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Associations of psychological resilience with macro- and microstructures in NREM and REM sleep in adolescents

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ABSTRACT

Study objectives: Previous evidence suggest that sleep contributed to resilience. However, specific sleep markers for resilience in adolescents remain unknown. This study aimed to examine the associations between macro- and microstructures of sleep with resilience in healthy adolescents. This study hypothesized that specific features of both NREM and REM sleep were associated with resilience in healthy adolescents.

Methods: Forty-two healthy adolescents (Mean age: 15.98 years, SD: 2.16 years; female: 57.1 %) were included in this study. Adolescents with any diagnosed sleep or psychiatric disorders were excluded. Participants completed questionnaires that assessed resilience capacity and outcome, childhood trauma, and mental well-being, and underwent polysomnography. Resilience capacity was defined using the score of the Resilience Scale for Chinese Adolescents (RSCA). Resilience outcome was calculated by the residual approach in a linear model using mental well-being (KIDSCREEN) as dependent variable and childhood trauma (Childhood Trauma Questionnaire) as independent variable. NREM and REM sleep macrostructures and microstructures were calculated.

Results: The results showed that higher fast beta power (24–32 Hz) in REM sleep and longer spindle duration in NREM sleep were significantly associated with higher resilience capacity. However, slow wave sleep properties were not associated with either resilience capacity or resilience outcome. In addition, macrostructures of sleep did not differ across resilience groups.

Conclusions: The findings suggest that microstructures of both REM and NREM sleep could serve as biomarkers for resilience. This study could potentially pave the way for prevention and intervention strategies of stress-related disorders in adolescents.

Introduction

Adolescence is a critical neurodevelopmental period, which is influenced by both biological and psychosocial factors, including sleep. During this time, significant neurophysiological changes occur, such as the development of hypothalamus-pituitary-adrenal gland function and the prefrontal cortex-amygdala connectivity (Smith and Pollak, 2020). These changes coupled with various challenges (e.g., academic pressure, peer pressure, family conflict) might increase adolescents' vulnerability to psychopathology (Golchoobi & Nooripour, 2025; Roberts & Lopez-Duran, 2019; Smith & Pollak, 2020). In this light, adaptive coping strategies and external support systems are important, as they empower adolescents to overcome challenges and maintain mental health during this important stage of growth (Ronen, 2021). Psychological resilience (Resilience), a crucial protective factor for mental health, refers to the capacity to adapt to stress, and is considered as a successful adaptation outcome after stress (Hofgaard et al., 2021). It involves internal coping style (e.g., cognitive reframing of challenges, emotional regulation) and external support (e.g., family support, social support) (Hu & Gan, 2008). These components serve to reduce the risk of developing mental health

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problems, and also to enhance the growth of adolescents (Nooripour et al., 2023a, b).

Sleep is theorized to contribute to resilience. Emerging studies have shown the associations between resilience and sleep, with resilient individuals reporting better sleep quality and adequate sleep duration (Arora et al., 2022; Parrino & Vaudano, 2018). Individuals who experienced stress but remained mentally healthy often have good sleep health (Natraj & Richards, 2023; Parrino & Vaudano, 2018; Wang et al., 2020). However, subjective reports of sleep are inadequate to fully capture the complexities of sleep architecture and patterns. Additionally, current research on resilience and sleep are devoid of objective physiological data that reflect macrostructures and microstructures of different sleep stages. To address this gap, recent research has explore the association between sleep neurophysiology and stress. For example, slow wave sleep, which plays a role in synaptic plasticity and memory consolidation, along with sleep spindles that contribute to memory consolidation and sleep continuity, may collectively support individuals' wellbeing (Fernandez & Lüthi, 2020; Léger et al., 2018; Parrino & Vaudano, 2018). Another sleep feature, notably microstructures in REM sleep (theta power), usually involve remodelling and reconsolidation of stress-related emotional memorythat may affect the emotional regulation (Natraj & Richards, 2023; van der Heijden et al., 2022). Notably, research has shown that trauma-resilient individuals demonstrated reduced spindle frequency and amplitude during NREM sleep, and increased theta power during REM sleep in comparison to those with post-traumatic stress disorder (PTSD) (Cowdin et al., 2014; van der Heijden et al., 2022; Wang et al., 2020). These suggest that resilience may be linked to the recovery processes that are associated with sleep stage-specific microstructures. Nonetheless, current research is devoid of evidence regarding the role of sleep microstructures in maintaining resilience, especially in healthy adolescents who could sustain their health and quality of life despite adversities experiences (Cowdin et al., 2014; van der Heijden et al., 2022; Wang et al., 2020).

Taken together, it is important to examine the association between sleep features and resilience in order to explore potential sleep markers in adolescents who are vulnerable to the onset of mental health disorders. This study aimed to investigate the associations between macrostructures and microstructures of sleep with resilience in healthy adolescents, focusing on power spectral density in both NREM and REM sleep, and the characteristics of slow wave activity and sleep spindles in NREM sleep. We hypothesized that both NREM and REM sleep macrostructures and microstructures would be associated with resilience in healthy adolescents.

Methods

Participants and study procedure

Participants were recruited from local schools and community, and were invited to attend a comprehensive screening process that included the modified Structural Clinical Interview of DSM-5 (SCID-CV)(First et al., 2016) and Diagnostic Interview for Sleep Patterns and Disorders (DISP) (Merikangas et al., 2014) for assessing psychiatric illnesses and sleep disorders, respectively. Adolescents meeting the following criteria were recruited: 1) Chinese aged between 12–18 years old, and 2) provision of student assent and parental consent. The exclusion criteria included: 1) with a current diagnosis of neuropsychiatric disorder(s); 2) with a prominent medical condition or taking medication with potential side effects that may influence sleep quantity and quality; 3) with sleep disorder such as insomnia, obstructive sleep apnoea, narcolepsy, and restless leg syndrome that may potentially contribute to the disruption of sleep quantity and quality. Of the 63 adolescents who were enrolled in the study, 14 were excluded due to the presence of sleep and psychiatric disorder. Seven participants withdrew from the study. Eventually, a total of 42 adolescents were included in this study.

The study adhered to strict ethical guidelines. Informed consent was obtained from all adolescents and their guardian(s) prior to enrolment to the study. This study was approved by the Joint Chinese University of Hong Kong-New Territories East Cluster Clinical Research Ethics Committee (No. 2021.416).

Measurements

Sleep and mood outcomes

Participants completed a set of online questionnaires that measure resilience (Resilience Scale for Chinese Adolescents, RSCA (Hu & Gan, 2008)), insomnia symptoms (Insomnia Severity Index, ISI (Chung et al., 2011)), chronotype (Morningness Eveningness Questionnaire, MEQ (Cheung et al., 2022)), childhood trauma (Childhood Trauma Questionnaire, CTQ (Lai et al., 2023)), quality of life (KIDSCREEN-52 (Ng et al., 2015)), and mood problems (The Generalized Anxiety Disorder-7, GAD-7 (Ip et al., 2022); and The Patient Health Questionnaire-9, PHQ-9 (Yu et al., 2012)).

Psychological resilience: outcome and capacity

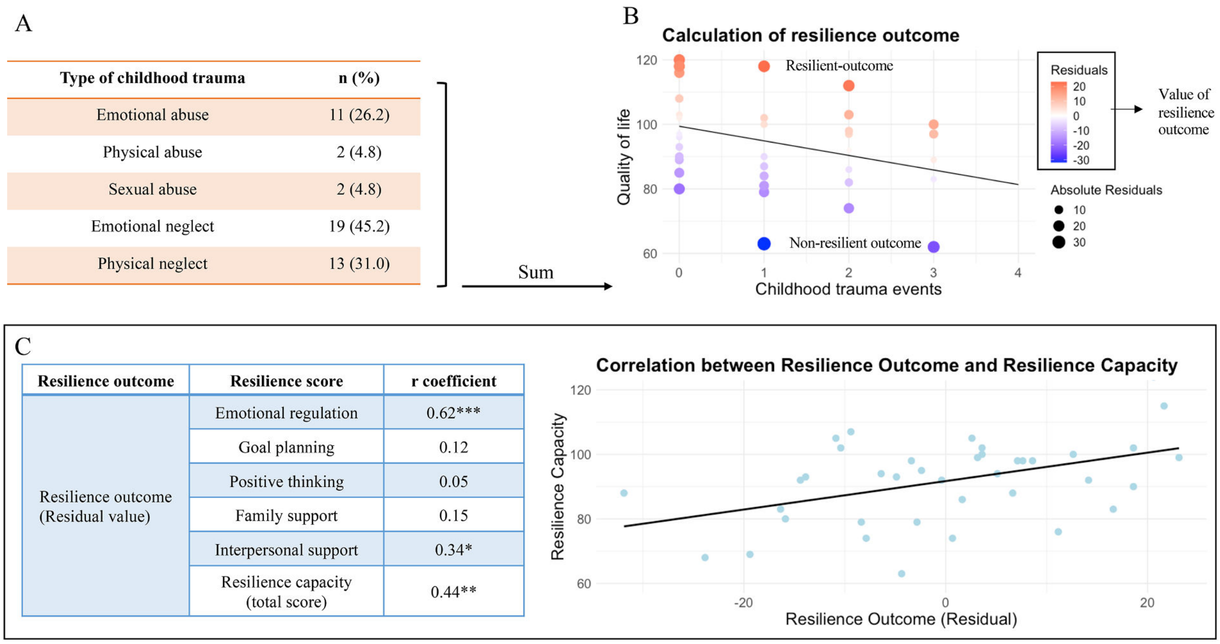
To capture the multifactorial feature of the resilience concepts, resilience was measured as both positive mental health outcome despite adversities and resilience capacity in this study.

The construct of resilience outcome was inspired by a previous study (Hofgaard et al., 2021), which defined resilience as the residual value of life satisfaction and internalizing symptoms after accounting for the impact of lifetime cumulative adversity. Given that the residual approach for calculating resilience has been validated in youth population (Cahill et al., 2022), we used the similar approach in our study. Specifically, resilience outcome was calculated by generating residual value from the regression model with life satisfaction (measured by KIDSCREEN (Ng et al., 2015)) as the dependent variable and childhood trauma events (measured by Childhood Trauma Questionnaire, CTQ (Lai et al., 2023)) as the independent variable (Cahill et al., 2022). We dichotomized the residual score into "Resilient outcome group" (Residual value ≥ 0) and "Non-resilient outcome" group (Residual value <0) (Cahill et al., 2022). Fig. 1AB shows the calculation methodology of resilience outcome.

Resilience capacity was measured by the validated Resilience Scale for Chinese Adolescents (RSCA) (Hu & Gan, 2008). The Resilience Scale for Chinese Adolescents (RSCA) was chosen due to its validated use in adolescent populations and its comprehensive assessment of resilience subscales (Hu & Gan, 2008). There are five subscales of RSCA: emotional regulation, goal planning, positive thinking, family support, and interpersonal support (Hu & Gan, 2008). The total score of RSCA was comprised by the summed up score of subscales, and the higher total scores indicate greater resilience capacity (Hu & Gan, 2008). Given that there is no standardized cut-off value of RSCA, we dichotomized resilience capacity into two groups (Low-level and High-level) based on the median value (the 50th percentile).

Ambulatory polysomnography (PSG)

Participants were invited to undergo one-night ambulatory PSG (Amb-PSG, Nox-A1, Nox Medical Inc., Reykjavik consisting, Iceland), which includes bilateral electroencephalogram (EEG, international 10–20 system) of six channels (C3, C4, F3, F4, O1, O2), bilateral electrooculogram (EOG), electrocardiogram (ECG) and electromyogram (EMG) of mentalis muscle and bilateral anterior tibialis muscles. The respiratory assessments included nasal airflow, thoracic and abdominal respiratory efforts, oxygen saturation (SpO2), breathing sound and body position. A registered PSG technologist (RPSGT) manually classified sleep stages, arousal, respiratory events, and movements according to the American Academy of Sleep Medicine (AASM) 2017 guidelines (Berry et al., 2017). Parameters of general sleep architecture that



Type of childhood trauma	n (%)
Emotional abuse	11 (26.2)
Physical abuse	2 (4.8)
Sexual abuse	2 (4.8)
Emotional neglect	19 (45.2)
Physical neglect	13 (31.0)

Resilience outcome	Resilience score	r coefficient
Resilience outcome (Residual value)	Emotional regulation	0.62***
	Goal planning	0.12
	Positive thinking	0.05
	Family support	0.15
	Interpersonal support	0.34*
	Resilience capacity (total score)	0.44**

Fig. 1. The calculation of resilience outcome and correlations between resilience capacity and resilience outcome. Note: A: Percentages of childhood trauma in this study. B: The calculation of resilience outcome by the residual approach. C: The correlations between resilience outcome (the residual value) and resilience capacity (Resilience scale for Chinese Adolescents, RSCA).

included total sleep time, sleep efficiency, sleep onset latency, wake time after sleep onset (WASO), the duration and percentages of NREM (N1, N2, N3) and REM, the apnea-hypopnea index (AHI) and the periodic leg movement index (PLMI) were reported (Berry et al., 2017).

Slow wave sleep, sleep spindle analysis and power spectral density analyses

All sleep EEG analyses were analysed using the sleep analysis toolbox, named "YASA (Yet another Spindle Algorithm)" within python (Vallat & Walker, 2021), which has been validated for detecting sleep architectures (Benedetti et al., 2023). The EEG signals were bandpass filtered between 0.1 Hz and 45 Hz respectively, to reduce excessive low frequency drifts and high-frequency noise. We then preprocessed the signal by using the approach that was based on distribution of standard deviations (SD) of each sleep epoch (30s) and each EEG channel. The resulting array of SD was normalized (log-transformed), and any epoch with ≥1 channel having values of signal amplitude greater than "mean value ± 2 times the SD" would be marked as artefact and excluded.

Properties of slow wave sleep and sleep spindles were computed by the functions of event detections and spectral analysis in "YASA" (Vallat & Walker, 2021). The algorithm of spindles detection applied threshold of the sigma power frequencies of interest (11–16 Hz for sigma power for total spindles, 11–14 Hz for slow sigma for slow spindles, and 14–16 Hz for fast sigma for fast spindles) (Vallat & Walker, 2021). It calculated relative power of sigma band by using the Short-Term Fourier Transform (STFT) based method on consecutive epochs of 2s (with 200 ms overlap) (Vallat & Walker, 2021), which was validated by the filtration of EEG signals using correlation approach and root mean square approach (Vallat & Walker, 2021). After auto-detection, properties of each individual spindle, including density (number/minute), duration (seconds), and median frequency (Hz) were extracted.

Slow wave sleep in stage 3 sleep, and sleep spindle properties in stage 2 and 3 sleep were extracted and calculated. Stage 1 sleep was excluded due to the nature of transition between wakefulness and sleep. Slow waves were detected using YASA's slow-wave detector, by identifying discrete slow waves with a frequency of 0.1–3.5 Hz, using the linear phase finite impulse response filter with a 0.2 Hz transition band. Within the determined bandpass frequencies, slow waves of negative trough amplitudes >40uV and <300uV, and positive peak amplitudes >10uV and <200uV were detected. After sorting identified negative peaks with subsequent positive peaks, the algorithm computes peak-to-peak amplitudes and retains slow waves between 75 and 500uV. Eventually, slow waves down-states lasting >300 and <1500 ms, and up-states lasting >100 ms and <1000 ms were retained for further analysis. Slow wave density (number of slow waves per minute), durations (second), and median frequency (Hz) were obtained (Carrier et al., 2011; Vallat & Walker, 2021).

In both NREM and REM sleep, we performed spectral analysis of the following frequency bands in each EEG channel: 1) Delta band: 0.1–3.5 Hz; Slow Delta: 0.1–1 Hz; Fast Delta: 1–3.5 Hz; 2) Theta band: 3.5–8 Hz; 3) Alpha band: 8–12 Hz; 4) Sigma band: 12–16 Hz; Slow Sigma: 12–14 Hz; Fast Sigma: 14–16 Hz; and 5) Beta band: 16–32 Hz; Slow Beta: 16–24 Hz; Fast Beta: 24–32 Hz, by using the Fast Fourier Transform-based Welch method with 4-second Hamming windows (Vallat & Walker, 2021). The absolute power of all mentioned frequency bands was log-transformed for statistical analyses. The log-transformed absolute power of delta band was used to indicate power of slow wave sleep, and the log-transformed absolute power of sigma band that composed of total sigma (12–16 Hz), slow sigma (12–14 Hz) and fast sigma (14–16 Hz) were used to indicate power of total sleep spindles, fast sleep spindles, and slow sleep spindles, respectively.

Statistical analyses

Normality of variables were assessed by the Shapiro-Wilk test. Demographics and subjective sleep characteristics were compared using the Chi-square tests and Independent T tests, whenever appropriate. The analysis of covariance (ANCOVA) was used to control for age and sex in each comparison of PSG parameters between resilience groups, given their known effects on sleep architectures and resilience due to biological and psychosocial maturations in adolescents (Baker et al., 2016). We applied partial correlational analyses to examine the association between power spectral density in NREM and REM sleep, and microstructural properties of slow wave sleep and spindles with resilience. Age and sex were also adjusted in partial correlational analyses. Significance of correlations were further examined with Bonferroni corrections.

Microstructural factors that showed significance in correlations were further analysed by the multiple linear regression models with covariates adjustment of age, sex, total sleep time and mood problems. Age and sex were first selected as covariates in Model 1, given their associations with slow waves and spindle performance and resilience in adolescence (Goldstone et al., 2019; Phillips et al., 2019; Roberts & Lopez-Duran, 2019). Further in Model 2, the total sleep time and the score of PHQ9 that may affect slow waves and spindle performance were additionally considered as covariates (Parker et al., 2022; Ritter et al., 2018). P values reported were two-sided, and those <0.05 were considered as with significance. All analyses were conducted using SPSS Version 27.0 and Python.

Results

Participant characteristics

A total of 42 adolescents were included in this study (Mean age: 15.98 years, SD: 2.16 years; females: 57.1 %). The value of resilience outcome was significantly correlated with resilience capacity (Fig. 1: Pearson's $r = 0.44$, p value <0.01). The level of resilience outcome was also associated with the resilience capacity subscales, particularly emotional regulation (Pearson's $r = 0.62$, $p < 0.01$) and interpersonal support (Pearson's $r = 0.34$, $p = 0.03$). Fig. 1 shows the calculation of resilience outcome and correlations between resilience outcome and resilience capacity.

Table 1 shows the demographics and subjective sleep characteristics between resilience capacity and resilience outcome groups. Adolescents in the low-level capacity group were younger compared to the high-level group, and they reported having more childhood trauma events (At least one type: 82.4 % > 44.0 %, $p = 0.01$), specifically in emotional abuse (47.1 % > 12.0 %, $p = 0.01$) and emotional neglect (64.7 % > 32.0 %, $p = 0.04$). While in resilience outcome, more female and more depressive symptoms were observed in the non-resilient outcome group than the resilient outcome group (PHQ9≥5: 70.0 % > 20.0 %, $p < 0.01$).

Sleep macrostructures and resilience

Table 2 shows the comparisons of sleep macrostructures between different resilience groups. Parameters including sleep onset latency, sleep efficiency, wake time after sleep onset, REM onset latency, NREM sleep duration, and REM sleep duration, were comparable between resilience capacity and resilience outcome groups, respectively (All p values > 0.05). The apnea-hypopnea index (AHI) was relatively higher in the low-level than high-level capacity group.

Sleep microstructures and resilience

Power spectral density in NREM and REM sleep: Fig. 2 shows the

Table 1
Demographic, resilience-related and sleep-related characteristics of participants.

Characteristics	Total $N = 42$	Resilience capacity			Resilience outcome		
		Low resilience capacity $n = 17$	High resilience capacity $n = 25$	P value	Non-resilient outcome $n = 21$	Resilient outcome $n = 21$	P value
Age, years	15.98 (2.16)	14.94 (2.28)	16.68 (1.80)	<0.01	16.52 (1.66)	15.43 (2.48)	0.10
Sex, female	24 (57.1)	10 (58.8)	14 (56.0)	0.86	17 (81.0)	7 (33.3)	<0.01
Grades							
Middle school	13 (30.9)	10 (58.7)	6 (24.0)	0.06	4 (19.0)	9 (42.8)	0.29
≥High school	29 (69.1)	7 (41.3)	19 (76.0)		17 (81.0)	12 (57.2)	
Family income level							
<20,000HKD/month	11 (26.2)	6 (35.3)	5 (20.0)	0.81	6 (28.6)	5 (23.8)	0.84
≥20,000HKD/month	31 (73.8)	15 (64.7)	16 (80.0)		15 (71.4)	16 (76.2)	
Housing type							
Public house	21 (50.0)	10 (58.8)	11 (44.0)	0.71	8 (38.1)	13 (61.9)	0.27
Private house	21 (50.0)	7 (41.2)	14 (56.0)		6 (28.6)	15 (71.4)	
Consume tea ≥3 times per week	9 (21.4)	4 (23.5)	5 (20.0)	0.63	4 (19.0)	5 (23.8)	0.64
Consume coffee ≥3 times per week	2 (4.8)	1 (5.9)	1 (4.0)	0.98	1 (4.8)	1 (4.8)	0.88
Consume energy drink ≥3 times per week	0	0	1 (4.0)	0.51	0	1 (4.8)	0.22
Drinking ≥3 times per week	0	3 (17.6)	4 (16.0)	0.31	4 (19.0)	3 (14.3)	0.91
Smoking ≥3 times per week	0	0	0	NA	0	0	NA
Insomnia severity (ISI) ≥9	5 (11.9)	2 (11.8)	3 (12.0)	0.98	4 (19.0)	1 (4.8)	0.15
Chronotype							
Morning chronotype	3 (7.1)	3 (17.6)	0	0.08	1 (4.8)	2 (9.5)	0.80
Intermediate type	30 (71.4)	10 (58.8)	20 (80.0)		15 (71.4)	15 (71.4)	
Evening chronotype	9 (21.4)	4 (23.5)	5 (20.0)		5 (23.8)	4 (19.0)	
Pre-sleep somatic arousal	10.20 (2.08)	11.19 (2.17)	9.54 (1.77)	0.01	11.10 (2.07)	9.30 (1.69)	<0.01
Pre-sleep cognitive arousal	15.25 (4.00)	14.69 (2.57)	15.63 (4.73)	0.02	16.00 (3.46)	14.50 (4.43)	0.24
Childhood trauma events							
Emotional abuse	11 (26.2)	8 (47.1)	3 (12.0)	0.01	4 (19.0)	7 (33.3)	0.29
Physical abuse	2 (4.8)	2 (11.8)	0	0.08	0	2 (9.5)	0.15
Sexual abuse	2 (4.8)	0	2 (8.0)	0.23	0	2 (9.5)	0.15
Emotional neglect	19 (45.2)	11 (64.7)	8 (32.0)	0.04	11 (52.4)	8 (38.1)	0.35
Physical neglect	13 (31.0)	8 (47.1)	5 (20.0)	0.06	6 (28.6)	7 (33.3)	0.74
Any type above	25 (59.5)	14 (82.4)	11 (44.0)	0.01	13 (61.9)	12 (57.1)	0.75
Potential mood problems							
Anxiety problem (GAD7≥5)	14 (35.0)	8 (50.0)	6 (25.0)	0.10	10 (50.0)	4 (20.0)	0.05
Depression problem (PHQ9≥5)	18 (45.0)	10 (62.5)	8 (33.3)	0.07	14 (70.0)	4 (20.0)	<0.01

Note: Data were presented as Mean (standard deviations), or n (%). Comparisons were performed by Chi-square tests (for categorical variables) or independent t tests (for continuous variables). Low resilience capacity was defined as RSCA < 50^{th} percentile, and high resilience capacity was defined as RSCA ≥ 50^{th} percentile.

Table 2
Sleep macrostructure across resilience groups when adjusted for age and sex.

Sleep macrostructures	Resilience capacity			Resilience outcome		
	Low resilience capacity $n = 17$	High resilience capacity $n = 25$	P value	Non-resilient outcome $n = 21$	Resilient outcome $n = 21$	P value
Total sleep time (min)	454.41 (102.79)	458.60 (85.49)	0.62	462.48 (108.63)	448.33 (72.63)	0.67
Sleep onset latency (min)	9.50 (4.56)	10.42 (5.47)	0.84	10.11 (4.90)	9.99 (5.38)	0.87
Sleep efficiency (%)	92.63 (2.38)	90.68 (2.61)	0.20	91.97 (2.31)	90.97 (2.95)	0.16
WASO (min)	25.43 (8.18)	36.40 (14.09)	0.06	29.67 (13.92)	34.25 (12.16)	0.18
REM sleep onset latency (min)	126.53 (61.91)	102.12 (47.66)	0.69	101.49 (42.90)	122.51 (63.42)	0.66
NREM stage 1 duration (min)	22.97 (14.13)	27.52 (18.90)	0.98	24.74 (12.82)	26.62 (20.80)	0.63
NREM stage 1 percentage (%)	5.07 (3.10)	6.00 (3.86)	0.87	5.34 (2.70)	5.90 (4.31)	0.49
NREM stage 2 duration (min)	208.53 (62.04)	211.94 (72.49)	0.63	218.76 (68.86)	202.36 (67.14)	0.57
NREM stage 2 percentage (%)	45.45 (5.75)	45.96 (11.13)	0.75	46.50 (6.76)	45.02 (11.33)	0.66
NREM stage 3 duration (min)	119.41 (29.92)	111.06 (51.84)	0.85	110.38 (31.49)	118.50 (54.32)	0.84
NREM stage 3 percentage (%)	27.26 (8.11)	24.79 (11.49)	0.83	24.89 (8.81)	26.69 (11.61)	0.76
REM duration (min)	101.53 (37.13)	107.98 (34.25)	0.74	109.98 (39.72)	100.76 (30.16)	0.68
REM percentage (%)	22.21 (4.67)	23.25 (4.33)	0.96	23.27 (4.52)	22.39 (4.43)	0.78
Arousal index (number/hour)	6.48 (4.02)	5.66 (2.77)	0.22	6.37 (3.76)	5.61 (2.83)	0.72
AHI	0.59 (0.16)	0.07 (0.13)	0.02	0.46 (0.15)	0.11 (0.15)	0.13
PLMI	0.03 (0.92)	1.83 (0.74)	0.15	1.64 (0.85)	0.56 (0.85)	0.40

Note: Comparisons were adjusted for age and sex, by using ANCOVA. Data are presented as mean (standard error). Low resilience capacity was defined as RSCA < 50^{th} percentile, and high resilience capacity was defined as RSCA ≥ 50^{th} percentile. WASO: Wake time after sleep onset (minute). REM sleep: Rapid eye movement sleep. NREM sleep: Non-rapid eye movement sleep. AHI: Apnea-hypopnea index. PLMI: Periodic leg movement index.

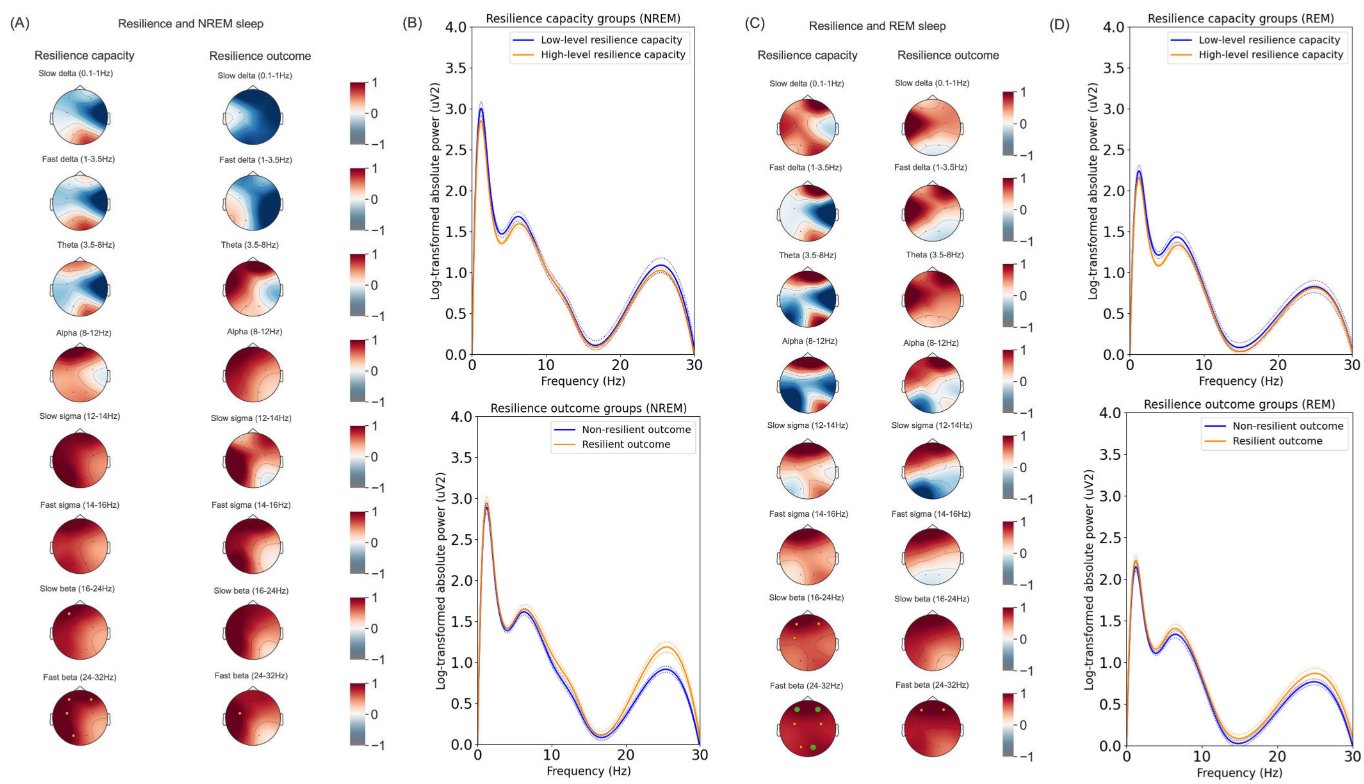


Fig. 2. Power spectral density in NREM and REM sleep and resilience.
Note: All correlations were performed by the partial correlational analyses, with age and sex adjusted. (A) Correlations between log-transformed power spectrum at the frontal, central and occipital regions in NREM sleep and resilience scores. The orange-colored dots indicated channels with uncorrected partial's correlations significance ($p < 0.05$). (B) Averaged log-transformed power spectrum at the left central region (C4-M1) between resilience capacity and between resilience outcome groups in NREM sleep. (C) Correlations between log-transformed power spectrum at the frontal, central and occipital regions in REM sleep and resilience scores. The orange-colored dots indicated channels with uncorrected partial's correlations significance ($p < 0.05$). The green-colored dots indicated channels with Bonferroni-corrected significance for the frequency bands (α=0.05/8). (D) Averaged log-transformed power spectrum (C4-M1) between resilience capacity and resilience outcome groups in REM sleep.

correlations between power spectral density in NREM and REM sleep with resilience. In NREM sleep, the higher power in beta frequency (16–32 Hz) were correlated with greater resilience capacity and resilience outcome (Fig. 2A). Similarly, in REM sleep, the higher power in beta power showed correlations with higher-level resilience capacity and resilience outcome. After Bonferroni correction, the correlation between resilience capacity and the fast beta (24–30 Hz) power in REM sleep remained significant, in the frontal brain region.

Fig. 3 shows the associations of beta power in REM sleep with resilience with covariates adjusted, and the correlation matrix of beta

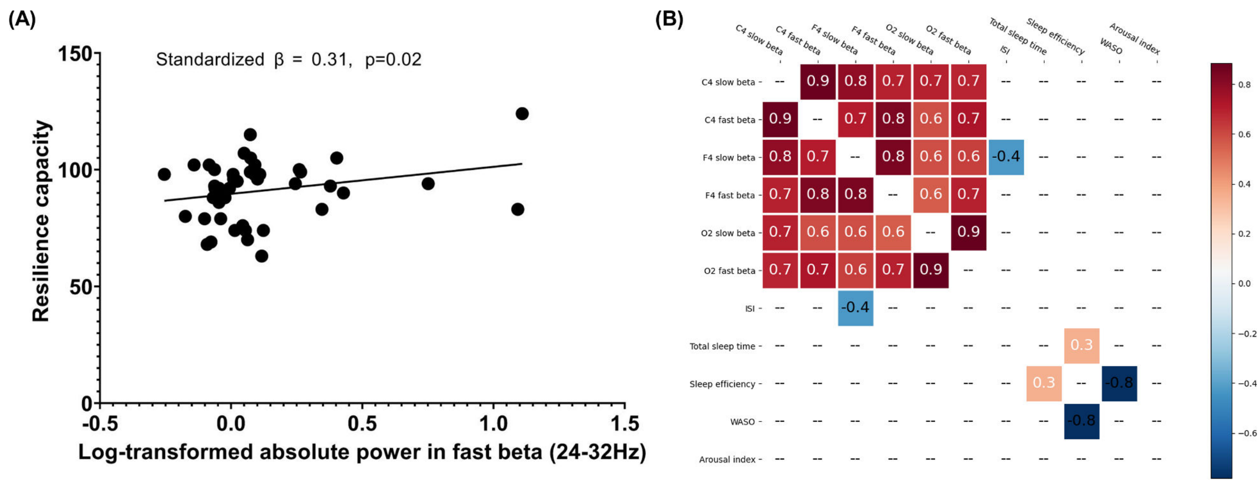


Fig. 3. (A) Multiple linear regression result of power of REM fast beta that showed significancy with resilience capacity, when age, sex, total sleep time, and depression problem were adjusted. (B) Heatmap showing the correlations of REM sleep beta power and insomnia severity index, total sleep time, sleep efficiency, wake time after sleep onset and arousal index in PSG. ISI: Insomnia severity index. WASO: Wake time after sleep onset. Arousal index: arousal count each hour of total sleep time. The color bar indicated levels of spearman's rho, p values < 0.05 were shown with color in the heatmap.

power and insomnia-related factors. After adjustment for age, sex, total sleep time and PHQ9, the higher power in fast beta band (24–32 Hz) in the frontal regions remained significantly associated with higher-level resilience capacity (Average value of fast beta in F4 and F3 channels: Standardized β=0.31, $p = 0.02$) (Fig. 3A). We further performed correlation analyses between sleep and beta power in REM sleep to examine whether beta power in REM sleep indicated hyperarousal (Zhao et al., 2021). As shown in Fig. 3B, the slow beta power was inversely correlated with insomnia symptoms (ISI: rho $= -0.43$, $p = 0.004$), suggesting that beta power may not indicate arousal level. These results suggest that the beta power REM sleep may be a marker of psychological resilience in adolescents.

Sleep spindle properties: Fig. 4 shows the associations of spindle characteristics and resilience scores in NREM sleep (stage 2 and 3) after age and sex were adjusted. The longer spindle duration in central and occipital regions showed significant correlation with resilience capacity, and the correlation in the left occipital region remained after the Bonferroni correction (Partial's correlation: Total spindle duration: $r = 0.44$, $p = 0.005$; Fast spindle duration: $r = 0.57$, $p = 0.0001$). The greater frequency of slow spindles in occipital regions also correlated with higher-level resilience capacity, whereas the significance did not remain after Bonferroni correction. Although we observed the trend of increasing resilience outcome with longer spindle duration and higher sigma power, the correlation did not reach significant level (Fig. 4B).

Given these results, we selected the duration feature of sleep spindles in regression model with covariates adjusted. We found that the longer duration of total spindle and fast spindles were associated with higher-level resilience capacity (Total spindle duration: Standardized β=0.34, $p = 0.01$; Fast spindle duration: Standardized β=0.42, $p < 0.01$) (Fig. 4C). The significant associations between sleep spindle duration and resilience capacity suggest that the sleep spindle duration may be an important feature linking resilience in adolescents.

Slow wave sleep properties: Fig. 5 shows the associations of slow wave sleep characteristics and resilience scores. There was no significant correlation between slow wave sleep properties and resilience scores (All $p > 0.05$).

Subgroup analyses: Further comparison of sleep features with resilience among different age groups and gender were conducted. There were significant associations of higher power in fast beta frequency in REM sleep with resilience (both capacity and outcome) in the 15–18 year age group compared to younger age group (12–14 years old). Similar trend was also observed in females compared to males (Supplementary Table 1–3). The longer duration of sleep spindles was probably associated with higher-level resilience capacity in the 12–14 year age group and among males.

Discussion

The present study examined the macro- and microstructures of NREM and REM sleep in relation to resilience capacity and outcome in adolescents who did not have any psychiatric or sleep disorder. We found that the higher power in fast beta frequency in REM sleep and the longer duration of sleep spindles in NREM sleep were significantly associated with higher resilience capacity. However, we did not find similar associations regarding resilient outcome, and the macrostructures of NREM and REM sleep did not significantly differ across different levels of resilience.

REM sleep and psychological resilience: the role of fast beta power

In this study, we did not find any association between REM theta power and resilience, which was contrary to our initial expectation. Nonetheless, we identified REM fast beta power (24–32 Hz) as a positive correlate of resilience capacity, with coefficients indicating moderate correlation across the scalp topography. Besides, the associations of REM fast beta power and resilience were more prominent in older adolescents and female subgroups, suggesting a possible developmental impact that may affect both sleep microstructures and resilience, especially in late pubertal stage and females. Future studies on sleep microstructures and resilience across different age and sex subgroups are needed.

Previous studies suggested that REM sleep play a critical role in emotional regulation and stress adaptation (Denis et al., 2021) which further supported the current findings, highlighting the importance of REM sleep in resilience. It has been suggested that resilient individuals who had experienced trauma between 1 month to 2 years had higher beta power in REM sleep (23.24–29.88 Hz) than individuals who developed PTSD, and the increase in high frequency power was associated with less psychopathology (Denis et al., 2021). However, beta activity was previously thought to be a marker of hyperarousal related to sleep disorders (e.g., nightmare, insomnia) (Zhao et al., 2021), one may wonder how the findings of higher beta power be interpreted in this study. One possibility is that the increased beta power in resilient individual might reflect enhanced information processing and emotional regulation rather than simply hyperarousal (Denis et al., 2021). To address this question, we further examined associations between

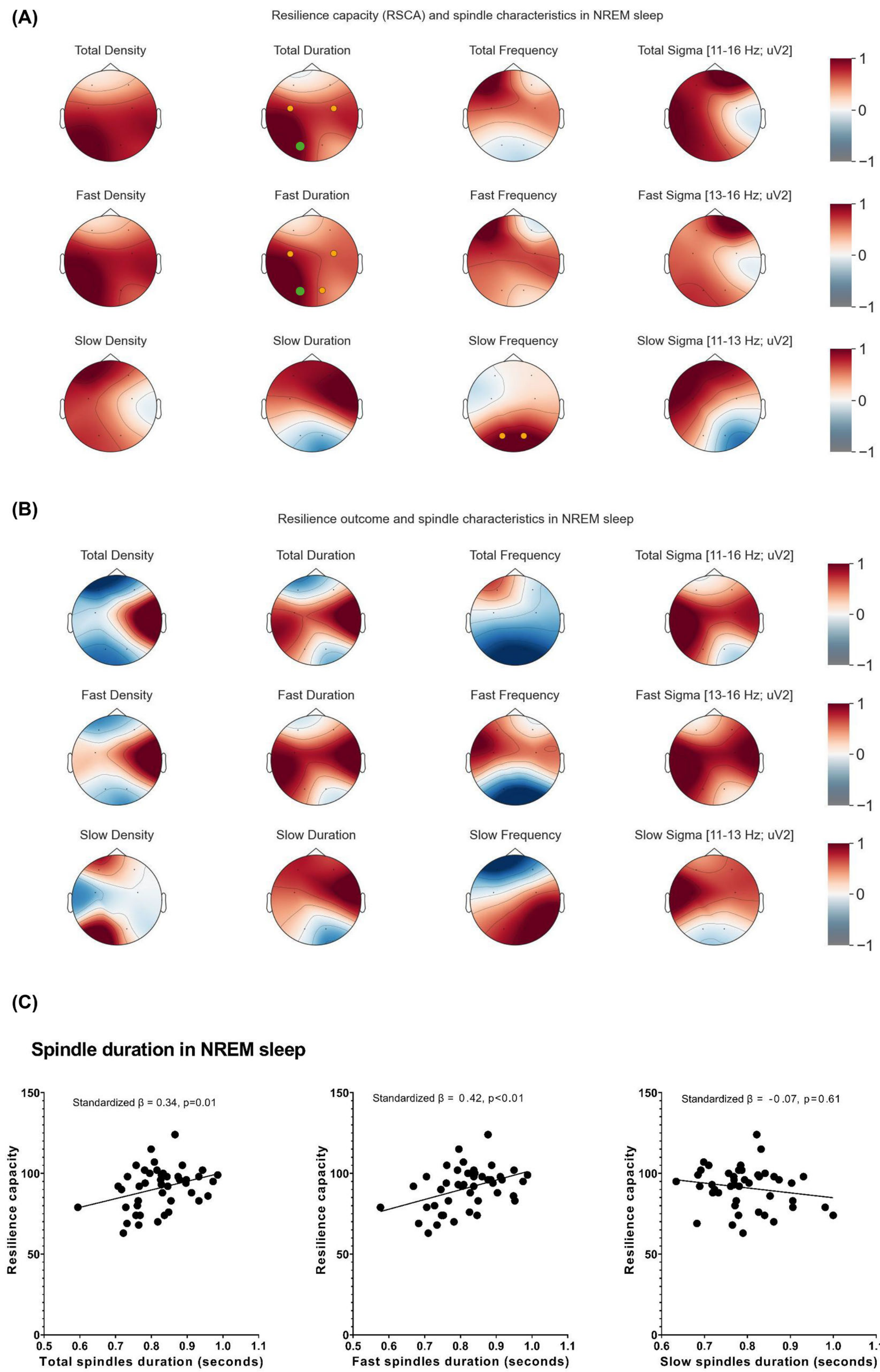


Fig. 4. Associations between sleep spindles and resilience.
Note: (A) Topographic plots of partial correlations between resilience capacity and spindle characteristics during NREM sleep. Age and sex were adjusted. The orange-colored dots indicated channels with significance ($p < 0.05$). The green-colored dots indicated channels with Bonferroni-corrected significance for the examined spindle properties (α=0.05/4). (B) Topographic plots of partial correlations between resilience outcome and spindle characteristics during NREM sleep. Age and sex were adjusted. (C) Multiple linear regression results of spindle durations that showed significancy with resilience capacity for the selected EEG channel based on previous results in this study. We used duration of total spindles, fast spindles, and slow spindles in left occipital channel (O1-M2) as the independent variables, and with resilience capacity as the dependent variable. All models were adjusted for age, sex, total sleep time (PSG) and depression problem (PHQ9).

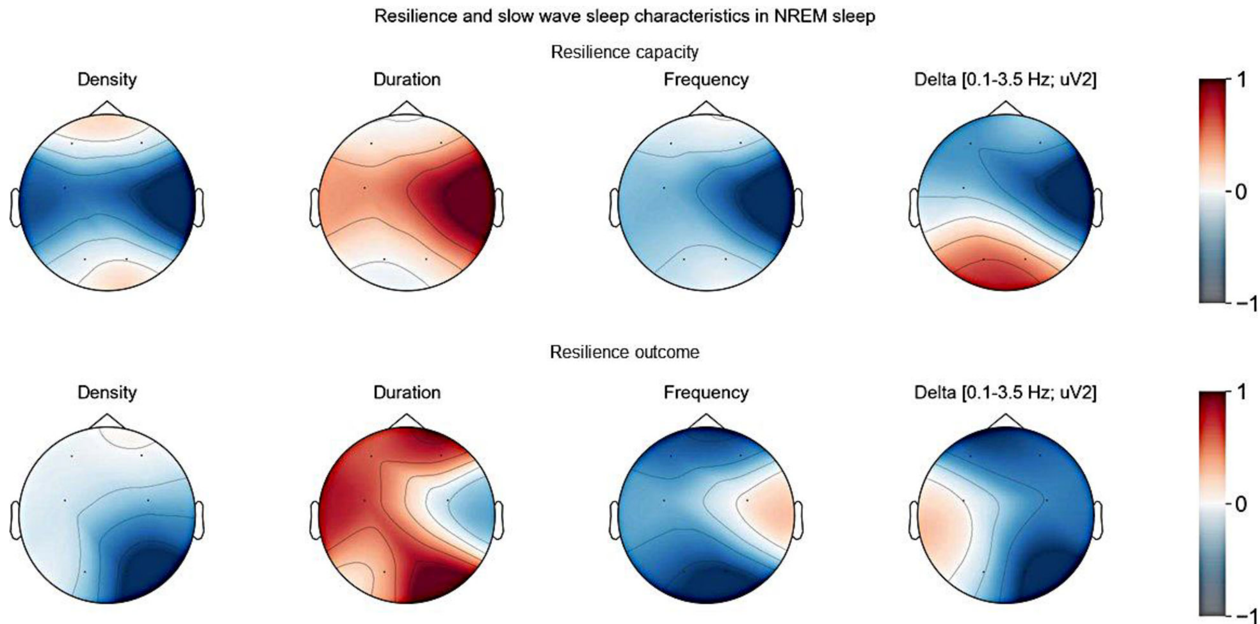


Fig. 5. Topographic plots of partial correlations between slow wave sleep characteristics during NREM stage 3 sleep and resilience scores. Age and sex were adjusted. Color bars indicated correlation coefficients.

subjective sleep appraisal and beta power. We found that the higher beta power was even associated with lower-level subjective insomnia, suggesting that the higher beta power in healthy adolescents in this study did not necessarily signify disrupted sleep. Nonetheless, future studies are needed to replicate our findings with consideration of sleep quality.

NREM sleep and psychological resilience: the role of sleep spindle duration

Another important finding is the association between longer spindle duration and higher resilience capacity. To the best of our knowledge, there is no such evidence in studies conducted in adolescent population. Some previous studies found that adults with PTSD had increased spindle frequency, density, and amplitude-calculated activity, when compared to trauma-resilient individuals (who successfully adapted to trauma without developing PTSD) (Natraj et al., 2023; van der Heijden et al., 2022; Wang et al., 2020). Although we did not observe similar findings in these spindle features (frequency, and density), we found significant associations between longer spindle duration and higher resilience capacity even after adjustment of age, sex, total sleep time, and mood problems, suggesting that spindle duration could be another correlated feature of resilience. Mechanistically, sleep spindles facilitates thalamocortical communications by organizing neural firing patterns temporally (Fernandez & Lüthi, 2020). A prolonged spindle duration may be related to the neural process that occur in thalamocortical connectivity (Barthó et al., 2014; Bonjean et al., 2011), particularly cognitive functions (Hwang et al., 2022). Therefore, we speculate that prolonged spindles may be related to cognitive control process that is linked to active coping abilities (e.g., goal concentration, emotion regulation and positive perception) (Hu & Gan, 2008), which constitute part of resilience capacity. However, our data did not support the associations between resilience outcome and spindle density, duration, frequency or power, thereby underscoring the needs for further investigations in future studies.

We did not find any association of resilience capacity or resilience outcome with slow wave sleep properties across topography, which is contrast to our hypothesis. It may be due to a limited sample size, or perhaps due to the complex interplay among developmental changes, reduced cortical thickness, and the substantial declining slow wave sleep during adolescence (Gonzalez-Escamilla et al., 2018; Ong et al., 2022).

Another nonsignificant finding is the lack of differences between sleep macrostructures and different resilience variables. This is somehow inconsistent with previous studies. A prior animal study employed a social-defeat stress model and found that male mice with more NREM sleep had better performance against social defeat stress, suggesting an important role of prolonged NREM sleep for improving resilience (Bush et al., 2022). Several human studies focused on extreme stress and sleep disturbance also found similar associations (Kovachy et al., 2013; Palmer et al., 2022). There are several possible explanations for these discrepancies. First, previous studies often included subjects with clinical sleep or mood problems (Denis et al., 2021), whereas the current study targeted healthy adolescents. Second, the relationship between sleep and resilience might be more evident at the microstructural level, rather than in broader macrostructural sleep parameters, particularly in the stage before the development of stress-related disorder.

Limitations

There are several limitations in this study. First, the cross-sectional study design limits our ability to infer causality, and the relatively modest sample size may have reduced the power to detect significant differences in sleep macrostructures and microstructures across different levels of resilience. Therefore, further experimental or longitudinal studies are needed to delineate whether REM sleep fast beta power and longer NREM spindle duration lead to higher resilience in adolescents. Besides, as sleep architectures change dramatically during pubertal development (Baker et al., 2016), it could be possible that the linkage between sleep and resilience differs across pubertal stages. Future studies should explore the causal relationships between sleep microstructures and resilience using longitudinal design with larger and more diverse sample. Second, we only used single-night PSG, which may not capture the full variability of sleep patterns. It would be more accurate to use multiple night sleep data to eliminate the possible confounding "first-night effect" of PSG (Ding et al., 2022). Future studies on resilience and sleep should apply multi-night recordings to enhance the reliability and generalizability of findings. Third, the method for spindle detection was based on YASA algorithm (Vallat & Walker, 2021), which may underestimate spindle numbers because it discarded potential sleep spindles with duration less than 0.5s and above 2s.

Conclusions

In summary, this study found that the higher power in fast beta frequency in REM sleep, and the longer spindle duration in NREM sleep were associated with higher psychological resilience capacity in healthy adolescents. These findings suggest that interventions targeting modification of sleep stage-specific microstructures may enhance resilience in adolescents and have a potential to reduce the risk of stress-related disorders. Moreover, these sleep microstructural characteristics may serve as potential early markers of resilience in adolescents, detectable even before the onset of any clinical psychopathology. Future longitudinal and experimental studies are needed to confirm whether these microstructural characteristics are reliable markers for psychological resilience. This may pave the way for future prevention and intervention targeting sleep health in enhancing resilience among susceptible adolescents.

Declaration of competing interest

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijchp.2025.100570.

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