Nature and Science of Sleep

Elevate Series

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ORIGINAL RESEARCH

# Effects of Short Naps on EEG Microstates: Improving Sleep Deprivation-Induced Cognitive Impairment

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**Purpose:** Sleep can repair the brain damage caused by sleep deprivation (SD), however in many cases, it may not be feasible to get sufficient sleep. Napping is a simple strategy to mitigate the detrimental impacts of SD. However, the underlying mechanism behind how napping contributes to brain repair remains unclear. Electroencephalogram (EEG) microstate analysis is sensitive in detecting bottom-up and top-down attention control and rapid transitions between quasi-stable brain states due to its temporal resolution. This study aims to explore the effects of napping on cognitive impairments cause by SD and the potential mechanisms of cognitive recovery.

**Patients and Methods:** We recruited forty-two healthy volunteers and recorded their EEG signals and psychomotor vigilance task (PVT) data at three time points: rested wakefulness, post-SD, and post-nap. EEG microstates analysis was used to explore changes of brain dynamic network. In addition, we investigate the alterations in microstate parameters and their correlation with behavior.

**Results:** We observed a significant decrease in participants' alertness levels following SD, which subsequently improved after napping. Four microstate classes (A, B, C, D) were identified by using EEG microstate analysis. The B-D transition increased significantly after SD and returned to baseline after napping, while A-D transition revealed opposite patterns. Notably, changes of time coverage and occurrence in microstate D were significantly correlated with changes of PVT performance after both SD and nap conditions.

**Conclusion:** Our results provide empirical evidence that short naps can effectively reverse negative effects of SD on vigilant attention, primarily through restoring the functionality of key brain networks involved in attention regulation.

**Keywords:** sleep deprivation, short naps, EEG microstate, psychomotor vigilance task, cognitive recovery

## Introduction

Sleep deprivation (SD) can significantly disrupt the normal functioning of the human brain, leading to increased reaction time, reduced alertness, and diminished cognitive abilities.[1,2] The brain function impairment caused by SD is temporary and can be completely reversed after adequate sleep.[3] However, the long-duration sleep for the brain recovery is luxury and not feasible in many high-demand cases, which raises the need for a quick cognitive recovery from SD. Napping is an excellent countermeasures to combat the negative effects of SD,[4,5] and have been demonstrated to promote alertness and enhance brain cognitive functions.[6] Although long naps (2–4 hours) can elicit more profound restorative benefits,[7] short naps (<30 min) is the intervention that may have broader scope to mitigate impairments caused by SD,[8] owing to its higher practicality in workplace environments.[9] However, current research on short naps that last an hour or less is still relatively sparse, and the mechanisms of short naps in mitigating the effects of SD remain unclear.

Received: 26 November 2024
Accepted: 23 March 2025
Published: 9 May 2025

Neuroimaging researches have extensively demonstrated the impact of SD on brain function and the potential cognitive benefits of napping.[10] Vigilance deficits after SD were associated with reduced activity in the frontoparietal attention network, salience network and intermittent periods of diminished thalamic activity.[10] Ju et al found the increases in hippocampal activation during memory tasks after the nap period, suggesting restored hippocampal function.[11] Static characteristics fail to account for the dynamic patterns of brain signals, potentially excluding essential temporal information.[12] Dynamic analysis was widely used to investigate the coupling and shift patterns of distinct brain connectivity states and present a more comprehensive perspective of brain function.[13] Xu et al utilized dynamic functional connection to examine brain changes across three time points—before SD, post-SD, and after nap.[3] Their study found that the proportion of state 2 (a "resting-like" stationary state) decreased significantly after SD, while state 3 (a "stationary" state) became dominant. After a nap, the proportions of states 2 and 3 reversed. These shifts in brain states were closely associated with improvements in cognitive performance. However, functional magnetic resonance imaging (fMRI) methods can hardly to capture the dynamic functional information limited by the delayed and slow hemodynamic response to neuronal activity.[14] Electroencephalogram (EEG) microstate analysis is more sensitive in detecting bottom-up and top-down attention control and rapid transitions between quasi-stable brain states due to its temporal resolution.[15] Changes in EEG microstates are thought to reflect alterations in brain connectivity, particularly in networks involved in cognitive control and attention regulation, such as the and the fronto-parietal network and attention network.[16,17] Therefore, microstate is a promising method to capture brain dynamic characteristics and reveal the potential mechanism of SD-induced cognitive impairment and cognitive recovery following a short nap.

Microstate analysis dissects multichannel EEG recordings into a series of transient, distinct patterns of stable electrical potentials known as "microstates".[18,19] It can reflect the different types of spontaneous activities and stimulation-induced psychological processes.[16,20] Microstates typically maintain stability for a span of 60–120 ms before swiftly transitioning to a new microstate.[21,22] Four canonical classes of quasi-steady microstates, labeled A–D, are widely accepted in characterizing spontaneous resting-state EEG activity.[21] These microstates correspond to the resting-state networks previously identified as associated with distinct cognitive functions - phonological processing (microstate A), the visual network (microstate B), the saliency network (microstate C), and attention network (microstate D).[23] By integrating EEG signals from the entire brain to comprehensively depict functional state, microstate analysis allows for an insightful assessment of the temporal characteristics of these four microstates, such as time coverage, duration, and occurrence.[24,25]

EEG microstates can be utilized to investigate brain networks during various cognitive states, such as fatigue induced by SD. This is due to the ability to capture the rapid sequential activations and transitions between brain activity states. Ke et al explored the impact of 24-hour SD on EEG microstates, observing a decrease in microstate A and an increase in microstate D, which were correlated with subjective sleepiness.[15] Similarly, Xin et al investigated the changes in EEG microstates, vigilance, and their relationships during 36 hours of total SD. They observed notable changes in transitions between microstates A and D which displayed a negative correlation with vigilance.[26] Nonetheless, it is important to note that the effects of short naps on restoring cognitive impairments induced by SD remain unclear. Thus, there is a clear need for further coherently analyze the changes in brain microstates during SD and nap processes. This approach would provide a more comprehensive insight to explore brain impairments cause by SD and the potential mechanisms of cognitive recovery following nap.

The objects of this study are as follows: (1) To assess whether short naps can serve as an effective intervention for mitigating the cognitive impairments of SD. (2) To explore the potential mechanisms of short napping on cognitive recovery through EEG microstates. We hypothesize that napping could reverse the cognitive impairment induced by SD and the cognitive recovery after napping is associated with the restoration of dynamic brain functional networks. To this end, we used psychomotor vigilance task (PVT) to evaluate changes in alert attention after SD and napping, and employed EEG microstate analysis to explore the temporal dynamics of brain networks and their relationship with PVT performance.

# Materials and Methods

## Participants

Healthy subjects were recruited from several local universities. A semi-structured interview was conducted to assess their eligibility. Participants were required to be aged between 18 and 25 years and considered good sleep habit (>6.5 h of

sleep per night).[3] Exclusion criteria were: (1) individuals with any physical illness, such as a brain tumor, hepatitis, or epilepsy, as assessed according to clinical evaluations and medical records; (2) Insomnia obstacles of history; (3) nap habit (4) a job that required shiftwork; or (5) those using prescription medications within the last month. The written informed consent of all participants was obtained. The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee/Institutional Review Board of Chengdu University.

## Experimental Design

The study consisted of three visits to the laboratory. The first visit involved briefing the participants on the study protocol and providing them with a wrist actigraphy (Actiwatch, Philips Respironics, USA) to monitor their sleep patterns. We conducted resting EEG recordings at the second visit, following 30 hours of SD and a subsequent 30-minute nap. During the third visit, EEG data was collected from the subjects while they were awake. To minimize the influence of the EEG recording sequence, the order of the second and third visits was pseudo-randomized. There was a two-week interval between these two visits to mitigate any residual effects of SD. Participants were required to abstain from smoking, vigorous activities, and consuming caffeinated beverages throughout the study. The SD period commenced at 8:00 a.m. and concluded at 2:00 p.m. the following day, immediately after which EEG data were collected. After completing the EEG recording in the SD condition, participants were allowed a 30-minute nap, followed by another EEG recording. The duration of the nap was monitored using the wristwatch, which confirmed that all participants slept for at least 20 minutes. Previous research has shown that the duration of sleep inertia typically does not exceed 30 minutes.[27] In studies comparing sleep inertia following an 8-h sleep opportunity to partial sleep deprivation, performance upon waking was significantly worse after the partial sleep deprivation night.[28] Given that sleep inertia is unavoidable, participants were given a 20-minute post-nap rest period. During this period, participants engaged in light activities, such as casual conversations with the experimenter about their subjective rest state and fatigue levels, as well as brief walking exercises. Moreover, EEG data collection preparations began only after this period, meaning that formal post-nap EEG recordings were conducted approximately 30 minutes after participants awoke from their nap. Throughout the whole SD experiment, two researchers supervised participants to ensure they remained awake during the SD period and did not unintentionally fall asleep.

## Psychomotor Vigilance Task

The Psychomotor Vigilance Task (PVT) was employed to assess visual vigilance attention and was implemented using the E-Prime software. The task required participants to attentively observe a blank screen until a red circle appeared, then respond by pressing a button as quickly as possible. The button reaction caused the circle to disappear and triggered feedback displaying the reaction time, which remained on the screen for 1000 milliseconds. The circle appeared at random intervals between 2 and 10 seconds. The task lasted 10 minutes. The primary variables of interest were the reaction times and lapse times. The lapse is defined as instances where reaction times exceeded 500 milliseconds.

## EEG Recording and Preprocessing

The whole EEG data collection was conducted in a noise-free and low-light laboratory, where the participants sat in a comfortable chair directly in front of the 24-inch monitor, 60 cm away, with the center of the participant's field of vision at the same level as the center of the monitor. EEG data were recorded by Neuroscan 64-channel EEG equipment according to the extended 10/20 international system (sampling rate: 1000 hz). All electrode impedances were kept below 5 kΩ. The subjects opened their eyes to collect resting EEG data for five minutes. EEG data were preprocessed using EEGLAB,[29] an open-source toolbox running in the MATLAB environment (R2021a; MathWorks, USA). EEG data were down-sampled to 250 hz and referenced to average. Then the data was bandpass filtered at 2–20 hz, which is widely used for microstate analysis. EEG data segmented into epochs with a window analysis time of 2000ms. The EEG data collected with eyes open were corrected for artifacts such as eye blinks, eye movements, and muscle activity using the Independent Component Analysis (ICA) algorithm in the EEGLAB toolbox. Components associated with artifacts were identified based on their time courses and topographies and removed from the EEG data.

## EEG Microstate Analysis

The microstate analysis was performed for combined EEG signals using the EEGLAB microstate plugin.[30] For each participant under each condition, we calculated the Global Field Power (GFP) as the standard deviation of the EEG signals across all electrodes at each time point. GFP represents the instantaneous strength of the EEG activity over the entire scalp and is calculated as follows.

$$GFP_{(t)} = \sqrt{\frac{\sum^{i=1} N(V_i(t) - \bar{V}(t))^2}{N}}$$

where t is the point in time, N is the number of electrodes, $V_i(t)$ is the i electrode at time t, and $\bar{V}(t)$ is the average value of the potential recorded by all electrodes at time t. Since EEG scalp topographies are stable around the peaks of the GFP, we extracted EEG topographies at these peaks and subjected them to clustering analysis. Our analysis employed the atomize–agglomerate hierarchical clustering (AAHC) method. The Krzanowski–Lai criterion was applied and identify four optimal clustering classes. For each participant and condition, we constructed EEG time series as sequences of microstates through a back-fitting procedure. This involved assigning the specific group-wise microstate to each time point based on the correlation coefficients calculated between EEG topographies at each time point and the four identified microstate topographies. Each EEG time point was then categorized as A–D, depending on its maximal correlation with a microstate. We computed spatial correlation to ensure microstate consistency across three time points. High spatial correlation indicated the microstate were similar between the four topographic maps in the rested wakefulness (RW), SD, and nap states (see Supplementary Table 1). From the time series of microstates, EEG microstate analysis involves extracting several key features to characterize the temporal dynamics of brain activity. These include duration, which refers to the average time a microstate remains stable before transitioning to another microstate; occurrence, which indicates the frequency at which a microstate appears within a given time period; and time coverage, which represents the proportion of total recording time during which a microstate is dominant. Additionally, global explained variance measures the portion of the EEG signal that can be explained by the four canonical microstates (A to D). Transition probabilities between different microstates are calculated to examine the likelihood of one microstate transitioning to another over time, thereby revealing the patterns of microstate shifts and the dynamic sequences of brain activity.

## Statistical Analysis

All statistical analyses were analyzed using the Statistical Package for the Social Sciences (SPSS, version 26.0, Chicago, IL) software. A one-way repeated-measures analysis of variance (ANOVA) was used to compare the PVT performance across the three timepoints. If the ANOVA indicated statistical significance for any metric, a post-hoc *t*-test with Bonferroni correction was conducted.

For each of the microstate parameters (time coverage, mean duration, and occurrence), we performed a two-way repeated-measures analysis of variance (rm-ANOVA) with three timepoint. This ANOVA incorporated two within-participant factors: microstate class (A–D) and condition (RW, SD, and nap). For each of the three analyses (RW vs SD, SD vs nap, RW vs nap), pairwise group comparisons for all microstate parameters and for each microstate class were corrected for with comparisons with Bonferroni for 12 comparisons (3 parameters × 4 classes).[22] Additionally, we employed a paired-sample *t*-test for each pair of microstate class transitions to investigate if there were significant differences in transition probabilities between conditions. To adjust for the risk of false positives due to multiple comparisons over each transition probability, we applied the false discovery rate (FDR) method to correct the P-values. Furthermore, to explore the relationship between the characteristics of the microstates and performance on the PVT, we conducted Pearson correlation analyses across participants. FDR correction was applied to the correlation analysis. The threshold for statistical significance was set at $p < 0.05$.

# Results

## Demographic Characteristics and Behavioral Results

In this study, a total of 44 participants were recruited. Two participants were excluded for failing to complete the trial. Healthy participants (all males) with a mean age of 21.53 ± 1.82 years (range:18–25) provided 42 participants remained for further analysis. The watch monitoring data showed the duration of nap were 24.93 ± 2.18 minutes with a sleep efficiency of 83.1 ± 7.27%. As shown in Figure 1, The PVT results revealed a significant increase in PVT performance under the SD condition compared to the RW and nap conditions.

## Microstate Temporal Characteristics

Figure 2A illustrates the topographies of the four dominant microstate classes for the RW, SD, and nap conditions. These four maps have right-frontal to left-posterior, left-frontal to right-posterior, frontal to occipital, and midline frontal to occipital topographies, and are labeled A, B, C, and D, respectively. The microstate classes were highly consistent across the three time points. The four microstate classes (A-D) accounted for >70% of the data variation for each group dataset (RW:77.2 ± 2.7%; SD:75.9 ± 3.5%; nap: 78.0 ± 3.3%). It confirms that these four microstates can well represent the EEG data in three conditions.

The mean duration, occurrence and time coverage for each microstate class are shown in Figure 2B–D. Analysis of mean duration revealed a significant main effect of microstate class ($F = 5.887$, $P < 0.001$) in which durations were longer for microstate C than for microstate A ($t = 2.559$, $P = 0.010$) and microstate B ($t = 3.992$, $P < 0.001$). The main effect of condition was not significant ($F = 2.676$, $P = 0.069$). The interaction between microstate class and condition was not significant ($F = 1.324$, $P = 0.331$). Post hoc comparisons showed that the mean duration of microstate B was longer in the SD condition than in the RW ($t = 3.48$, $P = 0.014$) and nap condition ($t = 3.39$, $P = 0.019$).

Analysis of occurrence revealed a significant main effect of microstate class ($F = 5.663$, $P < 0.001$) in which microstate frequency was higher for microstate D than for microstates A ($t = 3.629$, $P < 0.001$) and B ($t = 3.320$, $P = 0.001$). The interaction between microstate class and condition was significant ($F = 6.993$, $P < 0.001$). Post hoc comparisons revealed that the occurrence of microstate A was lower in the SD condition than in the RW ($t = 3.245$, $P = 0.029$) and nap condition ($t = 3.705$, $P = 0.007$). The occurrence of microstate B was higher in the SD condition than in the RW ($t = 3.047$, $P = 0.049$) and nap condition ($t = 4.010$, $P = 0.003$).

Analysis of time coverage revealed a significant main effect of microstate class ($F = 8.664$, $P < 0.001$) in which time coverage was higher for microstate C than for microstates A ($t = 3.236$, $P = 0.001$) and B ($t = 3.713$, $P < 0.001$), and microstate D was greater than for microstate A ($t = 3.458$, $P < 0.001$) and B ($t = 3.936$, $P < 0.001$). The interaction between microstate class and condition was significant ($F = 5.587$, $P < 0.001$). Post hoc comparisons showed that time coverage of microstate B was longer in SD condition than (RW vs SD: $t = 5.34$, $P < 0.001$; SD vs nap: $t = 6.35$, $P < 0.001$). The time coverage of microstate D under nap and RW conditions is longer than in the RW ($t = 5.34$, $P < 0.001$) and nap condition ($t = 6.35$, $P < 0.001$).

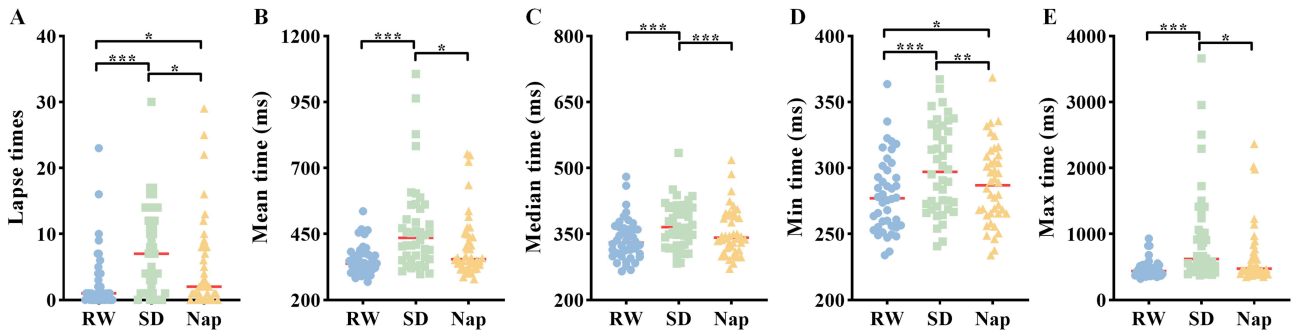


**Figure 1** PVT performances during RW, SD and nap conditions. (**A**) Lapse time, (**B**) Mean, (**C**) Median, (**D**) Minimum, and (**E**) Maximum of PVT task among timepoints. All *P*-values are corrected using Bonferroni's multiple comparisons test. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.


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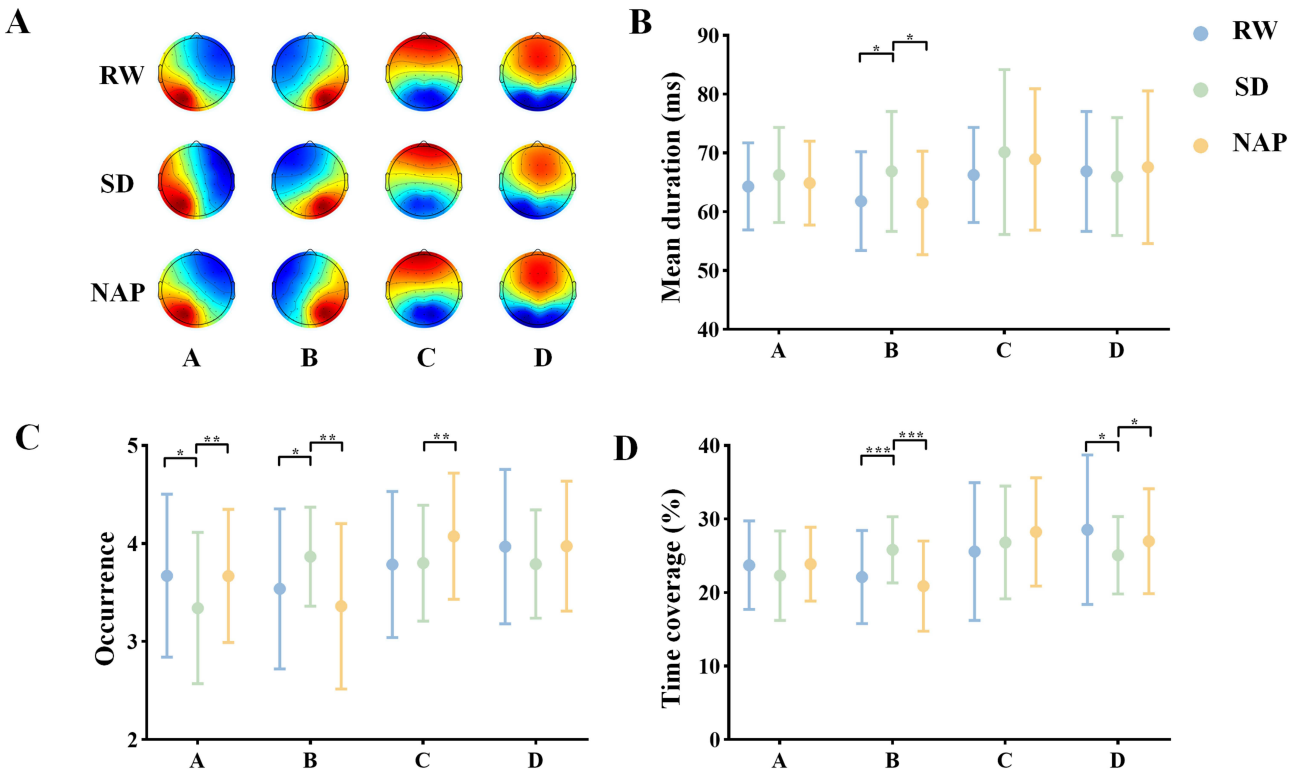


**Figure 2** Microstate topographies and their temporal characteristics in RW, SD and nap conditions. (**A**) The spatial configuration of the 4 microstate classes labeled with the letters A-D accordingly. Each row shows the 4 topographic on figurations for the RW, SD and nap conditions. (**B**) Mean duration of microstate. (**C**) Occurrence of microstate. (**D**) Time coverage of microstate. Temporal microstate characteristics were compared between RW, SD and nap conditions for each microstate. All *P*-values are corrected using Bonferroni's multiple comparisons test. **P* < 0.05; ***P* < 0.01; ****P* < 0.001.

## Transition Probabilities

The compare of RW and SD conditions in transition probability is shown in Figure 3A. Figure 3C demonstrates that, the transition probability of microstate increases significantly following SD compared to RW, including transitions B to D ($t = 2.78$, $P = 0.008$), D to B ($t = 2.55$, $P = 0.015$), B to C ($t = 3.91$, $P < 0.001$), and C to B ($t = 3.93$, $P < 0.001$). In contrast, the transition probability of microstate decreases significantly following SD compared to RW, including from A to D ($t = 3.02$, $P = 0.004$) and D to A ($t = 2.59$, $P = 0.013$). There was no significant difference in other transfer probabilities between RW and SD conditions ($P > 0.05$ for all comparisons).

The compare of nap and SD conditions in transition probability is shown in Figure 3B. Figure 3C demonstrates that, the transition probability of microstate decreases significantly following napping compared to SD, including transitions B to D ($t = 4.92$, $P < 0.001$), D to B ($t = 5.40$, $P < 0.001$), B to C ($t = 3.59$, $P < 0.001$), and C to B ($t = 3.63$, $P < 0.001$). In contrast, the transition probability of microstate decreases significantly following nap compared to SD, including from A to D ($t = 3.07$, $P = 0.004$), D to A ($t = 2.94$, $P = 0.005$). There was no significant difference in other transfer probabilities between nap and SD conditions ($P > 0.05$ for all comparisons). These results suggest that napping restores the dysregulation of transition probability.

## Correlation between Microstate Parameters and PVT Performance

To investigate the relationship between changes in microstate characteristics and changes in PVT performance, we performed a Pearson correlation analysis across subjects in three conditions. Figure 4 illustrates the correlations between microstate D and PVT performance. The change in occurrence of microstate D was significantly correlated with the change in PVT mean reaction time (both SD-RW and nap-SD). The change in time coverage of microstate D was significantly correlated with the change in PVT mean reaction time (both SD-RW and nap-SD). The change in occurrence and time coverage of microstate D was significantly correlated with the change in PVT lapse times (nap-SD).

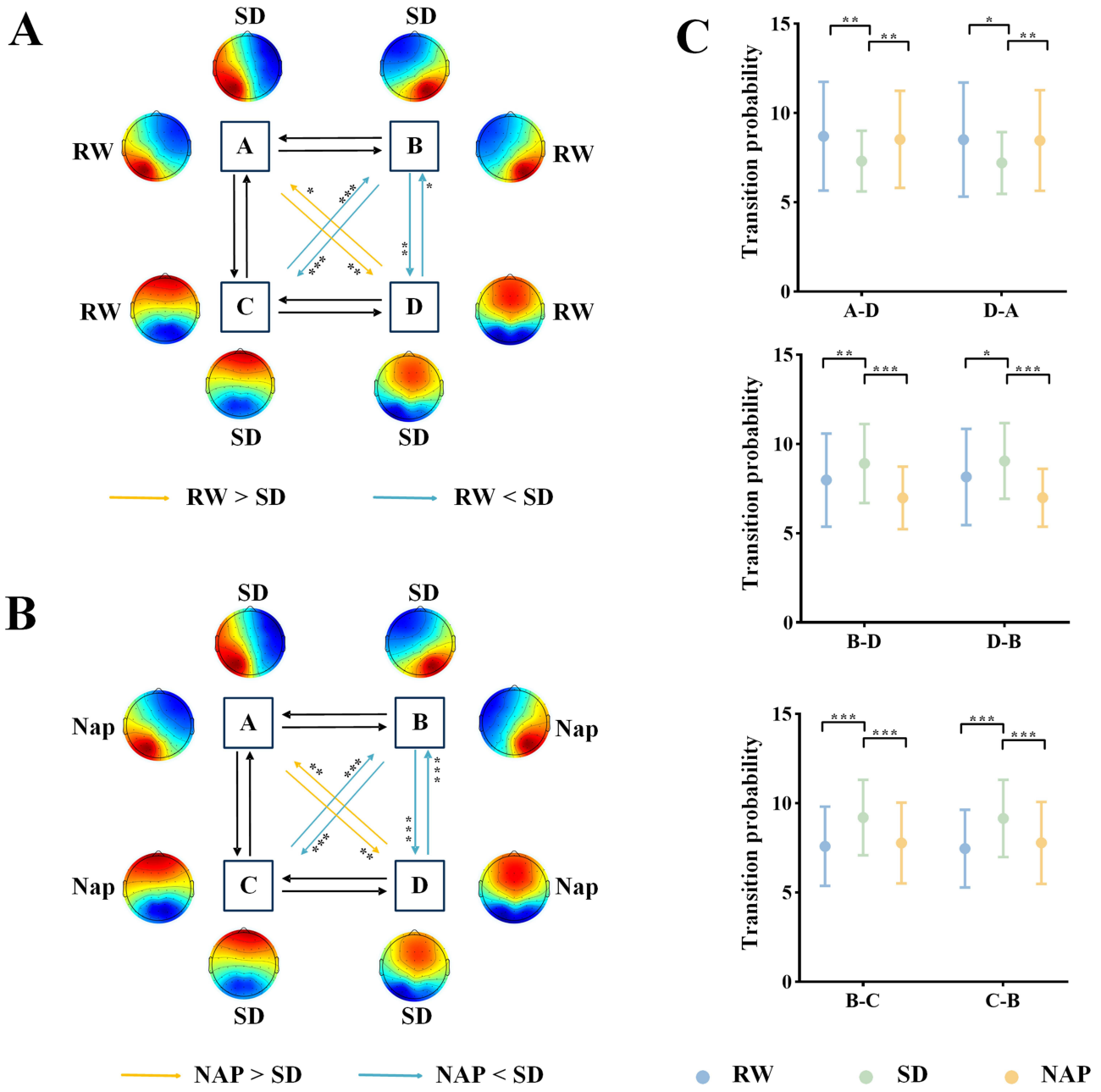


**Figure 3** Transition probabilities between microstates during RW, SD and nap conditions. (**A**) Transition probabilities for microstate classes were compared between RW and SD conditions. Solid arrows indicate significant differences, with yellow (blue) arrows representing more (fewer) transitions in the RW condition compared to the SD condition. (**B**) Transition probabilities for microstate classes were compared between nap and SD conditions. Solid arrows indicate significant differences, with yellow (blue) arrows representing more (fewer) transitions in the nap condition compared to the SD condition. (**C**) Error bar plots illustrate the ranges of the transition probabilities. All p-values were corrected using FDR. *P < 0.05; **P < 0.01; ***P < 0.001.

## Discussion

This study investigated the recovery of dynamic brain networks by a short nap following SD. Our findings revealed that SD negatively impacted the alertness levels which were subsequently improved after a short nap. EEG microstate analysis was utilized to investigate the temporal dynamics of brain networks under RW, SD and nap conditions. We found that parameters of microstate D decreased after SD and increased after nap. Notably, a significant positive correlation was observed between changes in microstate D and changes of alertness levels following both SD and napping. After SD, there was a significant increase in the transitions between microstate B and microstate D, which then returned to baseline after a nap. In contrast, the transitions between microstate A and microstate D showed the opposite pattern. Our results indicated that napping effectively


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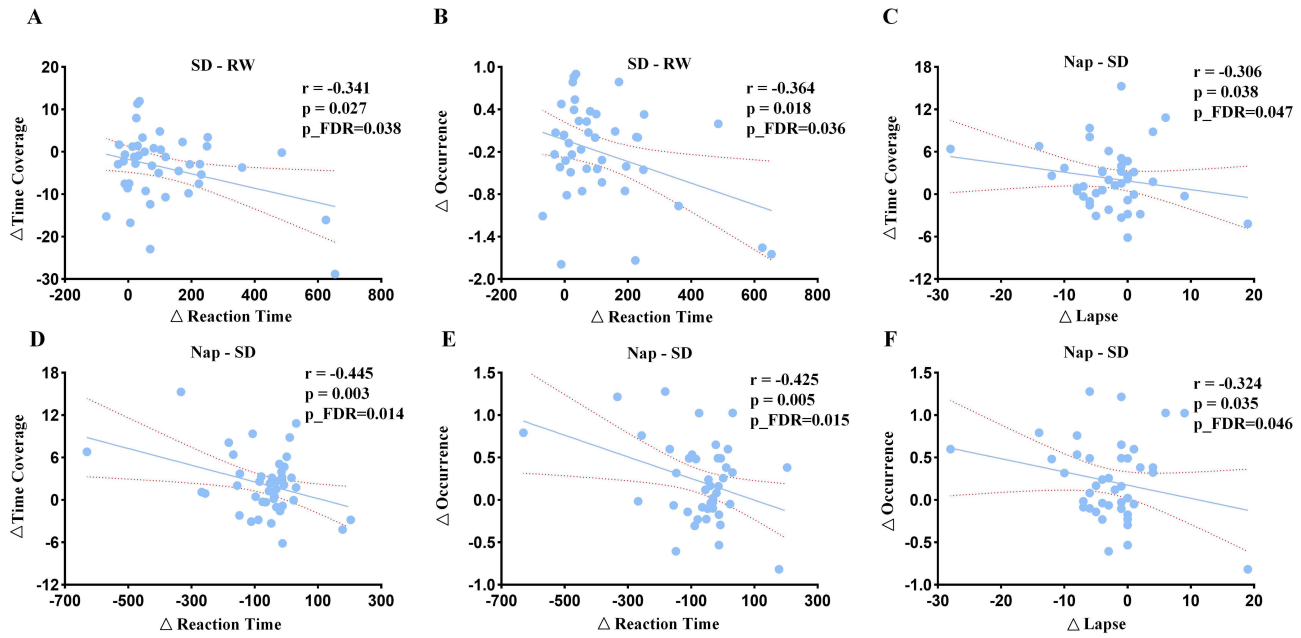


**Figure 4** Correlations between microstate parameters and PVT performance. (**A**) Between Δ time coverage and Δ reaction time (SD-RW), (**B**) between Δ occurrence and Δ reaction time (SD-RW), (**C**) between Δ time coverage and Δ lapse (nap-SD), (**D**) between Δ time coverage and Δ reaction time (nap -SD), (**E**) between Δ occurrence and Δ reaction time (nap -SD), (**F**) between Δ occurrence and Δ lapse (nap -SD).

restored cognitive impairment caused by SD and observed a relationship between this cognitive recovery and dynamic changes in the attention network primarily characterized by microstate D.

EEG microstate analysis can be used to assess large-scale brain networks which are associated with different brain functions and cognitive processes.[16,31] In our results, significant changes of microstates D were observed in microstate parameters across RW, SD and nap conditions. The parameters (occurrence and time coverage) of microstate D revealed a decreasing trend after SD and returned to baseline after napping. Furthermore, we found that the changes of parameters in microstate D were significantly correlated with the changes of PVT performance after both SD and nap conditions. It is widely reported that microstate D is mainly derived from the right superior and middle frontal gyri and associated with the attention networks.[23,32] SD generally leads to a decrease in cerebral metabolism, particularly in the prefrontal cortex, which could impair the ability to sustain focused attention tasks.[33,34] Our results of the decrease in microstate D likely reflects a reduction in neural activity within the attention network, especially in critical areas like the prefrontal cortex that are essential for maintaining vigilance and processing external stimuli.

It is notable that the parameters of microstate D decreases following SD, and this decline is notably restored after a nap. Napping appears to recharge the attention systems, possibly by enhancing synaptic connectivity and overall cerebral blood flow, especially within frontal brain regions.[6,35] We found that napping could alleviate the impairment of attention and promote the rebound of microstate D, which suggest enhanced attentional reorientation and network integration post-nap. Thus, our results may suggest that microstate D could serve as an indicator of the changed vigilance level and the brain ability to regulate attention and maintain attentiveness.

The recovery of attention after napping is associated with the increase in microstate D parameters. Napping appears to recharge the attention systems, possibly by enhancing synaptic connectivity and overall cerebral blood flow, especially within frontal brain regions.[6,35] We found that napping could alleviate the impairment of attention and promote the rebound of microstate D, which suggest enhanced attentional reorientation and network integration post-nap. Thus, our results may suggest that microstate D could serve as an indicator of the changed vigilance level and the brain ability to regulate attention and maintain attentiveness.

We found the occurrence, duration, and time coverage of microstate B increased markedly post-SD, which is consistent with previous studies on the microstates of SD.[15,26] Microstate B is associated with negative BOLD activation

in the bilateral occipital cortex located in the primary visual cortex.[16,32] Li et al observed that the duration of microstate B increased with declining cognitive ability,[36] and this decline in cognitive ability related to brain activity in the visual network. Deficits in visual processing capacity are central to explaining the neurobehavioral abnormalities observed in SD.[37] The increase of microstate B parameter reflected that SD may lead to an over-reliance on the visual network, possibly as a compensatory response to the demands on cognitive resources. After napping, the characteristic of microstate B decreased significantly and returned to baseline. This over-engagement is reversed following a short nap, implying a restorative effect on the visual network. Consistent with the change trend of microstate B, there was a significant increase in B-D transition after SD, and the transition returned to baseline following a nap. The transition between different microstates represents the sequential and coordinated functioning of distinct brain networks and is associated with functional connectivity across networks.[16,38] FMRI studies have reported not only impaired visual networks during SD, but also diminished connections between visual networks and other neural networks.[23,39] Therefore, our findings suggested that the increase of B-D transition may serve as a compensation approach for maintaining cognitive function in instances where attention are impaired. Napping seems to promote a restoration of network activity, specifically by lowering excessive involvement of the visual network. This may lead to a more balanced brain dynamic, which is crucial for optimal cognitive performance.

In our results, the occurrence, duration, and time coverage of microstate A decreased post-SD and returned to baseline after napping. Microstate A is implicated in auditory processing during the resting state.[16,23] In addition, we found a contrasting A-D transition pattern compare with B-D transition: the A-D transition decreased after SD and increased following nap. The decrease A-D transition after SD is consistent with previous research. Xin et al reported that A-D transition reflected compromised cognitive function and may serve as early warning indicators of attentional function following SD.[26] Attention is a selection mechanism to allocate limited information and a limited perceptual resource that would result in diminished auditory processing.[40–42] Our findings indicated that brain may rely more on visual cues to sustain attention in the wake of impaired auditory-attentional integration. Microstate time sequence is neither random nor predictable, the changes in transitions may characterize disruption in mental processes associated with SD. Sensory factors (auditory and visual corresponding to microstates A and B) are concerned with bottom-up attentional regulation.[43] After SD, the resource allocation shifts toward facilitating information transfer between attention and visual networks, reflecting a potential compensatory mechanism to cognitive impairment or an inefficient utilization of resources due to neural fatigue. This result suggested that SD not only leads to a general decline in brain activity or efficiency but rather induces specific alterations in the interaction and coordination of several brain networks, particularly affecting how sensory information is integrated into attentional processes. The transition switching back to baseline indicated that short naps could restore attention network and regulate resource allocation. Research have found napping can reverse performance deficits induced by SD, with benefits extending beyond improved attention and vigilance to positively affecting both auditory and visual stimuli.[5,44] Our study may suggest that napping can reverse the switching between auditory, visual, and attentional networks, thereby promoting the renormalization of network activity, and potentially restoring the more balanced neural dynamics necessary for cognitive function.

To summarize, the findings of this study have significant implications for both theoretical understanding and practical applications in the context of cognitive recovery following sleep deprivation. This is particularly relevant in occupations such as healthcare, emergency services, or transportation, where workers are often required to perform demanding tasks during night shifts or extended hours of wakefulness. In these environments, cognitive performance can be severely compromised by sleep deprivation. Our findings suggest that short naps could serve as an effective strategy to restore cognitive function and mitigate the negative effects of sleep deprivation, thereby improving overall performance and reducing the risk of errors and accidents in critical tasks. The study provides valuable insights into the neural mechanisms underlying these changes, contributing to the broader field of sleep medicine. Future research should explore the full range of nap durations to better understand their impact on cognitive recovery and the potential for individualized interventions in various real-world settings.

This study should be considered in light of the following limitations. First, this study included only male participants and single nap, which may limit the generalizability of the results. Future research should include both male and female participants to examine potential gender-specific effects and improve the applicability of the findings. Second, to mitigate

the risk of participants falling asleep, particularly after SD, we collected EEG data while the subjects kept their eyes open. The effect of eye-opening and eye-closing data on microstates is still controversial,[45] it may limit the generalizability of our findings. Third, while we provide correlative evidence linking changes in microstates to alterations in alertness, the causal relationship between EEG microstates and attention perception has yet to be established. Research has already indicated that microstate dynamics can be modulated by neurofeedback and external stimulation.[46] Future studies employing transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), and other stimuli could further elucidate the causal relationships between attention and microstates, potentially informing interventions to mitigate the cognitive effects of SD.

## Conclusion

Our findings demonstrate that napping effectively restores cognitive impairments induced by SD. We observed that cognitive recovery was associated with changes in attention network activity. Additionally, our results suggest that the integration of attention and sensory information is crucial for regulating alertness. EEG microstate analysis reveals the dynamic mechanisms underlying these effects, providing a novel perspective on cognitive recovery after SD. Given that microstate dynamics can be influenced by non-invasive techniques like neurofeedback and nerve stimulation, this study offers a foundation for future research into restorative strategies for SD.

## Data Sharing Statement

The data supporting the findings of the present study are available to obtain from the corresponding author, Fang Peng, upon reasonable request.

## Author Contributions

Conceptualization: Peng Fang, Wei He and Yuanqiang Zhu. Methodology: Chaozong Ma, Jiaxi Peng,Yangsen Huang, and Anping Ouyang. Investigation: Jiaxi Peng. Formal analysis: Chaozong Ma and Yan Li. Validation: Jiaxi Peng. Data curation: Chaozong Ma. Funding acquisition: Peng Fang. Supervision: Peng Fang. All authors took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

## Funding

This study was supported by the Natural Science Basic Research Program of Shaanxi Province (2024JC-YBQN-0209); the National Natural Science Foundation of China (32471081); the National Key Laboratory of Unmanned Aerial Vehicle Technology, NPU (WR202420-2); and the "Clinical Medicine + X" Research Center Research Project (LHJJ24XL03).

## Disclosure

The author(s) report no conflicts of interest in this work.

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