Infrared Spectroscopy (fNIRS) Study for Brain-Machine Interface (BMI). *Frontiers in neurorobotics* 2021, 15:605751.

43.Lim LG, Ung WC, Chan YL, Lu CK, Sutoko S, Funane T, Kiguchi M, Tang TB: A Unified Analytical Framework With Multiple fNIRS Features for Mental Workload Assessment in the Prefrontal Cortex. *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society* 2020, 28(11):2367-2376.

44.Uga M, Dan I, Sano T, Dan H, Watanabe E: Optimizing the general linear model for functional near-infrared spectroscopy: an adaptive hemodynamic response function approach. *Neurophotonics* 2014, 1(1):015004.

45.Abe MO, Koike T, Okazaki S, Sugawara SK, Takahashi K, Watanabe K, Sadato N: Neural correlates of online cooperation during joint force production. *NeuroImage* 2019, 191:150-161.

46.Tian F, Liu H: Depth-compensated diffuse optical tomography enhanced by general linear model analysis and an anatomical atlas of human head. *NeuroImage* 2014, 85 Pt 1(0 1):166-

180.

47.Chapman CL, Schafer EA, Potter AW, Lavoie EM, Roberts BM, Castellani JW, Friedl KE, Looney DP: Day-to-day reliability of basal heart rate and short-term and ultra short-term heart rate variability assessment by the Equivital eq02+ LifeMonitor in US Army soldiers. *BMJ military health* 2024.

48.Du K, Yang S, Wang J, Zhu G: Acupuncture Interventions for Alzheimer's Disease and Vascular Cognitive Disorders: A Review of Mechanisms. *Oxidative medicine and cellular longevity* 2022, 2022:6080282.

49.Wang L, Zhang J, Guo C, He J, Zhang S, Wang Y, Zhao Y, Li L, Wang J, Hou L *et al*: The efficacy and safety of transcutaneous auricular vagus nerve stimulation in patients with mild cognitive impairment: A double blinded randomized clinical trial. *Brain stimulation* 2022, 15(6):1405-1414.

50.Cao H, Shang L, Hu D, Huang J, Wang Y, Li M, Song Y, Yang Q, Luo Y, Wang Y *et al*: Neuromodulation techniques for modulating cognitive function: Enhancing stimulation precision and intervention effects. *Neural regeneration research* 2026, 21(2):491-501.

51.Leong RLF, Lau T, Dicom AR, Teo TB, Ong JL, Chee MWL: Influence of mid-afternoon nap duration and sleep parameters on memory encoding, mood, processing speed, and vigilance. *Sleep* 2023, 46(4).

52.Xie T, Ma N: Tracking vigilance fluctuations in real-time: a sliding-window heart rate variability-based machine-learning approach. *Sleep* 2025, 48(2).

53.Shokri-Kojori E, Tomasi D, Demiral SB, Wang GJ, Volkow ND: An autonomic mode of brain activity. *Progress in neurobiology* 2023, 229:102510.

54.Porges SW: The polyvagal perspective. *Biological psychology* 2007, 74(2):116-143.

55.Thayer JF, Lane RD: A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of affective disorders* 2000, 61(3):201-216.

56.Lyu J, Yeh CH, Shi W, Penzel T: Dynamic brain-heart interaction in sleep characterized by variational phase-amplitude coupling framework. *Communications biology* 2025, 8(1):1235.

57.Schiweck C, Aichholzer M, Brandt E, Schneider M, Meyer K, Hamzehloiya T, Qubad M, Uckermark C, Jacobsen L, Amaral K *et al*: The heart knows best: baseline heart rate variability as guide to transcutaneous auricular vagus nerve stimulation in depression. *Translational*

psychiatry 2025, 15(1):521.

58.Stavrakis S, Chakraborty P, Farhat K, Whyte S, Morris L, Abideen Asad ZU, Karfonta B, Anjum J, Matlock HG, Cai X *et al*: Noninvasive Vagus Nerve Stimulation in Postural Tachycardia Syndrome: A Randomized Clinical Trial. *JACC Clinical electrophysiology* 2024, 10(2):346-355.

59.Leddy JJ, Haider MN, Chizuk HM, Nazir MSZ, Worts P, Willer BS, Johnson BD: Cardiovascular and Respiratory Responses During Graded Exercise in Adolescents After Sport-Related Concussion. *Sports medicine (Auckland, NZ)* 2026, 56(1):271-282.

60.Proietti F, Ottaviani MM, Burchi E, Vivacqua G, Anzini G, Ricciuti RA, Capone F, Macefield VG, Di Lazzaro V, Marano M: Vagus Nerve Stimulation in Movement Disorders, from Principles to a Systematic Review of Evidence. *Movement disorders : official journal of the Movement Disorder Society* 2025, 40(12):2559-2577.

61.Murphy AJ, O'Neal AG, Cohen RA, Lamb DG, Porges EC, Bottari SA, Ho B, Trifilio E, DeKosky ST, Heilman KM *et al*: The Effects of Transcutaneous Vagus Nerve Stimulation on Functional Connectivity Within Semantic and Hippocampal Networks in Mild Cognitive Impairment. *Neurotherapeutics : the journal of the American Society for Experimental NeuroTherapeutics* 2023, 20(2):419-430.

62.Giraudier M, Ventura-Bort C, Burger AM, Claes N, D'Agostini M, Fischer R, Franssen M, Kaess M, Koenig J, Liepelt R *et al*: Evidence for a modulating effect of transcutaneous auricular vagus nerve stimulation (taVNS) on salivary alpha-amylase as indirect noradrenergic marker: A pooled mega-analysis. *Brain stimulation* 2022, 15(6):1378-1388.

63.Zou N, Zhou Q, Zhang Y, Xin C, Wang Y, Claire-Marie R, Rong P, Gao G, Li S: Transcutaneous auricular vagus nerve stimulation as a novel therapy connecting the central and peripheral systems: a review. *International journal of surgery (London, England)* 2024, 110(8):4993-5006.

64.Crawford LS, Yang S, Meylakh N, Sattarov L, Ramachandran A, Macefield VG, Keay KA, Henderson LA: Forebrain networks driving brainstem pain modulatory circuits during nocebo hyperalgesia in healthy humans. *Pain* 2025, 166(9):e276-e287.

65.Bijanki KR, Pathak YJ, Najera RA, Storch EA, Goodman WK, Simpson HB, Sheth SA: Defining functional brain networks underlying obsessive-compulsive disorder (OCD) using

treatment-induced neuroimaging changes: a systematic review of the literature. *Journal of neurology, neurosurgery, and psychiatry* 2021, 92(7):776-786.

66.Lee H, Choi J, Jung D, Hur JW, Cho CH: The Effects of Virtual Reality Treatment on Prefrontal Cortex Activity in Patients With Social Anxiety Disorder: Participatory and Interactive Virtual Reality Treatment Study. *Journal of medical Internet research* 2021, 23(12):e31844.

67.Lee TL, Guo L, Chan AS: fNIRS as a biomarker for individuals with subjective memory complaints and MCI. *Alzheimer's & dementia : the journal of the Alzheimer's Association* 2024, 20(8):5170-5182.

68.Wei Y, Tang X, Zhang T, Su W, Xu L, Cui H, Qian Z, Zhang T, Wang J: Reduced temporal activation during a verbal fluency test in clinical high risk of psychosis: a functional near-infrared spectroscopy-based study. *General psychiatry* 2022, 35(2):e100702.

69.McMorris T: Cognitive Fatigue Effects on Physical Performance: The Role of Interoception. *Sports medicine (Auckland, NZ)* 2020, 50(10):1703-1708.

70.Battaglia S, Thayer JF: Functional interplay between central and autonomic nervous systems in human fear conditioning. *Trends in neurosciences* 2022, 45(7):504-506.

71.Yang C, Hu Y, Talishinsky AD, Potter CT, Calva CB, Ramsey LA, Kesner AJ, Don RF, Junn S, Tan A *et al*: Medial prefrontal cortex and anteromedial thalamus interaction regulates goal-directed behavior and dopaminergic neuron activity. *Nature communications* 2022, 13(1):1386.

72.Mitterová K, Pupíková M, Gajdoš M, Eliášová I, Rektorová I: Optimizing tACS for working memory: differential outcomes in healthy aging and non-amnestic mild cognitive impairment. *Alzheimer's research & therapy* 2025, 18(1):2.

73.Xiao Q, Shen L, He H, Wang X, Fu Y, Ding J, Jiang F, Zhang J, Zhang Z, Grecucci A *et al*: Alteration of prefrontal cortex and its associations with emotional and cognitive dysfunctions in adolescent borderline personality disorder. *European child & adolescent psychiatry* 2024, 33(11):3937-3949.

74.Jeon S, Kang JE, Hwang J, Calhoun VD, Lee JH: Abnormal Association Between Neural Activity and Genetic Expressions of Impulsivity in Attention-Deficit/Hyperactivity Disorder: An Adolescent Brain Cognitive Development Study. *Biological psychiatry Cognitive*

neuroscience and neuroimaging 2025, 10(10):1078-1092.

75.Mansouri FA, Buckley MJ, Tanaka K: The neural substrate and underlying mechanisms of executive control fluctuations in primates. *Progress in neurobiology* 2022, 209:102216.

76.Qiu Y, Dou H, Becker B, He Z, Mei Y, Lei Y: Behavioral and neural dysfunctions in reward-related cognitive control among adolescents with major depressive disorder. *Psychological medicine* 2025, 55:e298.

77.Corcoran AW, Le Coz A, Hohwy J, Andrillon T: When your heart isn't in it anymore: cardiac correlates of task disengagement. *Communications biology* 2025, 8(1):1646.

78.Yoo HJ, Nashiro K, Min J, Cho C, Mercer N, Bachman SL, Nasseri P, Dutt S, Porat S, Choi P *et al*: Multimodal neuroimaging data from a 5-week heart rate variability biofeedback randomized clinical trial. *Scientific data* 2023, 10(1):503.

79.Zhu S, Liu Q, Zhang X, Zhou M, Zhou X, Ding F, Zhang R, Becker B, Kendrick KM, Zhao W: Transcutaneous auricular vagus nerve stimulation enhanced emotional inhibitory control via increasing intrinsic prefrontal couplings. *International journal of clinical and health psychology : IJCHP* 2024, 24(2):100462.

80.Tan G, Adams J, Donovan K, Demarest P, Willie JT, Brunner P, Gorlewicz JL, Leuthardt EC: Does vibrotactile stimulation of the auricular vagus nerve enhance working memory? A behavioral and physiological investigation. *Brain stimulation* 2024, 17(2):460-468.

Figures

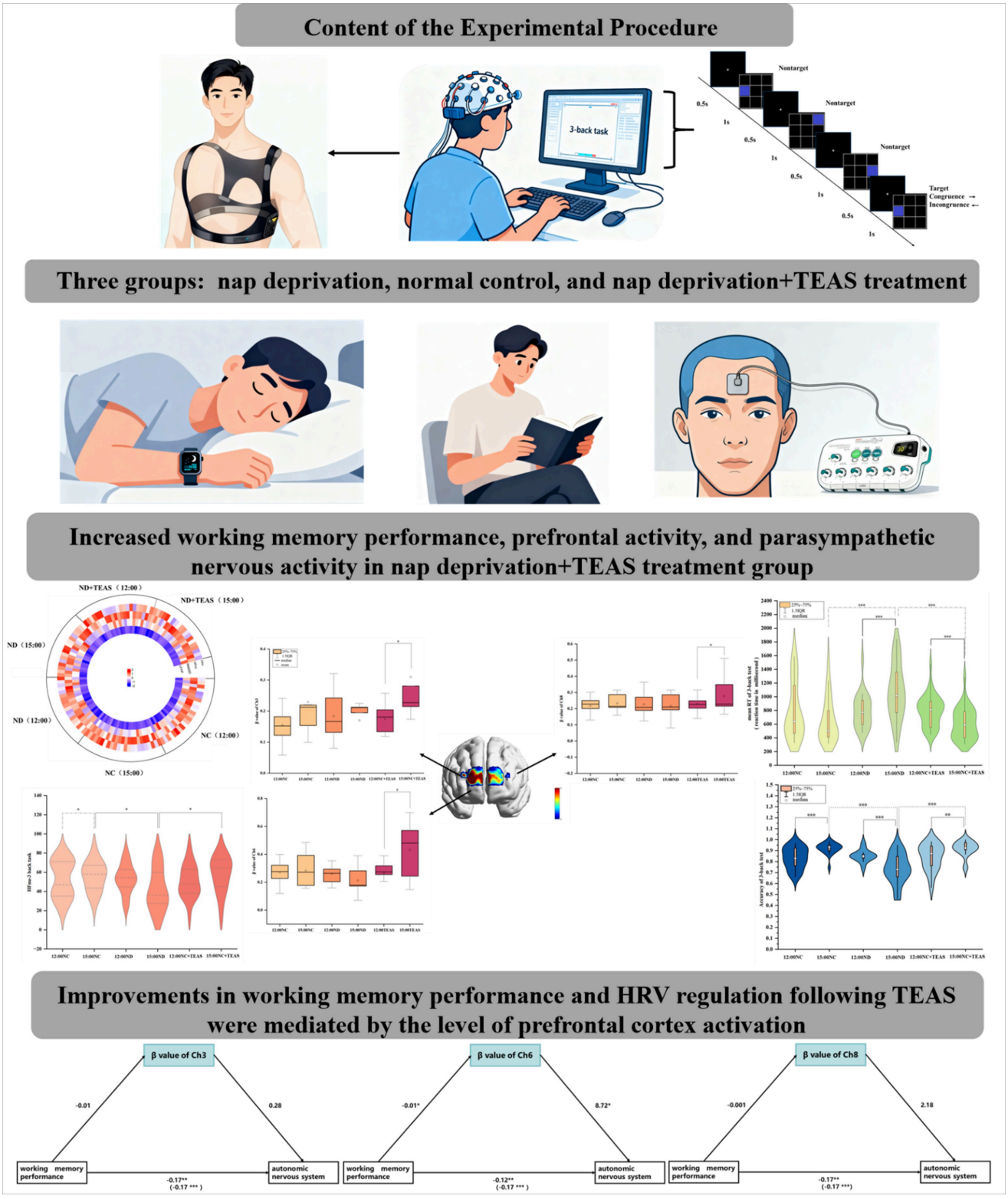


Figure 1

Schematic diagram of the experimental procedure.

NC: normal control group; ND: nap deprivation group; ND+TEAS: nap deprivation group receiving TEAS intervention

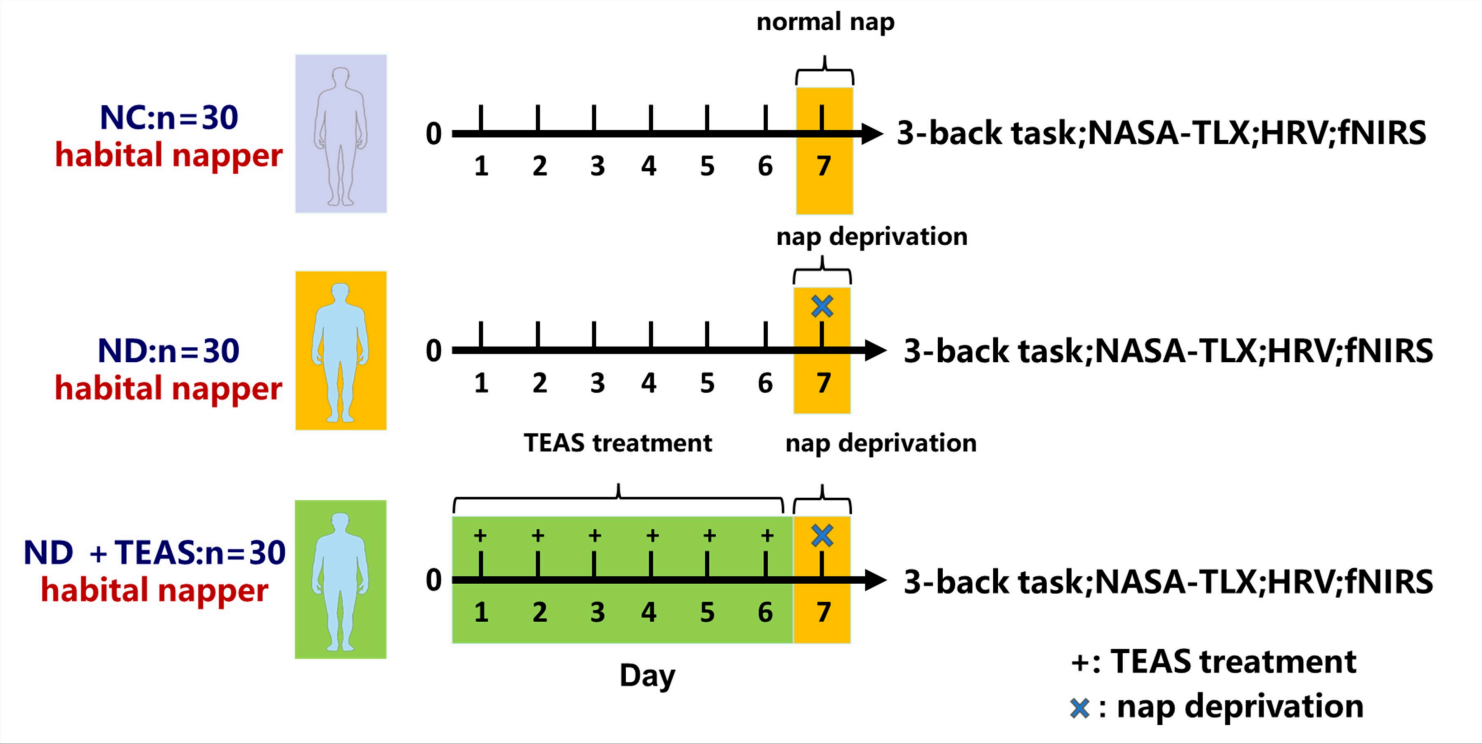


Figure 2

The flow path of the 3-back

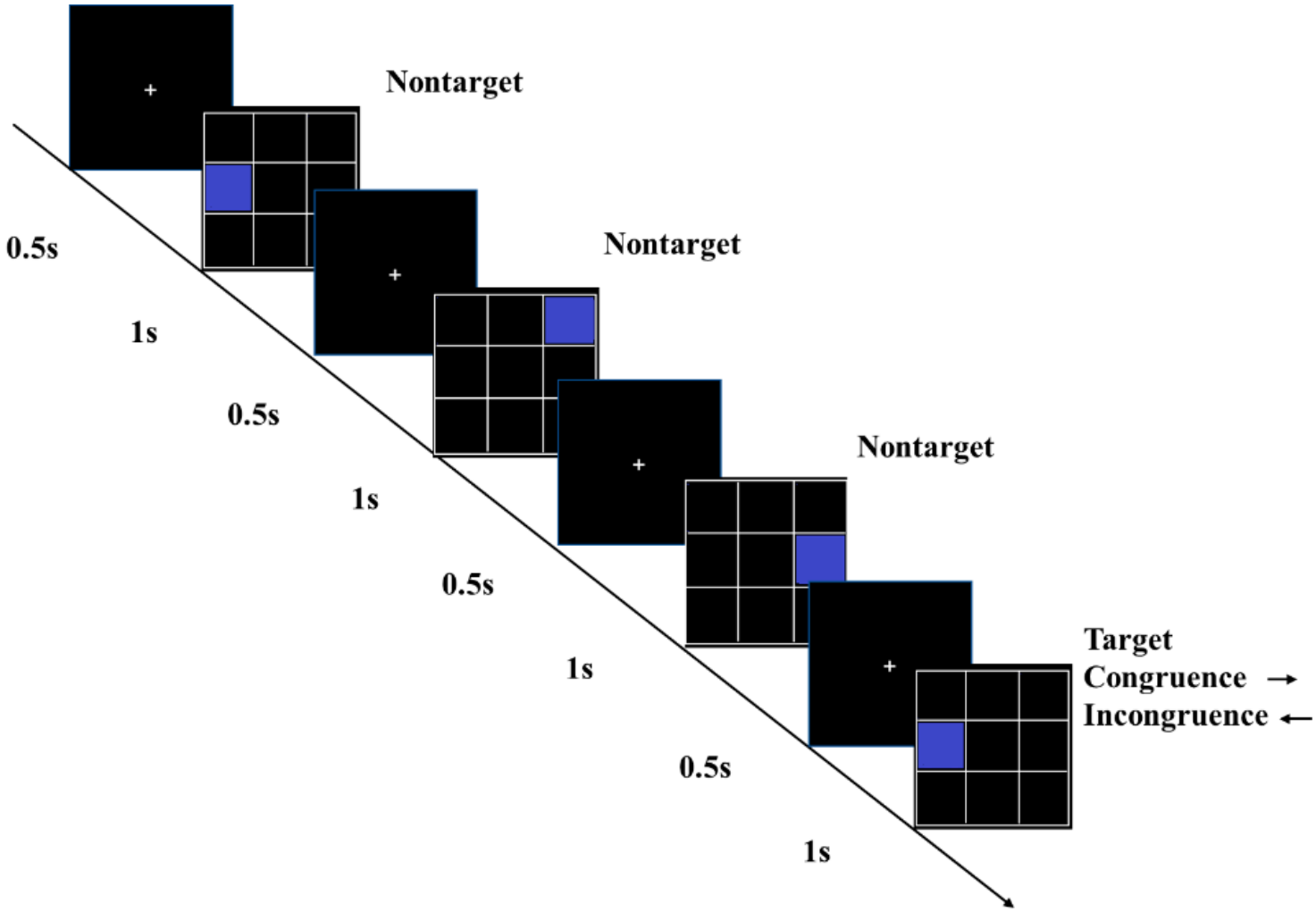
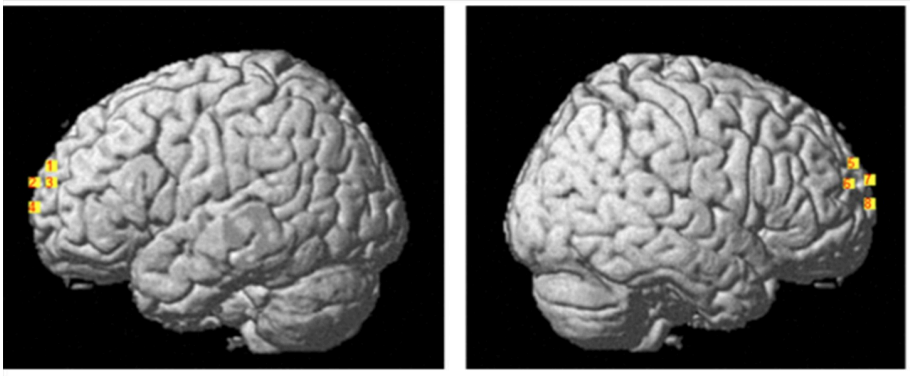


Figure 3

Optode placement on the forehead.



Channel	MNI		
Ch1	-38.67	66.39	32.11
Ch2	-30.25	73.72	27.46
Ch3	-45.02	67.68	15.14
Ch4	-34.7	75.52	11.82
Ch5	39.76	60.69	37.53
Ch6	42.24	67.12	19.74
Ch7	30.63	71.75	29.35
Ch8	34.81	73.86	15.02

Figure 4

The differences in NASA-TLX scale scores among three groups at 12:00 and 15:00. (A) Mental Demand (MD), (B)Physical Demand (PD), (C)Temporal Demand (TD), (D)Frustration (Fr), (E) Effort (Ef), and (F)Performance (Pe). Normal control group (NC), Nap deprivation group (ND) and Nap deprivation group receiving TEAS intervention (ND+TEAS). $^{*}p<0.05$,$^{**}p<0.01$,$^{***}p<0.001$.

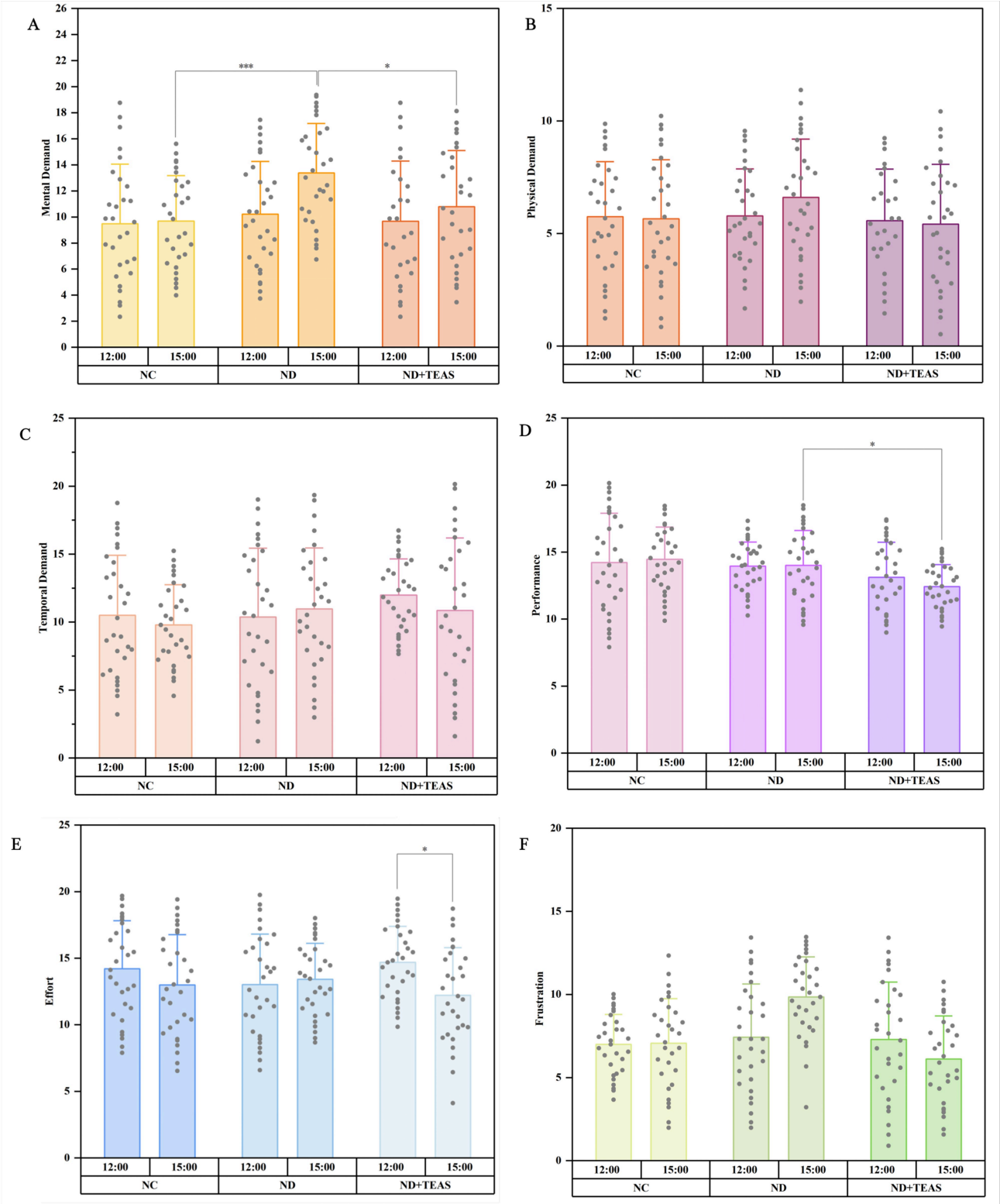


Figure 5

The differences in reaction time (A) and accuracy (B) among three groups during the 3-back test. The upper and lower lines of the box in a box-violin plot represent the upper and lower quartiles respectively. Normal control group (NC), Nap deprivation group (ND) and Nap deprivation group receiving TEAS intervention (ND+TEAS). $^{**}p<0.01$,$^{***}p<0.001$.

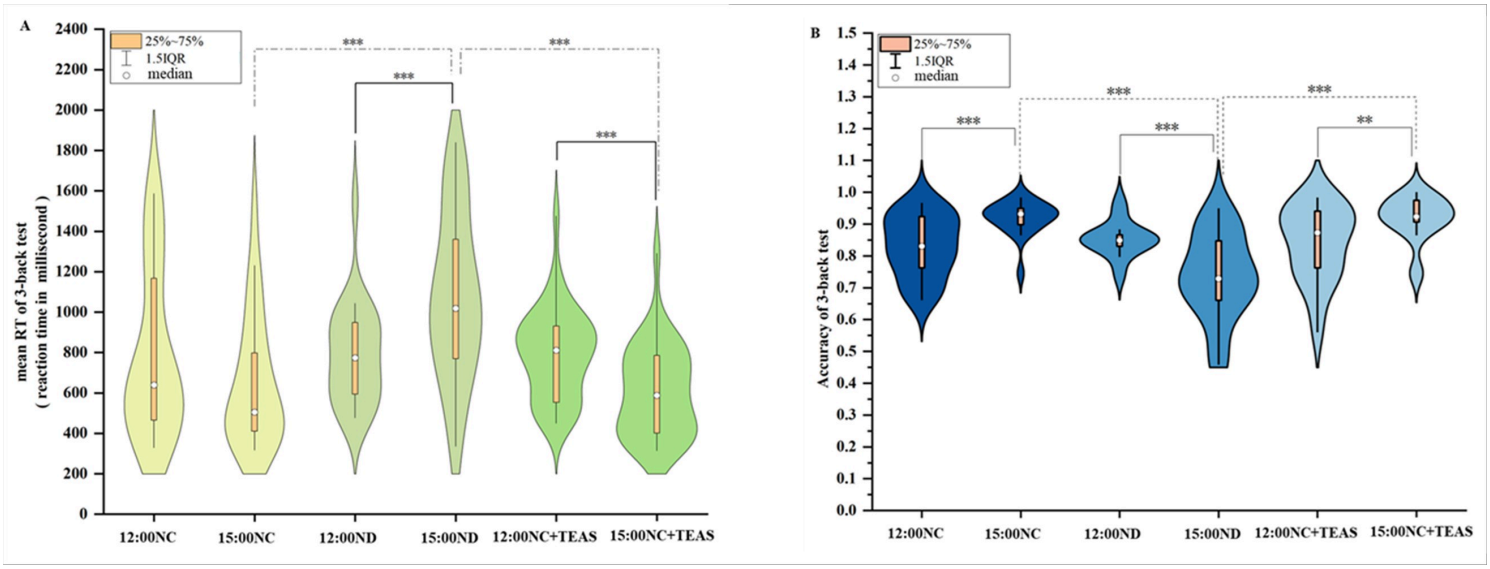


Figure 6

The differences in LFnu、HFnu、RMSSD and LF/HF among three groups during the 3-back task. The upper and lower lines of the box in a box-violin plot represent the upper and lower quartiles, respectively. Normal control group (NC), Nap deprivation group (ND) and Nap deprivation group receiving TEAS intervention (ND+TEAS). $^{**}p<0.01$,$^{***}p<0.001$.

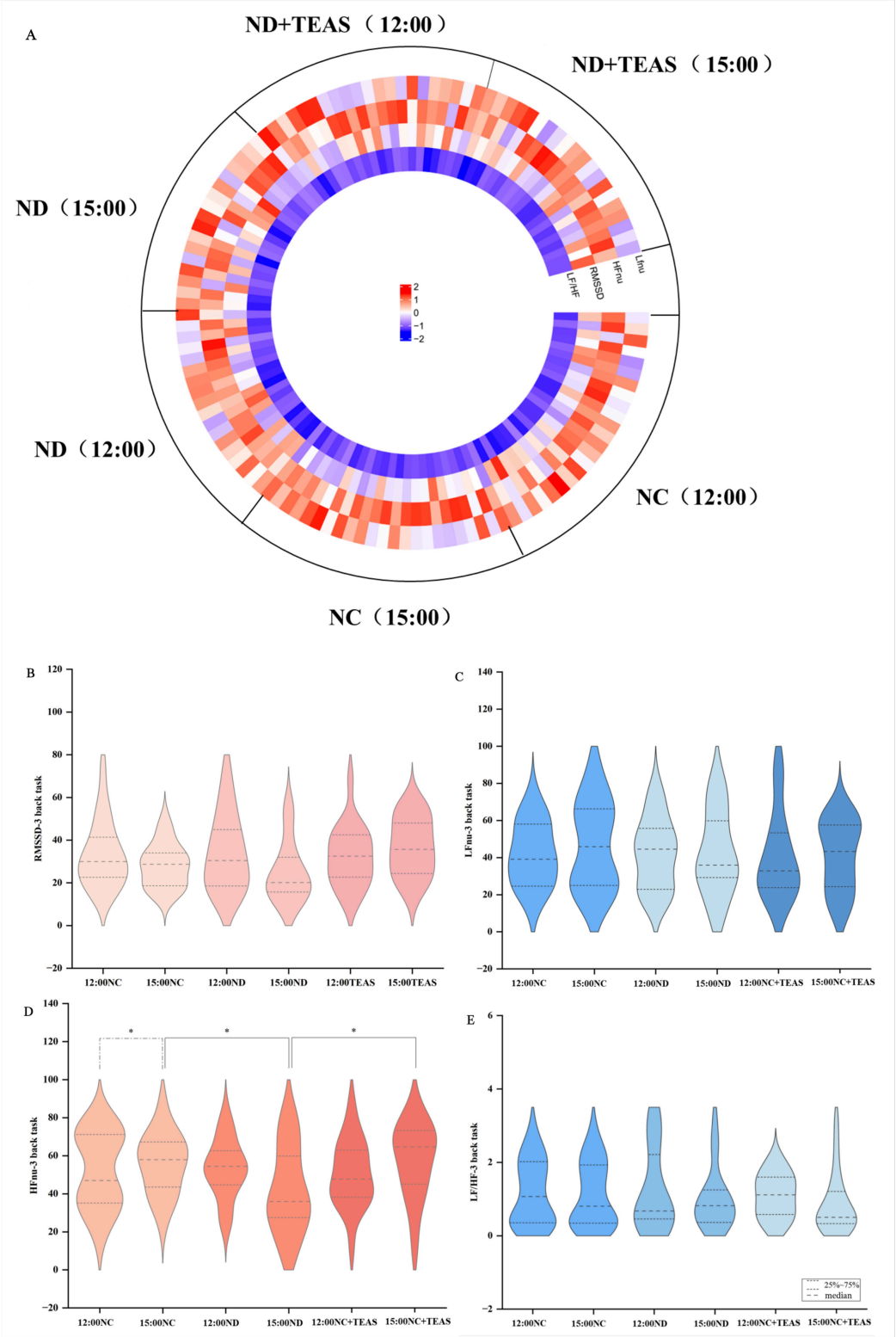


Figure 7

The graphs show corresponding changes in group-average HbO Beta values for each group and time.（A）Channel map of brain regions that showed interaction of group and time affecting HbO activation in the PFC. （B）The main effect of time on HbO activation in the PFC. （C）The main effect of group on HbO activation in the PFC.（D）The β values of Ch3 among three groups during the 3-back task. （E）The β values of Ch3 among three groups during the 3-back task. （F）The β values of Ch3 among three groups during the 3-back task. $^{*}p<0.05$

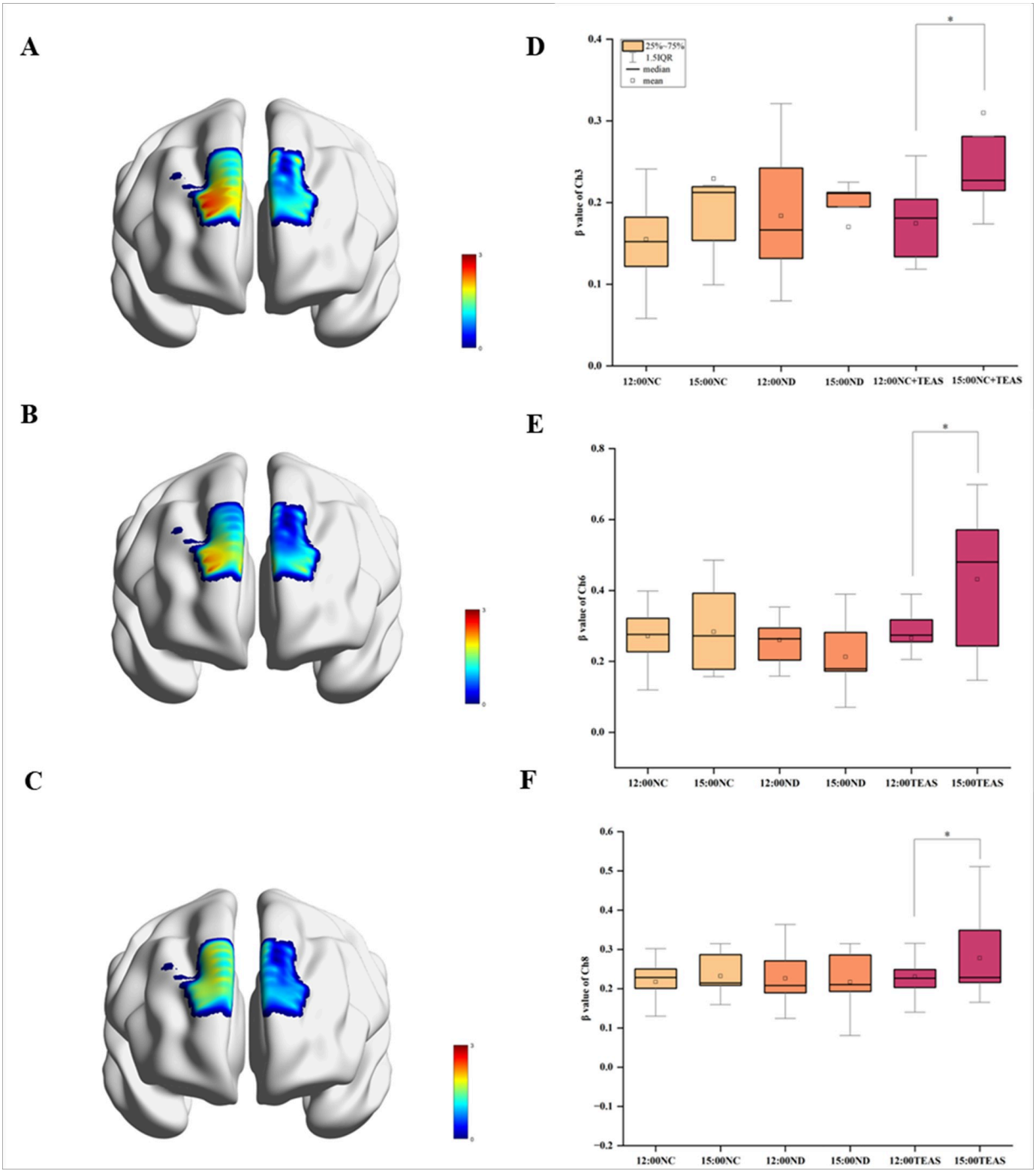


Figure 8

Results of the mediation analysis are presented as standardized coefficients. The total effect is reported in brackets and the direct effect above it. The mediators depicted were related to β values of Ch3, Ch6 and Ch8. Note. The total effect is reported in brackets. *$p < 0.05$**$p< 0.01$***$p< 0.001$.