



Original Article

Phase-amplitude coupling of Go/Nogo task-related neuronal oscillation decreases for humans with insufficient sleep

Peng Zhang¹, Chuancui Sun^{2,3}, Zhongqi Liu^{2,3} and Qianxiang Zhou^{2,3,*}

¹School of Psychology, Beijing Key Laboratory of Learning and Cognition, Capital Normal University, Beijing, China,

²School of Biological Science and Medical Engineering, Beihang University, Beijing, China and

³The First Affiliated Hospital of Shandong First Medical University, Nephrology, Jinan, China

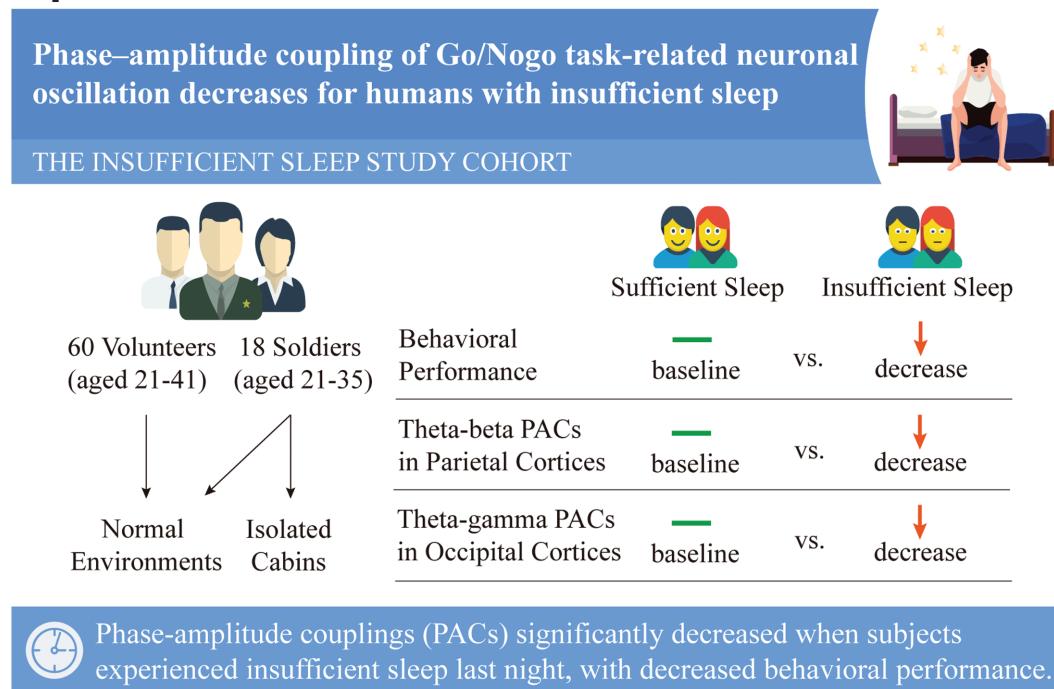
*Corresponding author: Qianxiang Zhou, School of Biological Science and Medical Engineering, Beihang University, No. 37, Xueyuan Road, Haidian District, Beijing 100191, China. Email: zqx_buaa@163.com.

Abstract

Phase-amplitude coupling (PAC) across frequency might be associated with the long-range synchronization of brain networks, facilitating the spatiotemporal integration of multiple cell assemblies for information transmission during inhibitory control. However, sleep problems may affect these cortical information transmissions based on cross-frequency PAC, especially when humans work in environments of social isolation. This study aimed to evaluate changes in the theta–beta/gamma PAC of task-related electroencephalography (EEG) for humans with insufficient sleep. Here, we monitored the EEG signals of 60 healthy volunteers and 18 soldiers in the normal environment, performing a Go/Nogo task. Soldiers also participated in the same test in isolated cabins. These measures demonstrated theta–beta PACs between the frontal and central-parietal, and robust theta–gamma PACs between the frontal and occipital cortex. Unfortunately, these PACs significantly decreased when humans experienced insufficient sleep, which was positively correlated with the behavioral performance of inhibitory control. The evaluation of theta–beta/gamma PAC of Go/Nogo task-related EEG is necessary to help understand the different influences of sleep problems in humans.

Key words: sleep problems; phase-amplitude coupling; EEG; Go/Nogo task; inhibitory control

Graphical Abstract



Phase-amplitude couplings (PACs) significantly decreased when subjects experienced insufficient sleep last night, with decreased behavioral performance.

Statement of Significance

Insufficient sleep has always been a problem for special populations working in environments of social isolation and is becoming increasingly common for ordinary workers in modern society. Our study provides new evidence of abnormal neural oscillation caused by human sleep problems. Our experiments proved that the theta-beta/gamma Phase-amplitude coupling (PAC) change could effectively evaluate insufficient sleep's neurological and behavioral influence. These particular neuronal PACs might serve as the basis for future sleep studies and act as a potential signature to guide countermeasures to sleep problems for humans in social isolation environments.

Introduction

Sleep disorders are severe problems for special populations working in environments of social isolation, presenting unprecedented behavioral challenges to humans [1]. Under normal conditions, the circadian process is synchronized with the light-dark cycle, which is different in space travel because the International Space Station orbits Earth every 90 minutes [2]; this problem accompanied by social isolation will result in sleep problems for astronauts. In today's busy society, the average sleep duration of the general population is also decreasing as stress increases. Falling asleep does not mean the brain switches off. Instead, the neural circuitry actively works through a complex architecture of sleep stages, including a series of carefully interleaved cognitive and physiological processing states [3–5]. Thus, we speculate that if humans do not sleep sufficiently on the first night, the neural circuit remains abnormal during tasks performed the next day, accompanied by decreased behavioral performance.

Phase-amplitude coupling (PAC) across frequency represents neuron synchronous discharge and might be associated with the long-range synchronization of brain networks, facilitating the spatiotemporal integration of multiple cell assemblies for information transmission [6]. Notably, the gamma rhythmic oscillation might enable information coding through spike-timing-dependent plasticity, and the slow-wave oscillation modulates the

activity in the gamma band, which might be a physiological basis of complex cognitive operations [7–9]. Takeuchi et al. [10] applied a recently developed empirical mode decomposition analysis and found strong cross-frequency PAC between high-frequency and slow-wave oscillations during sleep. They proposed that spatio-temporal integration through coupled oscillations occurring in slow-wave sleep states might be a physiological basis of system consolidation, and gamma bursts in rapid eye movement sleep might be related to synaptic consolidation. Sleep is a physiological state characterized by changes in neural oscillations [11], so we speculated that insufficient sleep may affect cortical information transmission based on cross-frequency PAC.

Previous studies have indicated that the trough of slow-wave oscillations is associated with faster neuronal spiking than the inhibitory peak, and this principle is also suggested to hold true for frontal theta waves as a component of inhibitory control [12]. James et al. [13] reported that theta band activities over the mid-frontal cortex appear to reflect a common computation used to achieve inhibitory control. These theta oscillations might be used to communicate the need for inhibitory control and implement such control across disparate brain regions as a biologically plausible candidate for neuronal communication. Berger et al. [14] further demonstrated that during task performance, the human brain used a theta-gamma PAC mechanism

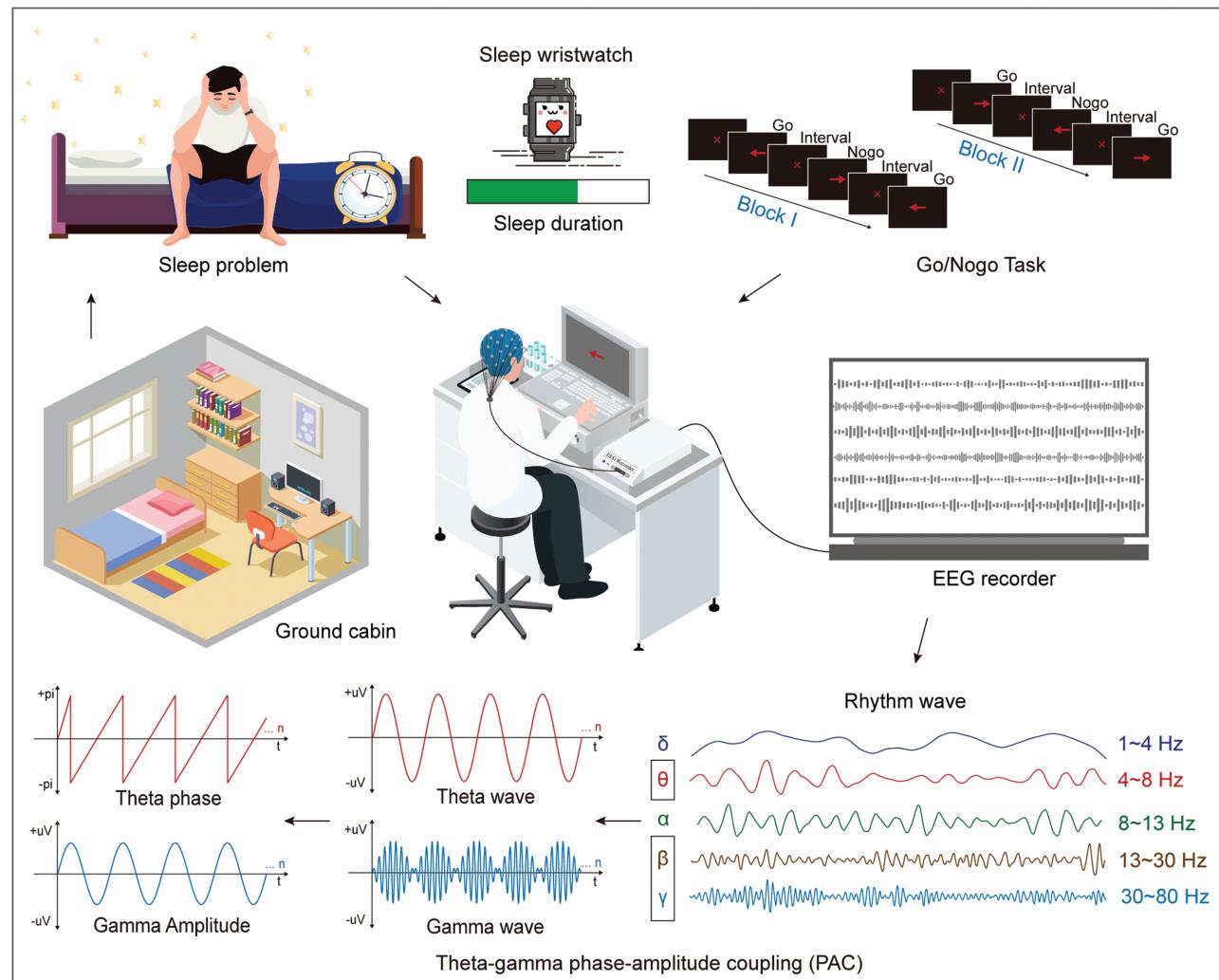


Figure 1. Experiment and task design. Participants settled in normal environments or isolated cabins, participants' psychological distress and sleep indices, including duration and efficiency, were assessed during the night, and awake EEG was simultaneously recorded when they performed the response inhibition task of a Go/Nogo paradigm. Two inversive Go and Nogo stimuli were appointed in two separate blocks for a response inhibition task. Left arrows indicated Go stimuli versus Nogo stimuli indicated by right arrows in one block and the opposite in another. Participants were asked to press the space bar on the keyboard with the index finger of the right hand when a Go stimulus was presented. Otherwise, no reaction was needed when a Nogo stimulus was presented on screen. Single-trial instantaneous phases from the theta wave and synchronous amplitudes from the gamma wave were extracted using the complex Morlet wavelet transform to assess the phase-amplitude coupling.

to regulate access to prefrontal cognitive resources, dynamically controlling interactions between the prefrontal cortex (PFC) and remote neocortical areas. In addition, a unique neural module in which subregions are dedicated to inhibiting dominant behaviors is located in the frontal lobes, as assumed by impulsivity studies [15]. The heightened frontal lobe activity during classical inhibitory paradigms, such as the Go/Nogo task, is the potential evidence for this assumption [16, 17]. A recent functional neuroanatomical study [18] based on a Go/Nogo task, using EEG beamforming approaches, shows that theta wave activity in the ventromedial frontal cortex is correlated with the proactive control in the pretrial interval and with theta-related processes in the right inferior frontal gyrus during response inhibition.

Thus, the PFC, a core cortical area for particular cognitive mechanisms supporting cognitive engagement, response selection, and action evaluation, may interact with posterior cortices [14, 19]. Human cognition requires the coordination of neural activity across widespread brain networks based on the biophysical

properties of theta oscillations for orchestrating processes across spatial distances, but we worry these mechanisms will become invalid when humans experience insufficient sleep. The purpose of this study was to analyze the changes in theta-beta/gamma PAC between the PFC and other cortical areas during a Go/Nogo task, focusing on the correlation among the sleep problem, PAC degree, and behavioral performance, as well as the difference in their relationship to the normal and social isolation environment. Three kinds of experiments were conducted successively, including healthy volunteers tested in normal environments and soldiers tested in normal and isolated environments (Figure 1). All participants were invited to perform a Go/Nogo task, accompanied by EEG acquisitions, after sufficient and insufficient sleep to investigate the PAC changes. We hypothesized that brain activities across cortices based on PAC are positively correlated with response controls for the current stimuli, and humans who experience insufficient sleep may have poor behavioral performance, which can be reflected in PAC decreases across the PFC and other cortical areas.

Methods

Study design and participants

The participants in this study were all healthy populations without sleep disorders who only occasionally experienced sleep problems due to external interference or psychological pressure. By contrast, military personnel often face harsh combat environments and significant psychological pressure, with frequent occurrences of insufficient sleep. Thus, we investigated soldiers and healthy volunteers from the community to obtain a comprehensive research conclusion. A total of 60 healthy volunteers (40 males and 20 females, age: 30.9 ± 5.7 years, and age range: 21–41 years) and 18 soldiers (12 males and 6 females, age: 29.7 ± 3.9 years, and age range: 21–35 years) were recruited to participate in the tests. These participants were right-handed, had normal or corrected-to-normal vision, and were free of mental and somatic disorders in the past or medication use in the latest month. In addition, all participants had no history of night work and were not taking caffeine, alcohol, or other stimulants. Participants had at least three insufficient nights of sleep during the detection period and participated in tests on the days of insufficient sleep and subsequent days of sufficient sleep. In normal environments, each participant was tested three times on sufficient and insufficient sleep conditions. In isolated cabins, each soldier was tested 3 times on sufficient and insufficient sleep conditions. The local ethical committee of the School of Biological Science and Medical Engineering, Beihang University, approved the testing protocol, and all the participants provided written informed consent and were compensated for participation.

Psychological distress and sleep monitoring

Before resting-state and task-related EEG recording during the day, participants' psychological distress and sleep indices, including duration and efficiency, were assessed at night. Psychological distress was measured from the Kessler 6 (K6) scale, which consisted of six questions about how often participants had felt nervous, hopeless, restless, depressed, that everything was an effort, and worthless during the past few days. Every question response was scored in the range of 0–4, generating a scale of 0–24, indicating mild to severe distress. The analysis utilized the dichotomized variable, in which a K6 score above 5 points was classified as moderate distress [20, 21]. Sleep duration and efficiency were monitored continuously using an actigraphy wristwatch (Huawei Watch D, CHN) worn on the non-dominant wrist. Mean behavioral activity over the recording period was automatically calculated using TruSleep software (Sleep analysis version 2.0, Harvard Medical School and Huawei Ltd., CHN). The wristwatch is a non-intrusive, cost-effective tool used to monitor sleep, which could eliminate participant impacts or laboratory effects. The wristwatch based on TruSleep technology has been compared with polysomnography, demonstrating high accuracy (93.8%) in monitoring sleep duration. It received the certification report from the Center for Dynamical Biomarkers, Beth Israel Deaconess Medical Center/Harvard Medical School. The participants were asked to record the times of going to bed, falling asleep, waking up, and leaving the bed. Sleep duration reflects time spent asleep during the nocturnal sleep period and is defined as the number of minutes scored as sleep during the sleep period [22]. Sleep efficiency reflects the percentage of time spent asleep during the sleep period and is defined as sleep duration/sleep period $\times 100$ [22]. In addition, sleep durations of less than 6 hours rather than 7 hours are classified as insufficient sleep, which has

been identified as a salient risk factor for health as widely used in nationally representative studies of adults [20, 23, 24].

Test paradigm of the Go/Nogo task

Participants performed a Go/Nogo task [18] with Go to Nogo ratios of 8 to 1, and they were asked to respond as quickly as possible after Go rather than Nogo stimuli. This task paradigm started with the presentation of an introduction prompt followed by a 5-second fixation cross. Red arrows were presented for 200 ms to the participant one at a time, following a red fixation cross that was shown in the middle at 1600 ms, with a random duration between 1400 and 1800 ms. These left or right arrows were alternated as Go and Nogo stimuli and divided into two separate blocks comprising 30 Nogo and 240 Go stimuli. Participants needed to press the space bar on the keyboard with the index finger of the right hand when a Go rather than Nogo stimulus was presented. Stimuli in one complete task were presented randomly, and the execution sequence of two blocks was counterbalanced across participants to avoid block order effects [25]. In addition, arrows varied randomly in five sizes to ensure that attentional or perceptual factors are unlikely to affect the test results [18, 26]. The task materials, including introduction, red arrows, and fixation crosses, were all presented centrally on the 16" screen of the laptop computer (Lenovo, Inc., CHN) and placed in front of participants at a distance of about 50 cm, with a 2560×1600 screen resolution. Presentations of these materials were controlled by a software platform (E-Prime v3.0, Psychology Software Tools, Inc., USA).

EEG recordings and preprocessing

Resting-state EEG recordings were collected in the morning for 5 minutes, followed by another 20-minute recording during the Go/Nogo task. Signals were acquired with a 64-channel amplifier system (BrainAmp, Brain Products, GER), and electrodes were mounted according to the international 10-10 system against a nose reference. The impedances of all electrodes were kept below 20 kilohms and registered between 0.01 and 80 Hz, with a sampling rate of 1000 Hz and the notch filter at 50 Hz. The ground point was set at the forehead center, and TP9-TP10 electrodes were mounted on the left and right earlobes for re-referencing the data offline to a digitally linked earlobe reference. The independent component analysis (ICA) algorithm was applied to remove eye blinks and movements, and residual artifacts were inspected and corrected manually. In this study, participants performed Go/Nogo tasks involving arrow switching in insufficient sleep conditions, where microsaccades were easily caused and capable of producing gamma activity. Thus, eye movements were synchronously recorded (RED, SMI, and GER) with EEG signals to remove saccade-related artifacts by an improved ICA procedure [27]. EEG preprocessing was completed in MATLAB (v.2019b, MathWorks, USA) involving EEGLAB v.2019 with the current source density toolbox.

Power analysis and PAC assessment

Power analysis.

Full EEG spectra were calculated by the periodogram method of spectral estimation to obtain the average power density in δ (1–4), θ (4–8), α (8–13), β (13–30), and γ (30–80) rhythm waves. The resting EEG of a 5-minute period of sustained wakefulness was used to calculate the average spectral power in every frequency band of artifact-free 1000 ms epochs. When analyzing the power of tasking EEG signals, event-related spectral perturbation (ERSP)

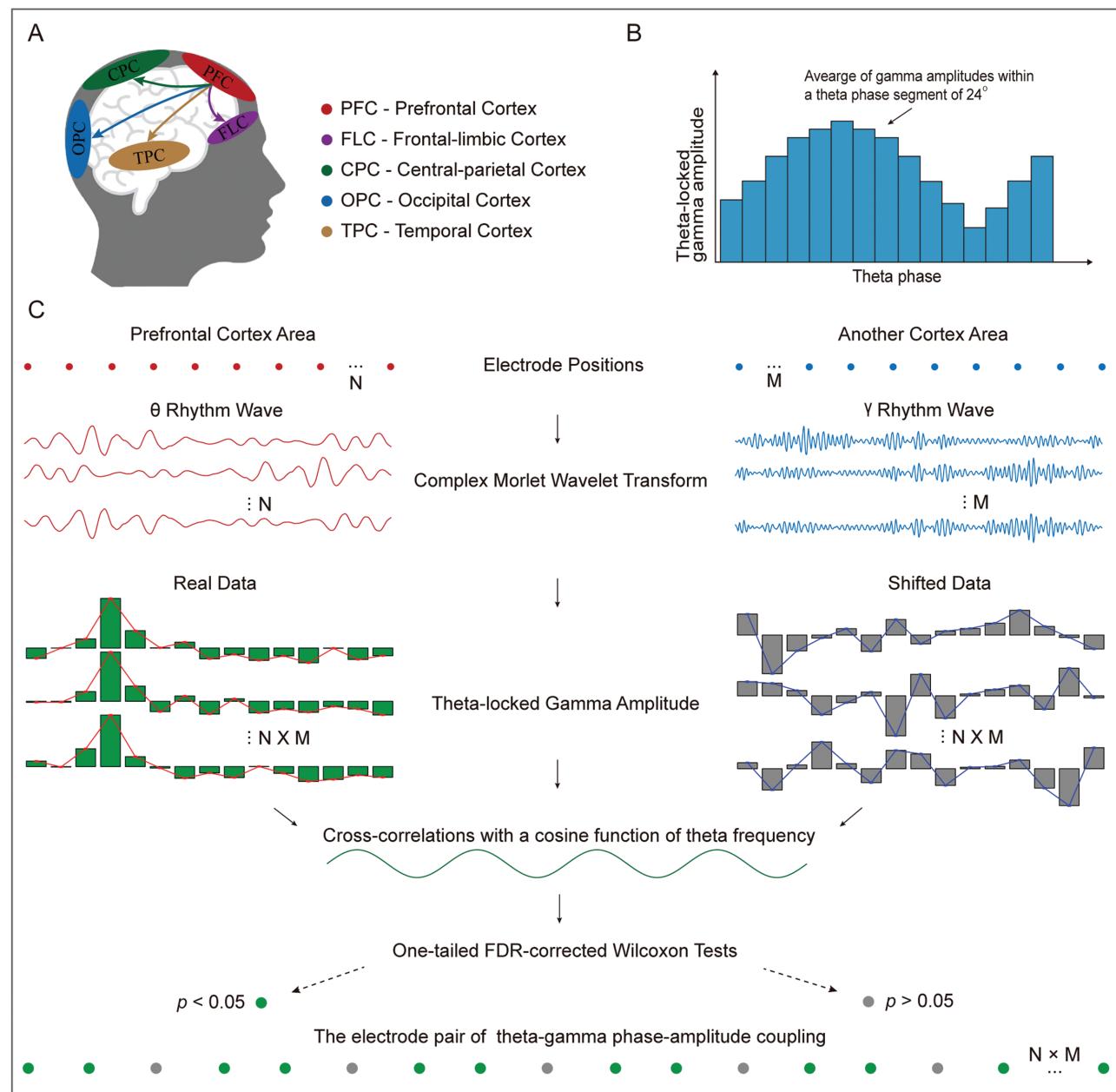


Figure 2. Idealized depiction of theta-locked gamma amplitude modulation. (A) Theta phases in the prefrontal cortex (PFC), as well as synchronous gamma amplitudes in the frontal-limbic cortex (FLC), central-parietal cortex (CPC), temporal cortex (TPC), and occipital cortex (OPC), are calculated in modulation analysis to reflect the phase-amplitude coupling. (B) Gamma amplitude values are sorted according to the appropriate theta phase. Last, sorted gamma amplitude values are averaged within segments of 24° of a theta cycle. (C) The complex Morlet wavelet transform was applied to extract theta rhythm wave in the prefrontal cortex (PFC) and the gamma rhythm wave in another cortex region. Theta-locked gamma amplitudes were calculated for real and shifted data. A cosine function of theta frequency was applied for cross-correlations with theta-locked gamma amplitudes. One-tailed FDR-corrected Wilcoxon tests were used to find the electrode pair of theta-gamma phase-amplitude coupling (PAC).

was shown in epochs from -400 ms to 1400 ms. All epochs of the artifact-free single trial from -500 ms to 1500 ms were used to generate the average ERSP for Go or Nogo stimuli. EEGLAB toolbox running under Matlab 2019b was employed to analyze ERSP from 0 ms to 1400 ms (post-stimulus onset) with a non-overlapping baseline of -400 ms to -100 ms (pre-stimulus onset). Baseline correction was conducted under a gain model, in which each time-frequency time point was divided by the average pre-stimulus baseline power from -400 ms to -100 ms relative to stimulus onset at the same frequency. Wavelet transformation using the Morlet waveform was implemented in the EEGLAB function newtimef.m as a mother wavelet was chosen, resulting in a frequency

resolution of approximately 1 Hz from 1 to 50 Hz. Bootstrap significance tests after FDR correction were selected in the shown ERSP figures.

PAC assessment.

We investigated how the PFC theta phase modulated beta or gamma rhythmical amplitude in other cortical areas as a signature of neuronal oscillations in humans with sleep problems. Thus, 62 electrodes were divided into five clusters (Figure 2A), namely, the PFC (Fz, F1-4, AFz, AF3-4, and Fp1-2), central-parietal cortex (CPC: Cz, C1-4, CPz, CP1-4, Pz, P1-4, FCz, and FC1-4),

occipital cortex (OPC: POz, PO3-4, PO7-8, Oz, and O1-2), temporal cortex (TPC: CP5-8, TP7-8, C5-6, T7-8, and P5-P8), and frontal-limbic cortex (FLC: FC5-10, F5-8, and AF7-8). Theta-gamma coupling was selected as an example to explain PAC computational procedure. Every coupling pair involving theta phases from a PFC electrode and gamma amplitudes from an electrode in other cortical areas was assessed, and the number of coupled pairs was used as an index to PAC degree between each cortical area and PFC. In addition, these theta phase-locked gamma amplitudes were averaged within each cortical area as another index to assess PAC at the regional level (Figure 2B). Every Go or Nogo stimulus interval of 1000 ms was used as the minimum unit to extract theta phase and synchronous gamma amplitudes. Figure 2C displays the system architecture flowchart for theta-gamma PAC assessment.

First, single-trial instantaneous phases from theta wave (6 Hz) in a PFC electrode and synchronous amplitudes from gamma wave (30–80 Hz with the 10 Hz step) in another electrode of other cortical areas were extracted using the complex Morlet wavelet transform [14, 28]. These theta phase-locked gamma amplitudes of 30, 40, 50, 60, 70, and 80 Hz were Z-transformed and averaged into 15 phase bins, covering 24° ($2\pi/15$) of a theta cycle for each bin. Second, a cosine function of two full theta periods (6 Hz and sampled at 55 Hz) with the same temporal resolution as the gamma averages were cross-correlated with the theta phase-sorted gamma amplitudes. Thus, a cross-correlogram with a clear peak different from zero was obtained when theta phases systematically modulated gamma amplitudes. Otherwise, we would obtain a flat cross-correlogram with coefficients close to zero. This cross-correlation procedure was used in each trial separately to form a maximum-value sequence from all absolute maxima of cross-correlograms, which can be used to measure the theta-gamma PAC. Third, the above cross-correlation procedures were performed again for surrogate data in which the theta phases were randomly shifted in each trial to obtain another maximum-value sequence. Finally, the above two Fisher-Z transformed maximum-value sequences were compared by one-tailed FDR-corrected Wilcoxon tests because the absolute maxima from the cross-correlograms were not normally distributed even after the Fisher-Z transformation [14]. Notably, there should no longer be a strong association between theta phases and gamma amplitudes when data were shifted, so the tested result of Wilcoxon significantly differed when theta phases systematically modulated the gamma amplitudes. Thus, all coupled electrode pairs between PFC and other cortical areas were found for each participant.

Statistical comparisons

The phase-locked amplitudes were averaged within each cortical area. One-way repeated-measures ANOVA, using “phase bin” (segments 1–15: each bin covering 24°) as a factor, was applied to assess further whether theta phases in PFC significantly modulate beta or gamma amplitudes in other cortical areas. In addition, the number of coupled electrodes, N score (the number of electrode pairs in which corrected p of Wilcoxon test was less than 0.05/ the total number of electrode pairs), was used to compare the PAC degree. To assess the behavior performance in the Go/Nogo task of participants, we calculated a discrimination index, D score (Nogo hit rate – Go miss rate), was calculated to combine performed results for Go and Nogo stimuli. For volunteers tested in the normal environment, two-way repeated-measures ANOVA, in which the “test sequence (First vs. Second vs. Third) × sleep status (Sufficient sleep vs. Insufficient sleep)” were factors, was used to determine whether they have a significant effect/interactions in D or N score. For

soldiers tested in the normal environment and isolated cabin, three-way repeated-measures ANOVA, in which the “test sequence (First vs. Second vs. Third) × sleep status (Sufficient sleep vs. Insufficient sleep) × experimental site (Normal environment vs. Isolated cabin)” were factors, was used to determine whether they have a significant effect/interactions in D or N score. For all outcome measures, the normal distribution tested by the Shapiro-Wilk test and the variance homogeneity tested by Bartlett's χ^2 -square were verified. In these statistical results, the Bonferroni-corrected two-tailed p of less than 0.05 signifies a significant difference. Statistical analyses were completed on Matlab 2019b and OriginPro 2021 (OriginLab, MA, USA), including image plotting.

Source reconstruction

Source reconstruction was performed using Brainstorm based on preprocessed EEGLAB data, including ICA artifact attenuation [29]. Given that individual MRIs were not available in this study, EEG data were registered with the template model. Electrode locations were visually inspected and manually corrected to fit default anatomies by the graphical interface of Brainstorm, in which OpenMEG toolbox with a forward model of the Symmetric Boundary Element Method was implemented. Pre-stimulus intervals (-200 ms to 0 ms) were used as a baseline to calculate participant noise covariance matrices, estimating individual noise standard deviations at each location. The constrained dipole orientation, oriented perpendicular to the cortical surface for each vertex, was selected for source reconstruction. Before that, EEG signals were re-referenced to the common average, achieving a net source activity of zero current flow to prevent bias in source strength estimates. Finally, active sources were estimated on the participant average from all single-trial EEG data.

Results

Sleep status and psychological distress

Data were divided into sufficient or insufficient sleep status depending on whether the sleep duration exceeded 6 hours. Four volunteers experienced less than three insufficient sleep events during our detection period, so data from the remaining 56 volunteers were analyzed. All soldiers had experienced at least three sufficient and insufficient nights of sleep during detection periods in normal and isolated environments. One-way repeated-measures ANOVA showed no significant differences in the three test sequences (Figure 3A). In addition, their sleep efficiency did not significantly differ for sufficient or insufficient sleep groups on the three test sequences (Figure 3B). Under sufficient status, the sleep efficiency of volunteers and soldiers was mainly greater than 65%, which was an apparent borderline between sufficient and insufficient sleep. The K6 scale indicated that participants usually had moderate or heavy psychological distress with a score above 5 points at night when they experienced insufficient sleep (Figure 3C). However, on different test sequences, K6 scores did not significantly differ for sufficient or insufficient sleep groups, implying that psychological distress did not show a time-cumulative effect with the continuous extension of the experiment. The above-mentioned results indicated that the test sequence's main effects were insignificant in sleep duration, sleep efficiency, and K6 scale. Thus, the data from the first, second, and third tests were mixed for all following analyses to maximize the limited samples of soldiers living in normal and isolated environments.

One-way repeated-measures ANOVA showed that the sleep duration of the sufficient sleep group in the isolated cabin was

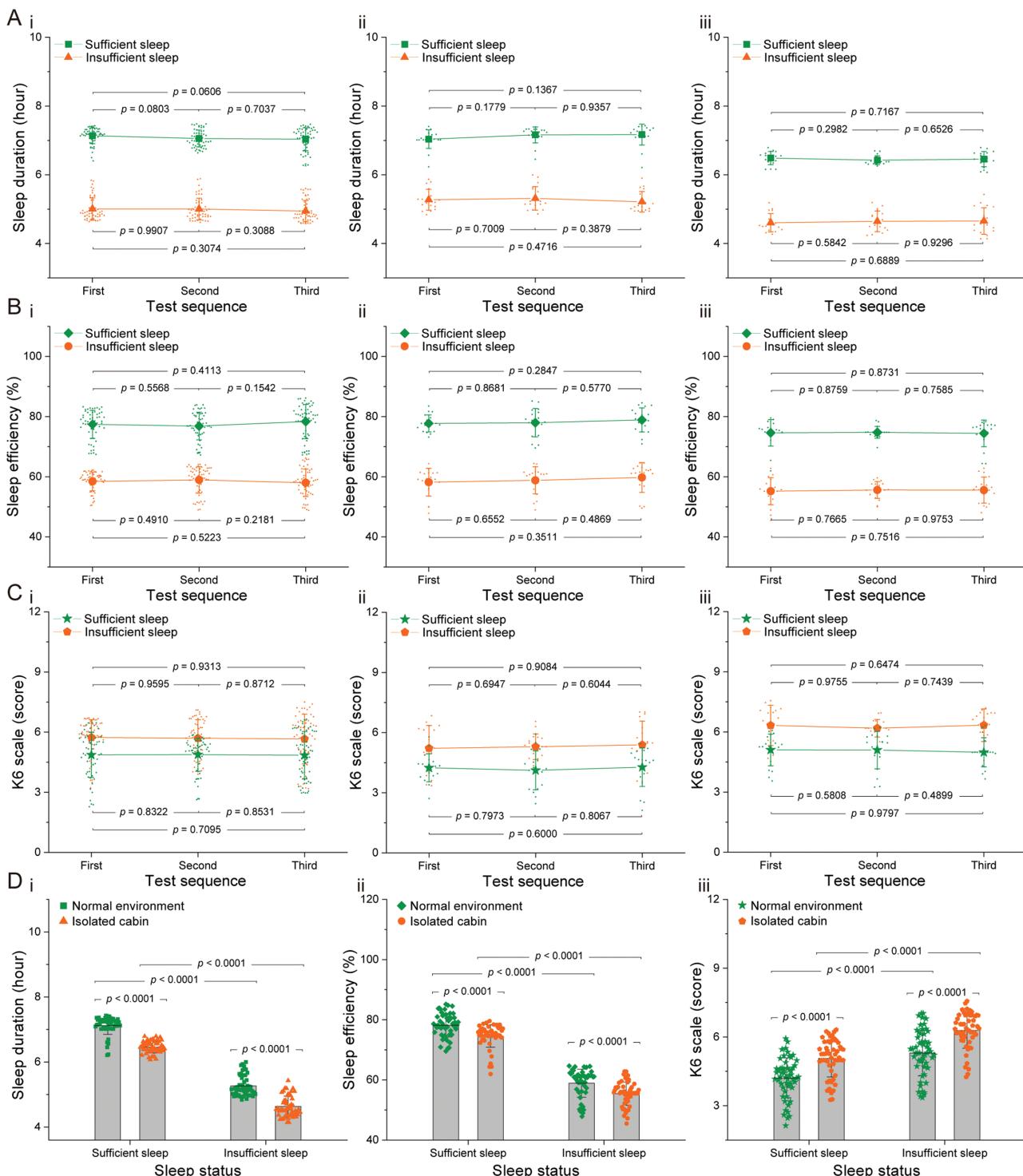


Figure 3. Results of sleep status and psychological distress. (A) Sleep durations of the first, second, and third test sequences were shown. (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (B) Sleep efficiencies of the first, second, and third test sequences were shown. (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (C) K6 scales of the first, second, and third test sequences were shown. (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (D) These data from the first, second, and third tests were mixed for soldiers. (i) showed the sleep durations of soldiers in normal environments and isolated cabins, respectively. (ii) showed the sleep efficiencies of soldiers in normal environments and isolated cabins, respectively. (iii) showed the K6 scales of soldiers in normal environments and isolated cabins, respectively.

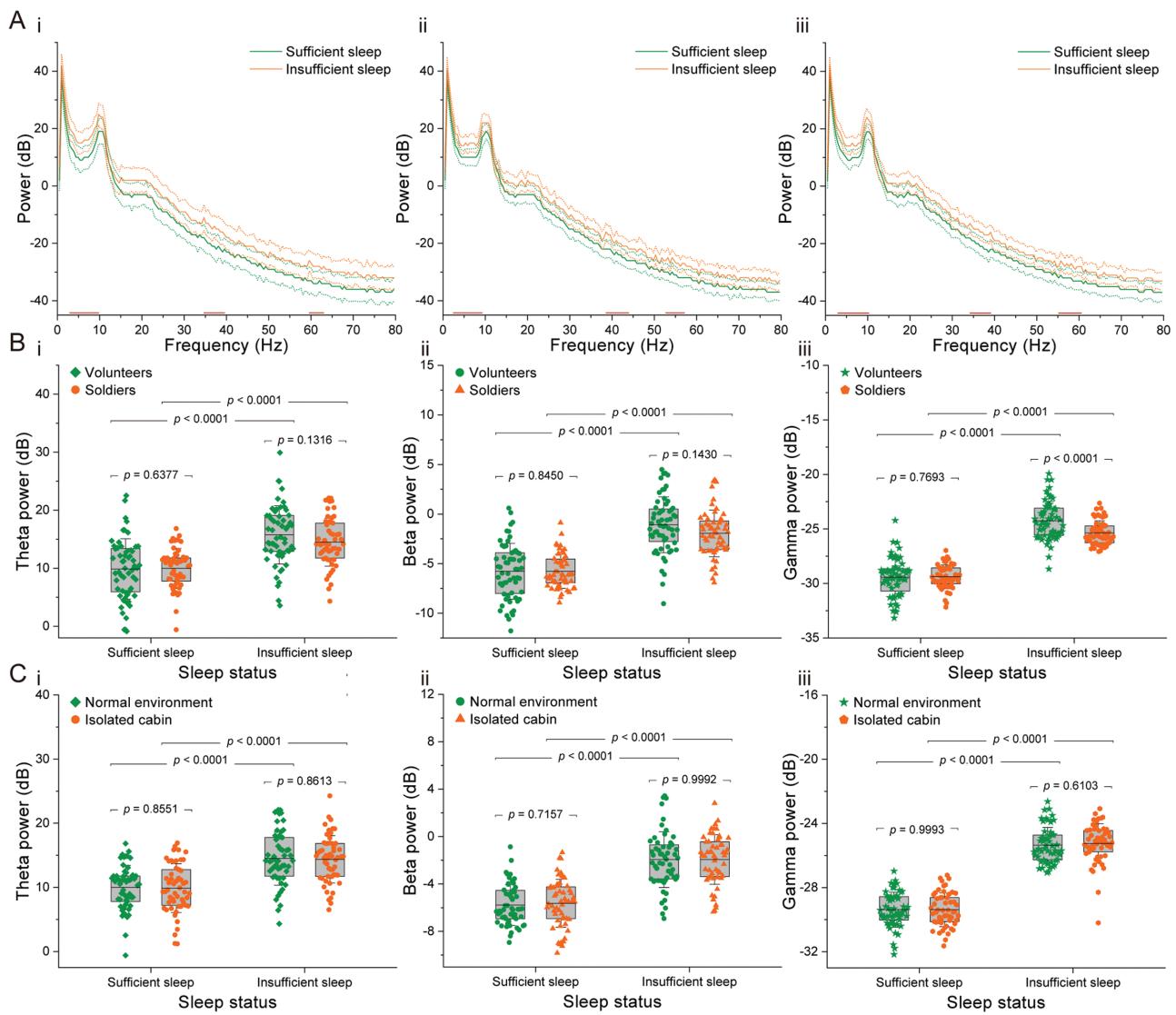


Figure 4. Results of resting power by the full EEG spectrum. (A) EEG spectrums of sufficient and insufficient sleep status were shown. (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (B) (i), (ii), and (iii) represented the average power within the theta (1–4 Hz), beta (13–30 Hz), and gamma (30–80) frequency bands, respectively. (C) (i), (ii), and (iii) represented the average power within the theta (1–4 Hz), beta (13–30 Hz), and gamma (30–80) frequency bands, respectively.

lower than that in the normal environment ($F_{1/53} = 322.5423$, $p < 0.0001$, Figure 3D-i), and this kind of sleep decrease was also observed in the insufficient sleep group ($F_{1/53} = 108.0872$, $p < 0.0001$, Figure 3D-i). Besides differences in sleep efficiency between the sufficient and insufficient groups (Normal environment: $F_{1/53} = 601.0013$, $p < 0.0001$; Isolated cabin: $F_{1/53} = 651.7795$, $p < 0.0001$; Figure 3D-ii), sleep efficiency significantly decreased in the isolated cabin compared with that in the normal environment (Sufficient group: $F_{1/53} = 27.0692$, $p < 0.0001$; Insufficient group: $F_{1/53} = 21.2653$, $p < 0.0001$; Figure 3D-ii). Meanwhile, social isolation could aggravate the psychological distress of sufficient and insufficient sleep (Sufficient group: $F_{1/53} = 28.9450$, $p < 0.0001$; Insufficient group: $F_{1/53} = 39.3651$, $p < 0.0001$; Figure 3D-iii).

Resting power and task-related ERSP of EEG signals

The full EEG spectrum was calculated to assess the power density of a resting EEG collection protocol. Resting EEG signals

demonstrated a highly significant increase in the whole theta (4–8 Hz) and part gamma (30–80 Hz) power in the insufficient compared with sufficient sleep status (Figure 4A, marked with a red line above the horizontal axis). The increased resting power during insufficient sleep usually existed in the theta range, and the gamma range of power increase was changeable between EEG spectra from volunteers (Figure 4A-i) and soldiers, which were collected in normal environments (Figure 4A-ii) and isolated cabins (Figure 4A-iii). As an exploratory investigation of insufficient sleep and a motor-related task, we also investigated the average power within the theta (1–4 Hz), beta (13–30 Hz), and gamma (30–80) frequency bands. One-way repeated-measures ANOVA showed that theta, beta, and gamma average powers all increased for volunteers or soldiers (All $F > 37.1453$, $p < 0.0001$, Figure 4B), and the average gamma power of volunteers was significantly higher than that of soldiers ($F = 18.7717$, $p < 0.0001$, Figure 4B-iii) during insufficient sleep status in the normal environment. Whether soldiers were in a normal environment or an isolated cabin, the theta, beta, and average gamma powers significantly increased because

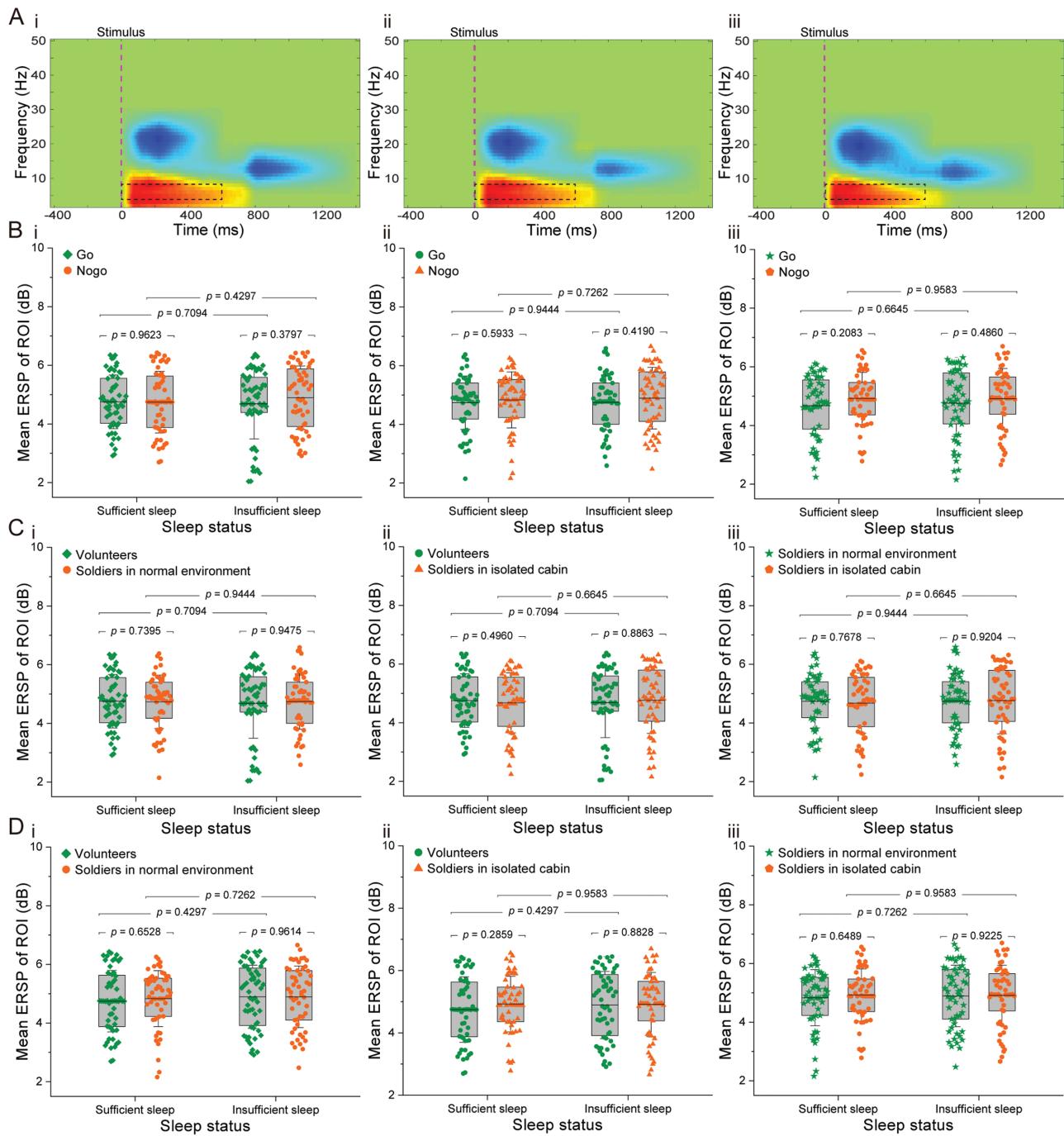


Figure 5. Results of task-related event-related spectral perturbation (ERSP) during the theta frequency range. (A) ERSPs of sufficient and insufficient sleep status were shown in the time-frequency spectrum. (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. Dashed black rectangles indicate the region of interest (ROI) during the theta frequency range. (B) Mean ERSPs of ROI during Go and Nogo stimuli, (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (C) (i), (ii), and (iii) represented mean ERSPs of ROI during Go stimuli between volunteers and soldiers in the normal environment, volunteers in the isolated cabin, and soldiers in the normal environment and in the isolated cabin, respectively. (D) (i), (ii), and (iii) represented mean ERSPs of ROI during Nogo stimuli between volunteers and soldiers in the normal environment, volunteers in the isolated cabin, and soldiers in the normal environment and in the isolated cabin, respectively.

of insufficient sleep, and the isolated cabin would not deteriorate this phenomenon (Figure 4C).

ERSPs were calculated to assess changes in spectral power associated with stimulus onset for task-related EEG signals. We observed the stable synchronization enhancement in the theta range from 0 ms time point representing stimulus onset

to around 600 ms. Dashed black rectangles in Figure 5A indicate the region of interest (ROI) during the theta frequency range, in which the mean ERSP was further calculated to compare sufficient and insufficient sleep status. However, participants' response inhibition demands differed between Nogo and Go stimuli, so these two kinds of stimuli were divided at ERSP

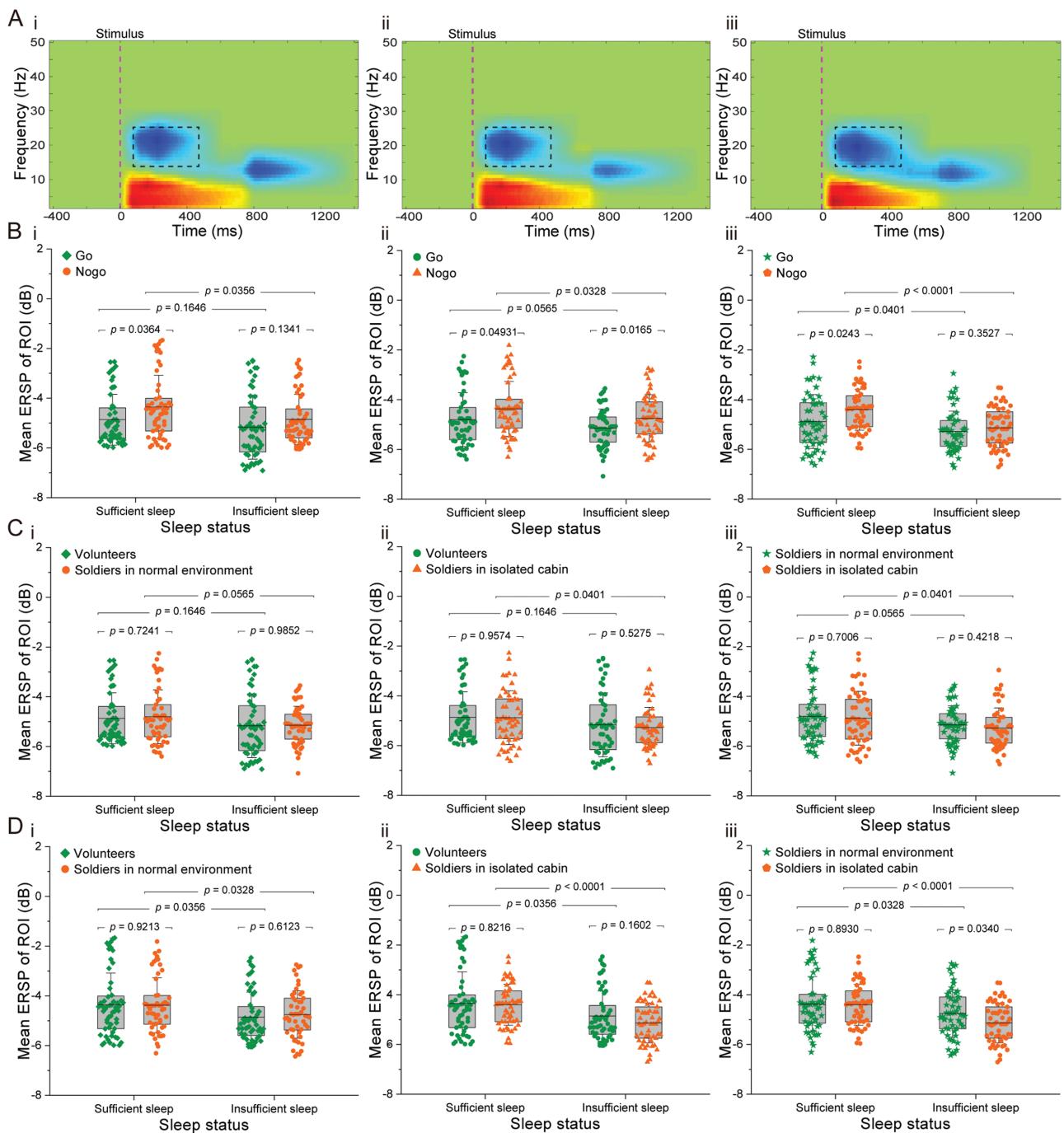


Figure 6. Results of task-related event-related spectral perturbation (ERSP) during the beta frequency range. (A) ERSPs of sufficient and insufficient sleep status were shown in the time-frequency spectrum. (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. Dashed black rectangles indicate the region of interest (ROI) during the beta frequency range. (B) Mean ERSPs of ROI during Go and Nogo stimuli, (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (C) (i), (ii), and (iii) represented mean ERSPs of ROI during Go stimuli between volunteers and soldiers in the normal environment, volunteers in the normal environment and soldiers in the isolated cabin, and soldiers in the normal environment and in the isolated cabin, respectively. (D) (i), (ii), and (iii) represented mean ERSPs of ROI during Nogo stimuli between volunteers and soldiers in the normal environment, volunteers in the normal environment and soldiers in the isolated cabin, and soldiers in the normal environment and in the isolated cabin, respectively.

analyses. One-way repeated-measures ANOVA showed that the mean ERSPs of ROI for the theta frequency range were not significantly different between Go and Nogo stimuli within volunteers (Figure 5B-i), soldiers in the normal environment (Figure 5B-ii), and soldiers in the isolated cabin (Figure 5B-iii). No significant differences were found among volunteers, soldiers in the normal

environment, and soldiers in the isolated cabin for Go (Figure 5C) or Nogo stimuli (Figure 5D).

In addition, we observed a stable synchronization abatement in the beta range from 80 ms time point representing stimulus onset to around 500 ms. Dashed black rectangles in Figure 6A indicate an ROI during the beta frequency range, in which the

mean ERSP was further calculated to compare sufficient and insufficient sleep status. One-way repeated-measures ANOVA showed that the mean ERSPs of ROI within the beta frequency range at sufficient sleep condition significantly increased during Nogo stimuli compared with those during Go stimuli for volunteers ($F_{1/55} = 4.5998, p = 0.0364$, Figure 6B-i), soldiers in the normal environment ($F_{1/55} = 4.0482, p = 0.0493$, Figure 6B-ii), and soldiers in the isolated cabin ($F_{1/55} = 5.373, p = 0.0243$, Figure 6B-iii). When they experienced nights of insufficient sleep, the mean ERSPs during Nogo stimuli significantly descended for volunteers ($F_{1/55} = 4.6421, p = 0.0356$, Figure 6B-i), soldiers in the normal environment ($F_{1/55} = 4.8072, p = 0.0328$, Figure 6B-ii), and soldiers in the isolated cabin ($F_{1/55} = 27.090, p < 0.0001$, Figure 6B-iii). Only soldiers in the isolated cabin had lower mean ERSPs during Go stimuli ($F_{1/55} = 4.4292, p = 0.0401$, Figure 6B-iii) than the other participants. During Go stimuli, no significant differences were found among volunteers and soldiers in the normal environment or in the isolated cabin (Figure 6C). When soldiers in the isolated cabin experienced insufficient sleep, the mean ERSPs during Nogo stimuli significantly decreased compared with those in the normal environment ($F_{1/55} = 4.7372, p = 0.0340$, Figure 6D-iii).

Theta–beta/gamma PAC and behavior performance

N score (the number of electrode pairs in which the corrected p of the Wilcoxon test was less than 0.05/ the total number of electrode pairs) was used to compare the PAC degree between sufficient and insufficient sleep status. The PFC theta phase modulates beta or gamma rhythmical amplitude in other cortical areas, where the PAC degree may differ. Thus, as an exploratory investigation, we compared the N score during resting, Go, or Nogo periods in volunteers' FLC, CPC, OPC, and TPC cortical areas. The results demonstrated that the theta–beta PAC degrees during resting periods were not significantly different in FLC, CPC, OPC, and TPC cortical areas (Figure 7A-i). However, during task-related periods, the degree of theta–beta PAC significantly increased in Go intervals for CPC compared with those for FLC, OPC, and TPC cortical areas (Figure 7A-ii), and it still increased in Nogo intervals (Figure 7A-iii). Interestingly, this theta–beta PAC of Go ($F_{1/55} = 121.5800, p < 0.0001$, Figure 7A-ii) and Nogo ($F_{1/55} = 92.4140, p < 0.0001$, Figure 7A-iii) intervals significantly decreased when volunteers experienced insufficient sleep.

During resting periods and Go or Nogo intervals, the theta phase-locked beta amplitudes were averaged within the CPC area. One-way repeated-measures ANOVA, using "phase bin" (segments 1–15: each bin covering 24°) as a factor, was applied to assess further whether theta phases in PFC significantly modulate these beta amplitudes. In this way, we discovered that the theta phase of the PFC did not modulate beta amplitude during resting periods (Sufficient group: $F_{1/55} = 0.9159, p = 0.5411$; Insufficient group: $F_{1/55} = 1.0754, p = 0.3764$, Figure 7B-i), but theta–beta PAC appeared in Go (Sufficient group: $F_{1/55} = 154.8719, p < 0.0001$, Figure 7B-ii) and Nogo (Sufficient group: $F_{1/55} = 152.1112, p < 0.0001$, Figure 7B-iii) intervals. Notably, during Go intervals, the maximal beta amplitudes were locked near the trough of the theta cycle whether volunteers slept sufficiently or insufficiently (Insufficient group: $F_{1/55} = 114.3008, p < 0.0001$, Figure 7B-ii). In addition, the maximal beta amplitudes were coincidentally locked at the trough of the theta cycle, but the phase to locked beta amplitudes deviated from the trough when they slept insufficiently during Nogo intervals (Insufficient group: $F_{1/55} = 117.3106, p < 0.0001$, Figure 7B-iii).

The theta–gamma PAC degrees during resting periods (Figure 7C-i) or Go intervals (Figure 7C-ii) were also not significantly different in FLC, CPC, OPC, and TPC cortical areas. However, the degree of theta–gamma PAC significantly increased in Nogo intervals for OPC compared with FLC, CPC, and TPC cortical areas (Figure 7C-iii), and it decreased when volunteers experienced insufficient sleep ($F_{1/55} = 123.9249, p < 0.0001$, Figure 7C-iii). The theta phase-locked gamma amplitudes were averaged within the OPC area, and one-way repeated-measures ANOVA, using "phase bin" (segments 1–15: each bin covering 24°) as a factor, was applied to assess further whether theta phases in PFC significantly modulate these gamma amplitudes. In this way, we discovered that the theta phase of the PFC did not modulate gamma amplitude during resting periods (sufficient group: $F_{1/55} = 1.2150, p = 0.6122$; Insufficient group: $F_{1/55} = 0.6106, p = 0.7645$; Figure 7D-i) and Go intervals (Sufficient group: $F_{1/55} = 1.1444, p = 0.0934$; Insufficient group: $F_{1/55} = 1.0907, p = 0.4447$; Figure 7D-ii), but theta–gamma PAC appeared in Nogo (sufficient group: $F_{1/55} = 174.7108, p < 0.0001$; Figure 7D-iii) intervals. In addition, the maximal gamma amplitudes were coincidentally locked at the trough of the theta cycle, but the phase to locked gamma amplitudes deviated from the trough when they slept insufficiently during Nogo intervals (insufficient group: $F_{1/55} = 133.3440, p < 0.0001$; Figure 7D-iii).

One-way repeated-measures ANOVA showed that N scores for theta–beta PAC were significantly different between Go and Nogo stimuli for volunteers (sufficient group: $F_{1/55} = 52.1083, p < 0.0001$; Insufficient group: $F_{1/55} = 59.2276, p < 0.0001$; Figure 8A-i), soldiers in the normal environment (Sufficient group: $F_{1/55} = 58.7226, p < 0.0001$; Insufficient group: $F_{1/55} = 78.9515, p < 0.0001$; Figure 8A-ii), and soldiers in the isolated cabin (sufficient group: $F_{1/55} = 90.0524, p < 0.0001$; insufficient group: $F_{1/55} = 77.9251, p < 0.0001$; Figure 8A-iii). The N scores both in Go and Nogo intervals significantly decreased when they experienced insufficient sleep (All $F > 64.7156, p < 0.0001$, Figure 8A). In sufficient sleep status, linear regression results of N and D scores showed that theta–beta PAC degrees both in Go and Nogo intervals were positively correlated with behavioral performance (all $R^2 > 0.0624$, Pearson's $r > 0.2498$, Figure 8B). However, the correlation would decrease in insufficient sleep status, especially during Nogo intervals.

In addition, one-way repeated-measures ANOVA showed that N scores for theta–gamma PAC were significantly different between Go and Nogo stimuli for volunteers (Sufficient group: $F_{1/55} = 626.9856, p < 0.0001$; Insufficient group: $F_{1/55} = 600.0084, p < 0.0001$; Figure 8C-i), soldiers in the normal environment (Sufficient group: $F_{1/55} = 1043.6341, p < 0.0001$; Insufficient group: $F_{1/55} = 424.9856, p < 0.0001$; Figure 8C-ii), and soldiers in the isolated cabin (Sufficient group: $F_{1/55} = 831.6041, p < 0.0001$; Insufficient group: $F_{1/55} = 294.9921, p < 0.0001$; Figure 8C-iii). The N scores only in Nogo intervals significantly decreased when they experienced insufficient sleep (All $F > 123.9249, p < 0.0001$, Figure 8C). In sufficient sleep status, the linear regression results of N and D scores showed that theta–gamma PAC degrees in both Go and Nogo intervals were positively correlated with behavioral performance (all $R^2 > 0.0283$, Pearson's $r > 0.1684$, Figure 8D). However, this correlation would also decrease in insufficient sleep status, especially during Nogo intervals.

Go/Nogo task-related source reconstruction

Go/Nogo task-related source reconstruction was performed to test for the neural sources leading to the above specific EEG power or PAC differences. During stimulus intervals, occipital and parietal cortices were activated (Figure 9), confirming prior statistics that

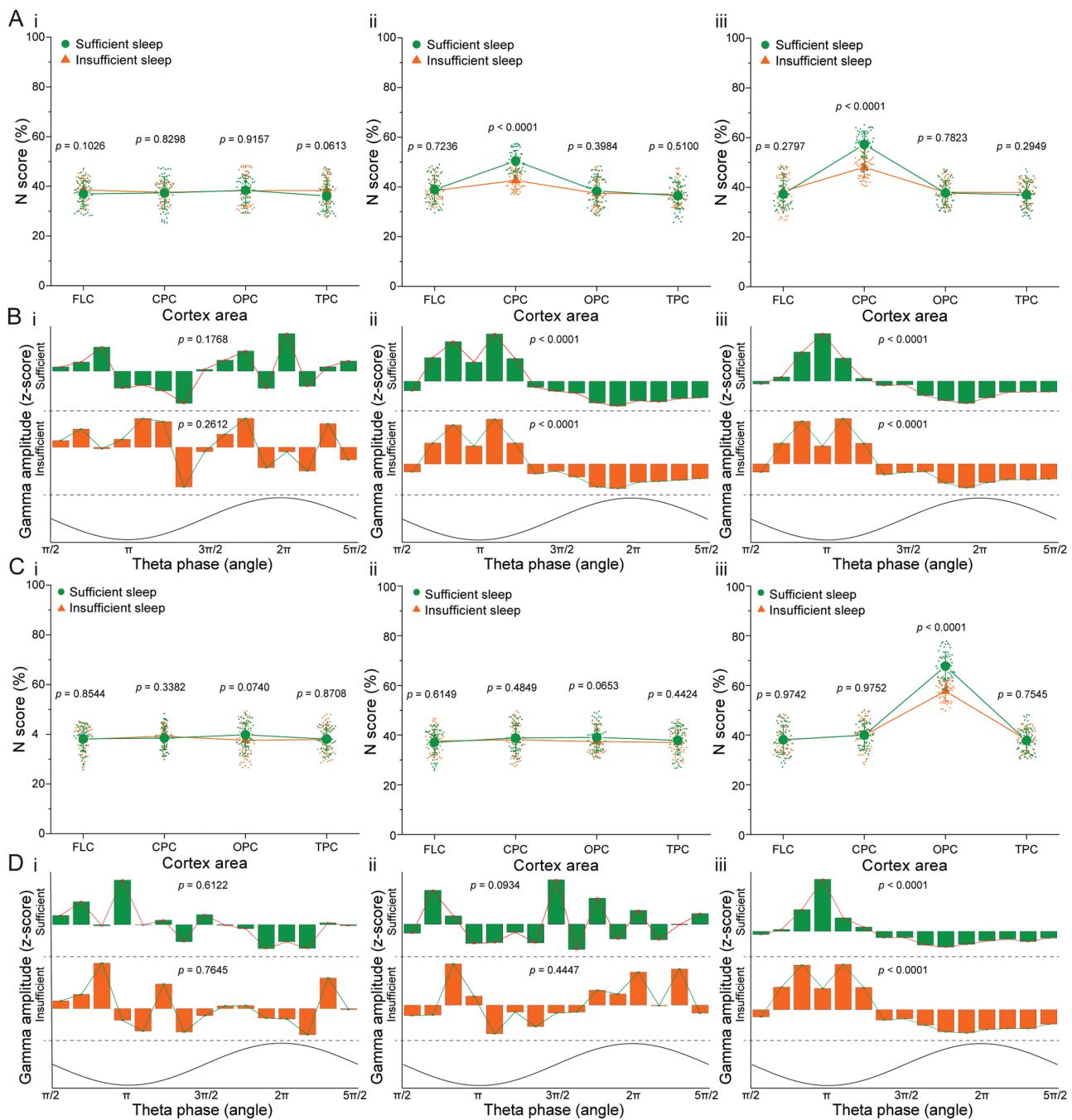


Figure 7. Results of theta–beta/gamma phase-amplitude coupling (PAC). (A) The N scores of theta–beta PAC in the frontal-limbic cortex (FLC), central-parietal cortex (CPC), occipital cortex (OPC), and temporal cortex (TPC) were shown. (i), (ii), and (iii) represented tests of volunteers in resting, Go, and Nogo situations, respectively. (B) Theta phase-locked beta amplitudes of CPC were shown. (i), (ii), and (iii) represented tests of volunteers in resting, Go, and Nogo situations, respectively. (C) The N scores of theta–gamma PAC in the FLC, CPC, OPC, and TPC were shown. (i), (ii), and (iii) represented tests of volunteers in resting, Go, and Nogo situations, respectively. (D) Theta phase-locked gamma amplitudes of OPC were shown. (i), (ii), and (iii) represented tests of volunteers in resting, Go, and Nogo situations, respectively.

the significant changes in EEG power or PAC degree focused on OPC and CPC. However, some electrode positions on the scalp surface beyond the source location may be due to the absence of individual MRI templates and the spatial resolution limitation of EEG signals. In addition, the source map showed that the activation level of the right hemisphere was higher than that of the left hemisphere. The large activation area indicated that executive control functions in bilateral hemispheres were unbalanced during Go/Nogo tasks. Statistical comparisons on source reconstruction were not performed in this study, as EEG power or PAC degree already

demonstrated significant differences, and statistical comparisons may only be reliable with individual MRI registration.

Discussion

In this study, we evaluated the PAC of beta or gamma amplitudes in four cortical areas modulated by theta phases of PFC during sufficient or insufficient sleep status, aiming to characterize the relationships between PAC degree and behavioral performance of inhibitory control. Recording EEG signals during sleep may

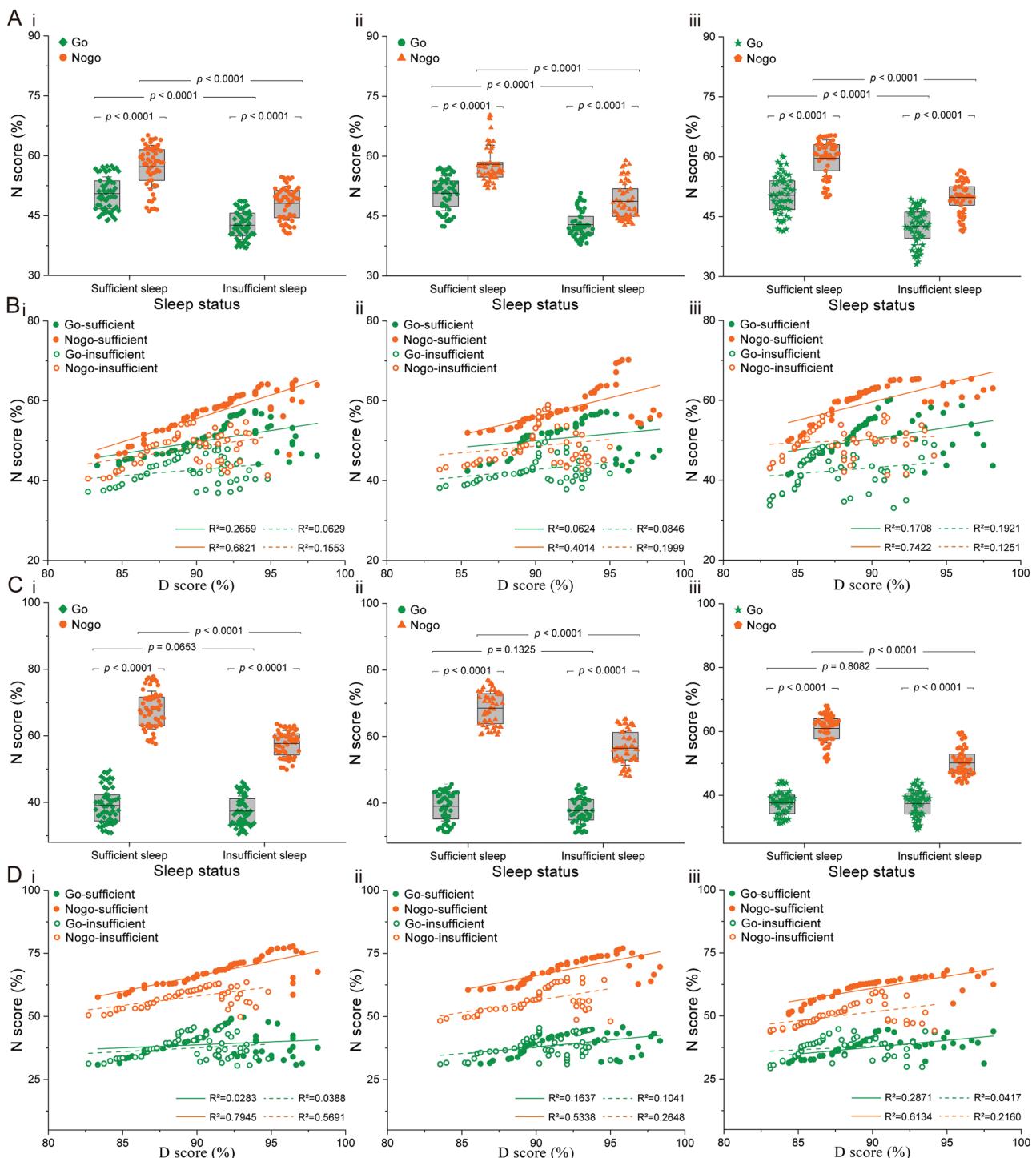


Figure 8. Results of N score compare and N and D scores linear regression. (A) N score of theta–beta PAC during Go and Nogo stimuli, (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (B) N and D scores linear regression of theta–beta PAC, (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (C) N score of theta–gamma PAC during Go and Nogo stimuli, (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively. (D) N and D scores linear regression of theta–gamma PAC, (i), (ii), and (iii) represented tests of volunteers in normal environments, soldiers in normal environments, and isolated cabins, respectively.

influence a wide range of participants' emotions because discomfort negatively affects sleep quality [11, 30]. Therefore, we expected to use waking EEG signals to find neurological activity changes between sufficient or insufficient sleep status in different cortical areas. Cluster neurons may generate activity patterns in the cerebral cortex that represent information about stimuli during tasks, transmitting activity patterns across synapses to

spatially distributed areas [31] where these task-related neuronal oscillations cannot appear in resting EEG signals. As an exploratory investigation, we used Go/Nogo task-related EEG signals, raising the possibility that PACs across frequency can develop as an alternative marker of sleep problems.

EEG signals recorded from the brain usually show an increase in resting theta power at 4–8 Hz for sleep deprivation compared

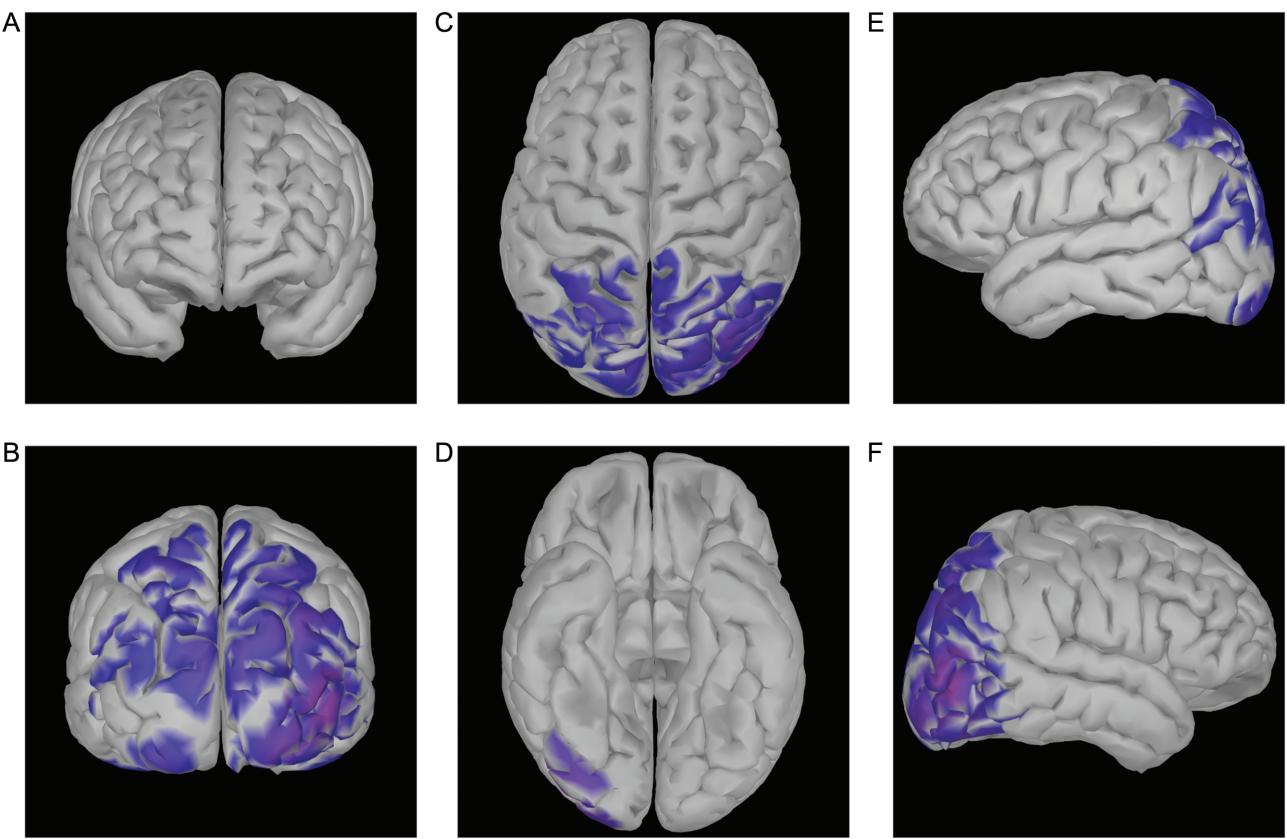


Figure 9. Results of the Go/Nogo task-related source reconstruction. Shown was the activation at the latency of the N100 peak of group averages for the left or right hemisphere, which did not depict positive or negative voltages, only where a region was activated. (A), (B), (C), (D), (E), (F) displayed the activated cortices by the front, rear, top, bottom, left, and right visual angles, respectively.

with the baseline state [32, 33]. Using the full EEG spectrum, we detected that the resting power also demonstrated a significant increase in the whole theta frequency for insufficient sleep compared with sufficient sleep. This result demonstrated that the homeostatic mechanism regulating neural activity was broken, causing the cortex to undergo hyperactivity unless sufficient sleep occurred. However, theta wave power in the resting EEG cannot directly reflect brain cognitive processing and performance errors in specific tasks. Individuals may appear fully awake based on their general behavior and EEG signals, but some cortical areas may be turned OFF at unpredictable times because of potential problems of insufficient sleep, with potentially adverse effects on inhibitory control and behavioral performance. Bernardi et al. [34] investigated whether behavioral errors show a temporal association with the occurrence of theta waves over task-related areas. They demonstrated an association between theta waves during wakefulness and performance errors, and their findings may help explain behavioral impairments under sleep deprivation or restriction conditions. Recent research by Magnuson et al. [35] found a small difference in amplitude between Go and Nogo trials for the event-related potential components and indicated that sleep deprivation slows neural processing and impairs inhibitory behavior performance during Go/Nogo tasks. In the present study, we established a direct connection between PACs and behavior performance to help elucidate the neural mechanism for Go/Nogo task-related failures because of insufficient sleep. The theta-beta/gamma PAC degree between the frontal and central-parietal/occipital cortex would decrease with the poor task-related hit rate, which might be an alternative marker of the connection between insufficient sleep and inhibitory control.

Previous studies also assessed the effects of sleep problems on inhibitory control by the Go/Nogo task, which shows that the prefrontal and anterior cingulate cortices alter neural activity in response to stimuli [36–38]. Although sleep deprivation leads to increased amplitude of an event-related potential component [39–41], previously, no study has assessed PAC across cortices for inhibitory control to face Go/Nogo stimuli in insufficient sleep status. In the present study, PFC theta phases methodically modulated beta/gamma amplitudes in stimulus intervals, indicating a cortical synchronized instantaneous communication mechanism established under high response inhibition evoked by Go/Nogo stimuli. This result supported James and colleagues' report [13] that the theta rhythmic wave over the frontal cortex appears to reflect a common computation used to achieve inhibitory control and subsequently implement such control across disparate cortical areas as a biologically plausible candidate for neuronal communication. Palermo et al. [42] also provided evidence through Go/Nogo tasks for the critical role of the frontal cortex in behavior control and demonstrated that the frontal–network hypofunction is associated with task-related control disorder. In our study, although frontal theta phases dynamically modulated central-parietal beta or occipital gamma amplitudes when the brain required high inhibitory control, insufficient sleep would weaken these modulation capabilities.

Signals for cross-frequency PAC estimate are derived from two electrodes: one frontal electrode provides the theta wave of 6 Hz, and another occipital electrode provides the gamma wave of 40 Hz. Although we cannot directly define which neuronal cluster in the cerebral cortex generates signals of these two electrodes, source reconstruction by all electrodes in stimulus intervals

helps us indirectly retrace the neural sources leading to this specific PAC. The occipital lobe is mainly responsible for normal visual function and serves as the location of the visual center. The sensory cortex is located in the parietal lobe, and its health status can affect the motor cortex. In this study, PFC modulated OPC and CPC based on PACs when humans performed the Go/Nogo task. The results of the source reconstruction indicated that partial cortices of occipital and parietal lobes were activated during Go/Nogo stimulus intervals, confirming prior statistics that the significant changes in PAC degree focused on OPC and CPC. This phenomenon was consistent with magnetoencephalography experimental results from Sugawara et al. [43], who reported that the repeated practice of a Go/Nogo visuomotor task induces a neuroplastic change in the human posterior parietal and occipital cortex. Some electrode positions on the scalp surface beyond the source location of the parietal and occipital cortex may be due to the absence of individual MRI templates and the spatial resolution limitation of EEG signals in this study.

In conclusion, theta-beta/gamma PAC used in this study effectively represented the differences in neuronal oscillations by EEG signals between sufficient and insufficient sleep status. In particular, the PAC degree during stimulus intervals could be a potential indicator of sleep status, as it was positively connected with behavior performance of inhibitory control. The evaluation of theta-beta/gamma PAC of Go/Nogo task-related EEG signals is necessary to support commonly used methods and expand the current knowledge about complex neuronal oscillations and their evolution on the different sleep statuses in humans. Furthermore, sleep duration for healthy humans becomes shorter with increasing pressure and worsens when soldiers work in environments of social isolation. The motivation to seek social contact may arise from either positive or negative emotional states, thereby affecting the sleep quality of humans because social interaction may be rewarding while social isolation may be aversive [44]. However, very little is known about how this isolation-induced insufficient sleep status is represented at a neural oscillation level. This study further demonstrated that social isolation could worsen psychological distress and sleep problems in humans, decrease the degree of theta-beta/gamma PAC during stimulus intervals, and worsen the behavior performance of inhibitory control. Our study is an exploratory investigation that bears some limitations. For example, a large sample would have clarified interaction mechanisms between insufficient sleep and social isolation, and other physiological data deserve to be exploited by researching sleep problems with a broad perspective and the use of powerful tools.

Funding

This study has been partially supported by the Academy of Military Medical Sciences, China, under contract BME-2020-102315 grants for researchers and participants.

Acknowledgments

We thank all participants for their contributions to the data acquisition.

Author Contributions

P.Z.: conceptualization, methodology, investigation, software, formal analysis, visualization, writing-original draft, writing-review

and editing, validation, data acquisition, and data curation; C.S.: conceptualization, investigation, data acquisition, supervision, funding acquisition; Z.L.: conceptualization, resources, writing-review and editing; Q.Z. conceptualization, methodology, writing review and editing, coordination, supervision, validation, and funding acquisition.

Disclosure Statement

Conflict of Interest: none. Financial Disclosure: none. Nonfinancial Disclosure: none.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

References

- Romanella S, Sprugnoli G, Ruffini G, Seyedmadani K, Rossi S, Santarnecchi E. Noninvasive brain stimulation & space exploration: opportunities and challenges. *Neurosci Biobehav Rev*. 2020;119(1):294–319. doi: [10.1016/j.neubiorev.2020.09.005](https://doi.org/10.1016/j.neubiorev.2020.09.005)
- Petit G, Cebolla AM, Fattinger S, et al. Local sleep-like events during wakefulness and their relationship to decreased alertness in astronauts on ISS. *NPJ Microgravity*. 2019;5(1):1–9. doi: [10.1038/s41526-019-0069-0](https://doi.org/10.1038/s41526-019-0069-0)
- Lowe CJ, Safati A, Hall PA. The neurocognitive consequences of sleep restriction: a meta-analytic review. *Neurosci Biobehav Rev*. 2017;80(1):586–604. doi: [10.1016/j.neubiorev.2017.07.010](https://doi.org/10.1016/j.neubiorev.2017.07.010)
- Krause AJ, Simon EB, Mander BA, et al. The sleep-deprived human brain. *Nat Rev Neurosci*. 2017;18:404–418. doi: [10.1038/nrn.2017.55](https://doi.org/10.1038/nrn.2017.55)
- Pereira SIR, Lewis PA. Sleeping through brain excitation and inhibition. *Nat Neurosci*. 2020;23:1035–1039. doi: [10.1038/s41593-020-0697-4](https://doi.org/10.1038/s41593-020-0697-4)
- Singer W, Gray CM. Visual feature integration and the temporal correlation hypothesis. *Annu Rev Neurosci*. 1995;18(1):555–586. doi: [10.1146/annurev.ne.18.030195.003011](https://doi.org/10.1146/annurev.ne.18.030195.003011)
- Buzsáki G, Wang X-J, Wang X-J. Mechanisms of gamma oscillations. *Annu Rev Neurosci*. 2012;35:203–225. doi: [10.1146/annurev-neuro-062111-150444](https://doi.org/10.1146/annurev-neuro-062111-150444)
- Bragin A, Jandó G, Nádasdy Z, Hetke J, Wise K, Buzsáki G. Gamma (40–100 Hz) oscillation in the hippocampus of the behaving rat. *J Neurosci*. 1995;15(1):47–60. doi: [10.1523/JNEUROSCI.15-01-00047.1995](https://doi.org/10.1523/JNEUROSCI.15-01-00047.1995)
- Fell J, Axmacher N. The role of phase synchronization in memory processes. *Nat Rev Neurosci*. 2011;12(2):105–118. doi: [10.1038/nrn2979](https://doi.org/10.1038/nrn2979)
- Takeuchi S, Mima T, Murai R, Shimazu H, Isomura Y, Tsujimoto T. Gamma oscillations and their cross-frequency coupling in the primate hippocampus during sleep. *Sleep*. 2015;38(7):1085–1091. doi: [10.5665/sleep.4818](https://doi.org/10.5665/sleep.4818)
- Migliorelli C, Bachiller A, Andrade AG, et al. Alterations in EEG connectivity in healthy young adults provide an indicator of sleep depth. *Sleep*. 2019;42(6). doi: [10.1093/sleep/zsz081](https://doi.org/10.1093/sleep/zsz081)
- Haegens S, Nácher V, Luna R, Romo R, Jensen O. α-Oscillations in the monkey sensorimotor network influence discrimination performance by rhythmical inhibition of neuronal spiking. *Proc Natl Acad Sci USA*. 2011;108(48):19377–19382. doi: [10.1073/pnas.1117190108](https://doi.org/10.1073/pnas.1117190108)

13. Cavanagh JF, Frank MJ. Frontal theta as a mechanism for cognitive control. *Trends Cogn Sci.* 2014;**18**(8):414–421. doi: [10.1016/j.tics.2014.04.012](https://doi.org/10.1016/j.tics.2014.04.012)
14. Berger B, Griesmayr B, Minarik T, et al. Dynamic regulation of interregional cortical communication by slow brain oscillations during working memory. *Nat Commun.* 2019;**10**(1):1–11. doi: [10.1038/s41467-019-12057-0](https://doi.org/10.1038/s41467-019-12057-0)
15. Erika-Florence M, Leech R, Hampshire A. A functional network perspective on response inhibition and attentional control. *Nat Commun.* 2014;**5**(1):1–12. doi: [10.1038/ncomms5073](https://doi.org/10.1038/ncomms5073)
16. Aron AR, Poldrack RA. Cortical and subcortical contributions to stop signal response inhibition: role of the subthalamic nucleus. *J Neurosci.* 2006;**26**(9):2424–2433. doi: [10.1523/JNEUROSCI.4682-05.2006](https://doi.org/10.1523/JNEUROSCI.4682-05.2006)
17. Rubia K, Smith AB, Brammer MJ, Taylor E. Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. *Neuroimage.* 2003;**20**(1):351–358. doi: [10.1016/s1053-8119\(03\)00275-1](https://doi.org/10.1016/s1053-8119(03)00275-1)
18. Adelhöfer N, Beste C. Pre-trial theta band activity in the ventromedial prefrontal cortex correlates with inhibition-related theta band activity in the right inferior frontal cortex. *Neuroimage.* 2020;**219**(1):117052–117123. doi: [10.1016/j.neuroimage.2020.117052](https://doi.org/10.1016/j.neuroimage.2020.117052)
19. Harding IH, Yücel M, Harrison BJ, Pantelis C, Breakspear M. Effective connectivity within the frontoparietal control network differentiates cognitive control and working memory. *Neuroimage.* 2015;**106**:144–153. doi: [10.1016/j.neuroimage.2014.11.039](https://doi.org/10.1016/j.neuroimage.2014.11.039)
20. Kim B, Troxel WM, Dubowitz T, et al. Mediating role of psychological distress in the associations between neighborhood social environments and sleep health. *Sleep.* 2022;**45**(8). doi: [10.1093/sleep/zsac087](https://doi.org/10.1093/sleep/zsac087)
21. Kessler RC, Green JG, Gruber MJ, et al. Screening for serious mental illness in the general population with the K6 screening scale: results from the WHO World Mental Health (WMH) survey initiative. *Int J Methods Psychiatr Res.* 2010;**19**(S1):4–22. doi: [10.1002/mpr.310](https://doi.org/10.1002/mpr.310)
22. Spaeth AM, Khetarpal R, Yu D, Pien GW, Herring SJ. Determinants of postpartum sleep duration and sleep efficiency in minority women. *Sleep.* 2021;**44**(4). doi: [10.1093/sleep/zsaa246](https://doi.org/10.1093/sleep/zsaa246)
23. Liu Y, Wheaton AG, Chapman DP, Croft JB. Sleep duration and chronic diseases among US adults age 45 years and older: evidence from the 2010 Behavioral Risk Factor Surveillance System. *Sleep.* 2013;**36**(10):1421–1427. doi: [10.5665/sleep.3028](https://doi.org/10.5665/sleep.3028)
24. Grandner MA, Chakravorty S, Perlis ML, Oliver L, Gurubhagavatula I. Habitual sleep duration associated with self-reported and objectively determined cardiometabolic risk factors. *Sleep Med.* 2014;**15**(1):42–50. doi: [10.1016/j.sleep.2013.09.012](https://doi.org/10.1016/j.sleep.2013.09.012)
25. Dippel G, Beste C. A causal role of the right inferior frontal cortex in implementing strategies for multi-component behaviour. *Nat Commun.* 2015;**6**:687–695. doi: [10.1038/ncomms7587](https://doi.org/10.1038/ncomms7587)
26. Dippel G, Mückschel M, Ziemssen T, Beste C. Demands on response inhibition processes determine modulations of theta band activity in superior frontal areas and correlations with pupillometry—Implications for the norepinephrine system during inhibitory control. *Neuroimage.* 2017;**157**:575–585. doi: [10.1016/j.neuroimage.2017.06.037](https://doi.org/10.1016/j.neuroimage.2017.06.037)
27. Dimigen O. Optimizing the ICA-based removal of ocular EEG artifacts from free viewing experiments. *Neuroimage.* 2020;**207**:116117. doi: [10.1016/j.neuroimage.2019.116117](https://doi.org/10.1016/j.neuroimage.2019.116117)
28. Sauseng P, Klimesch W, Heise KF, et al. Brain oscillatory substrates of visual short-term memory capacity. *Curr Biol.* 2009;**19**(21):1846–1852. doi: [10.1016/j.cub.2009.08.062](https://doi.org/10.1016/j.cub.2009.08.062)
29. Stropahl M, Bauer A-KR, Debener S, Bleichner MG. Source-modeling auditory processes of EEG data using EEGLAB and brainstorm. *Front Neurosci.* 2018;**12**(1):309. doi: [10.3389/fnins.2018.00309](https://doi.org/10.3389/fnins.2018.00309)
30. Baglioni C, Nanovska S, Regen W, et al. Sleep and mental disorders: a meta-analysis of polysomnographic research. *Psychol Bull.* 2016;**142**(9):969–990. doi: [10.1037/bul0000053](https://doi.org/10.1037/bul0000053)
31. Ju H, Bassett DS. Dynamic representations in networked neural systems. *Nat Neurosci.* 2020;**23**(8):908–917. doi: [10.1038/s41593-020-0653-3](https://doi.org/10.1038/s41593-020-0653-3)
32. Finelli L, Baumann H, Borbély A, Achermann P. Dual electroencephalogram markers of human sleep homeostasis: correlation between theta activity in waking and slow-wave activity in sleep. *Neuroscience.* 2000;**101**(3):523–529. doi: [10.1016/s0306-4522\(00\)00409-7](https://doi.org/10.1016/s0306-4522(00)00409-7)
33. Cajochen C, Brunner DP, Krauchi K, Graw P, Wirz-Justice A. Power density in theta/alpha frequencies of the waking EEG progressively increases during sustained wakefulness. *Sleep.* 1995;**18**(10):890–894. doi: [10.1093/sleep/18.10.890](https://doi.org/10.1093/sleep/18.10.890)
34. Bernardi G, Siclari F, Yu X, et al. Neural and behavioral correlates of extended training during sleep deprivation in humans: evidence for local, task-specific effects. *J Neurosci.* 2015;**35**(11):4487–4500. doi: [10.1523/JNEUROSCI.4567-14.2015](https://doi.org/10.1523/JNEUROSCI.4567-14.2015)
35. Magnuson JR, Kang HJ, Dalton BH, McNeil CJ. Neural effects of sleep deprivation on inhibitory control and emotion processing. *Behav Brain Res.* 2022;**426**:113845. doi: [10.1016/j.bbr.2022.113845](https://doi.org/10.1016/j.bbr.2022.113845)
36. Yoo S-S, Gujar N, Hu P, Jolesz FA, Walker MP. The human emotional brain without sleep—a prefrontal amygdala disconnect. *Curr Biol.* 2007;**17**(20):R877–R878. doi: [10.1016/j.cub.2007.08.007](https://doi.org/10.1016/j.cub.2007.08.007)
37. Gujar N, Yoo S-S, Hu P, Walker MP. Sleep deprivation amplifies reactivity of brain reward networks, biasing the appraisal of positive emotional experiences. *J Neurosci.* 2011;**31**(12):4466–4474. doi: [10.1523/JNEUROSCI.3220-10.2011](https://doi.org/10.1523/JNEUROSCI.3220-10.2011)
38. Zhang J, Lau EYY, Hsiao JH-w. Using emotion regulation strategies after sleep deprivation: ERP and behavioral findings. *Cogn Affect Behav Neurosci.* 2019;**19**(2):283–295. doi: [10.3758/s13415-018-00667-y](https://doi.org/10.3758/s13415-018-00667-y)
39. Schulz KP, Fan J, Magidina O, Marks DJ, Hahn B, Halperin JM. Does the emotional go/no-go task really measure behavioral inhibition?: convergence with measures on a non-emotional analog. *Arch Clin Neuropsychol.* 2007;**22**(2):151–160. doi: [10.1016/j.acn.2006.12.001](https://doi.org/10.1016/j.acn.2006.12.001)
40. Cote KA, Mondloch C, Sergeeva V, Taylor M, Semplonius T. Impact of total sleep deprivation on behavioural neural processing of emotionally expressive faces. *Exp Brain Res.* 2014;**232**(5):1429–1442. doi: [10.1007/s00221-013-3780-1](https://doi.org/10.1007/s00221-013-3780-1)
41. Connell A, Danzo S, Magee K, Dawson G. Rumination in early adolescent girls: an EEG study of cognitive control and emotional responding in an emotional Go/NoGo task. *Cogn Affect Behav Neurosci.* 2020;**20**(1):181–194. doi: [10.3758/s13415-019-00761-9](https://doi.org/10.3758/s13415-019-00761-9)
42. Palermo S, Morese R, Zibetti M, et al. Impulse control disorder and response-inhibition alterations in Parkinson's disease. A rare case of totally absent functionality of the medial-prefrontal cortex and review of literature. *J Adv Res.* 2017;**8**(6):713–716. doi: [10.1016/j.jare.2017.09.004](https://doi.org/10.1016/j.jare.2017.09.004)
43. Sugawara K, Onishi H, Yamashiro K, et al. Repeated practice of a Go/NoGo visuomotor task induces neuroplastic change in the human posterior parietal cortex: an MEG study. *Exp Brain Res.* 2013;**226**(1):495–502. doi: [10.1007/s00221-013-3461-0](https://doi.org/10.1007/s00221-013-3461-0)
44. McDermott CM, LaHoste GJ, Chen C, Musto A, Bazan NG, Magee JC. Sleep deprivation causes behavioral, synaptic, and membrane excitability alterations in hippocampal neurons. *J Neurosci.* 2003;**23**(29):9687–9695. doi: [10.1523/JNEUROSCI.23-29-09687.2003](https://doi.org/10.1523/JNEUROSCI.23-29-09687.2003)