Predicting sleep quality from brain white matter volume: A voxel-based morphometry study

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Abstract

Most previous studies have explored the relationship between gray matter volume and sleep quality, but little is known about the relationship between white matter volume and sleep quality. Data were collected using the Pittsburgh Sleep Quality Index and voxel-based morphometry among 352 healthy college students. Results showed that the global PSQI score was negatively associated with the white matter volume, including in the right middle occipital gyrus, the left superior temporal gyrus, the right the precentral gyrus, the left supramarginal gyrus, the left middle frontal gyrus, the left precunes, and the right superior frontal gyrus. Results also indicated that the white matter volume in specific regions negatively predicted the factor of PSQI. These specific brain regions may be replicated in brain areas related to sleep quality. In summary, we suggested that an investigation of white matter structural alterations in the specific regions might be beneficial to tackle underlying neurological mechanisms of sleep quality.

Introduction

Sleep is an inseparable part of human health and life, and is pivotal to learning and practice as well as physical and mental health (Jalali et al., 2020). Sleep quality can be assessed in the non-clinical population by using the most widely Pittsburgh Sleep Quality Inventory (PSQI) (Lo et al., 2018; Mollayeva et al., 2016; Neumann et al., 2020). It includes subscales assessing subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, daytime dysfunctions, and use of sleep medication (Buysse et al., 1989). Recent studies reported that 25.7% experienced poor sleep quality in Chinese college students (Li et al., 2018; Zhai et al., 2021). Importantly, one study indicated that poor sleep impaired specific areas were necessary for complex cognitive tasks (e.g., attention, learning, working memory) (Lim & Dinges, 2010). Moreover, ample evidence also suggested that college students experienced chronic sleep problems negatively impacted their health, well-being (Gaultney, 2010; Lund et al., 2010; Nyer et al., 2013), and academic life (Dinis & Bragança, 2018). To sum up, it was indispensable to study the reasons of poor sleep quality.

Previous research explored that sleep was affected by the brain's structure, and influential on neuropsychological performance for better or worse (Colrain, 2011). Buysse et al. (2011) proposed a neurobiological model of insomnia, which assumed that the characteristic of insomnia was that sleep and wake-like activation patterns, used to regulate sleep-wake state, simultaneously existed in specific brain regions, including the default mode network (DMN) (e.g., precuneus, lateral parietal, ventromedial prefrontal, mid-dorsolateral prefrontal, and superior temporal regions), the hypothalamic centers, and the brainstem hypothalamic arousal centers (e.g., posterior hypothalamus, locus coeruleus, raphe nuclei, and cholinergic brainstem nuclei) (Buysse et al., 2011, Zhang et al., 2020). Meanwhile, numerous studies suggested that poor sleep quality was significantly associated with some brain regions (Amorim et al., 2018; Sexton et al., 2014; Tashjian et al., 2018). For instance, a recent study revealed that variation in sleep quality was related to a weaker intrinsic default mode network (Tashjian et al., 2018), involving two key brain areas: the left precuneus (Prcu) and bilateral inferior parietal lobule (IPL). Sexton et al. (2014) indicated that poor sleep quality was correlated to increased atrophy in the frontal, temporal, and parietal

lobes. Li et al. (2016) found that poor sleep quality was associated with the left parietal lobe. Furthermore, studies found that primary insomnia patients showed a significant reduction of gray matter concentration in left or right dorsolateral prefrontal cortices (i.e., right superior frontal gyrus (SFG), and left middle frontal gyrus (MFG)), left precentral gyrus (PreCG), bilateral postcentral gyrus, and superior temporal gyrus compared to normal controls (DelRosso & Hoque, 2014; Joo et al., 2013). Notably, the increased activity in the bilateral precentral gyrus might be associated with high sensitivity during falling asleep (Wang et al., 2016). Recently, a structural MRI study analyzed concerning sleep duration and revealed the brain areas (i.e., the orbitofrontal cortex, prefrontal, temporal cortex, precuneus, and supramarginal gyrus (SMG)) (Cheng et al., 2020). Taken together, literatures suggested that poor sleep quality was associated with some specific brain regions, which involving the inferior parietal lobule, the superior temporal gyrus, the precentral gyrus, the supramarginal gyrus, the middle frontal gyrus, and the precuneus.

However, most studies focused on the above regional gray matter volume correlates of sleep quality (Joo et al., 2013; Li et al., 2016; Sexton et al., 2014). The white matter was a crucial component of the human brain, which was composed of myelinated axons. These axons were organized into tracts, which were essential for facilitating communication among brain regions (Fields, 2008, 2010), and were responsible for transmitting neural communication between regions in the gray matter (Liu et al., 2016). Meanwhile, with the increase of brain size, the volume of the subcortical white matter tends to increase faster than of the cortical gray matter itself (Zhang & Sejnowski, 2000).

Only a few studies had explored the relation between white matter and sleep. For example, Kocevska et al. (2019) showed that poor sleep quality might destabilize axonal integrity and deteriorate white matter. Higher sleep efficiency was prospectively associated with white matter volume at follow-up. Telzer et al. (2015) indicated self-reported sleep duration variability had been associated with lower white matter integrity longitudinally. Khalsa et al. (2017) revealed that objective and subjective measures of habitual sleep were associated with the brain's white matter structure. Other studies have shown that both short (Yaffe et al., 2016) and long (Ramos et al., 2014) self-reported sleep duration was associated with white matter alterations. Yaffe et al. (2016) found that short sleep was associated with an elevated ratio of white matter hyperintensities (WMH) in the parietal lobe and increased mean diffusivity in frontal, parietal, and temporal white matter. These WMH changes were accompanied by attention and memory deficits, as well as cognitive function. Rocklage et al. (2009) examined cognitive vulnerability to total sleep deprivation in relation to white matter differences. In general, these studies suggested that white matter structure was related to sleep.

Until now, most studies focused on special groups (i.e., community-dwelling older adults, depression symptomatology, primary insomnia, Parkinson's Disease, and Mild traumatic brain injuries), and the relationship between sleep and brain white matter microstructure by utilizing diffusion tensor imaging (DTI) (Altendahl et al., 2020; Li et al., 2020; Raikes et al., 2018; Wei et al., 2019). For example, patients with insomnia tended to show altered diffusion-tensor based network characteristics between the right frontal, temporal, and subcortical areas (including the hippocampus, thalamus, and precuneus) (Wei et al., 2019).

White matter was notable in regulating brain activity and mediating the functional coupling between brain regions and behavior (Bi et al., 2017; Leong et al., 2016; Yuan et al., 2016). The volume of the white matter was currently mainly determined by voxel-based morphometry, which shows morphological changes of the white matter by calculating the volume and density of the white matter (Liu et al., 2016). Although there was some evidence to support the relationship between brain white matter and sleep (Kocevska et al., 2019; Li et al., 2020; Ramos et al., 2014; Sexton et al., 2017), whether the change in white matter volume could predict the sleep quality of college students remain less unclear.

In present study, sleep quality was measured by Pittsburgh Sleep Quality Index (PSQI). The global PSQI score consists of seven distinct subcomponents (Buysse et al., 1989). Therefore, it could be possible that significant sleep quality-WMV associations in these studies were driven by one of these subcomponents (e.g., sleep latency). This motivated us to further investigate the association of sleep quality with white matter structure separately by using the respective subcomponents of PSQI. Thus, the purpose of the present study was to explore white matter volume associated with sleep quality and the relationship between white matter volume and the dimension of sleep. In light of previous neuroscience findings (Joo et al., 2013; Li et al., 2016; Sexton et al., 2017; Yaffe et al., 2016), we hypothesized that sleep quality might be associated with rWMV in brain regions (i.e., IPL, MOG, STG, PreCG, SMG, MFG, and Prcu). Moreover, we also predicted that seven factors of PSQI score were correlated with the white matter volume of regions of interest (ROIs). Previous studies have shown that voxel-based morphometry (VBM) was a fully automated technique allowing identification of regional differences in the amount of GM and WM with no a priori region of interest, enabling an objective analysis of the whole brain between groups of subjects (Ashburner & Friston, 2000; Good et al., 2001). The volume of white matter was currently mainly determined by voxel-based morphometry, which showed morphological changes of the white matter by calculating the volume and density of the white matter (Liu et al., 2016). Thus, we used voxel-based morphometry (VBM) and a questionnaire (Pittsburgh Sleep Quality Index, PSQI) to assess sleep quality to identify the white matter correlated of each factor of individual sleep quality (subjective sleep quality factor, sleep latency factor, sleep duration factor, sleep efficiency factor, sleep disturbance factor, daytime dysfunctions factor, and use of sleep medication factor) in a larger healthy college student sample. By exploring white matter volume to understand the brain changes associated with sleep quality may provide a reliable path for clinical interventions, particularly in college students.

Methods

Participants and Procedures

The sample consisted of 352 (male = 190; mean age = 20.03 ± 1.34 years) healthy college students from Southwest University in China. All subjects were right-handed, with normal vision or corrected vision, no psychiatric symptoms, and a history of mental illness according to the self-assessment questionnaire. First, subjects signed informed consent before the experiment. Next, subjects experienced an MRI scan wherein they were instructed to keep their heads still and to remain awake. Finally, after the MRI scan, all

participants completed the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989). The study was approved by the Research Ethics Committee of Southwest University, Chongqing.

Assessment of sleep quality

The 19-item Pittsburgh Sleep Quality Index (PSQI) is a standardized, quantitative measure of sleep quality with demonstrated high consistency, reliability, and validity (Buysse et al., 1989; Carpenter & Andrykowski, 1998; Fichtenberg, 2001). It gives information about the participant's subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, daytime dysfunctions, and use of sleep medication. Each component score was weighted equally on a 0–3 scale with lower scores indicating no problems and higher scores indicating progressively worsening problems as follows: subjective sleep quality (very good to very bad), sleep latency (≤ 15 minutes to > 60 minutes), sleep duration (≥ 7 hours to < 5 hours), sleep efficiency (≥ 85% to < 65% hours sleep/hours in bed), sleep disturbances (not during the past month to ≥ 3 times per week), use of sleeping medications (none to ≥ 3 times a week), and daytime dysfunction (not a problem to a very big problem) (Buysse et al., 1989; Vargas et al., 2014). These seven component scores are added to gether to form a global PSQI score, ranges from 0 to 21. Buysse and colleagues proposed a cut-off score of ≤ 5 to indicate good sleep quality and > 5 to indicate severe sleep difficulties. Each component is scored from 0 to 3 points where maximum score for each component is 3. The PSQI has high sensitivity (89.6%) and specificity (86.5%) (Buysse et al., 1989). The Chinese version of PSQI has been verified with good reliability (Cronbach's α = 0.84) and validity (factor loading of each component: > 0.5) in Chinese students (Liu et al., 1996).

Image acquisition

All structural and functional MRI data were collected on a 3T Siemens MRI scanner at the Southwest University Brain Imaging Center (Siemens Medical, Erlangen, Germany). High-resolution 3D T1-weighted anatomical images were acquired by employing the following magnetization-prepared rapid gradient echo (MPRAGE) sequence: repetition time (TR) = 1900ms; slices = 32; echo time (TE) = 30 ms; layer thickness = 3 mm; resolution matrix = 64 × 64; flip angle (FA) = 90°; field of view (FOV) = 256 × 256 mm^2; slice gap = 1 mm; and voxel size = 1 ×1 × 1 mm^3. Before the resting-state scan, all subjects were instructed to relax and close their eyes, but not to sleep.

Image pre-processing

The structural MR images were processed with VBM-DARTEL using SPM8 (http://www.fil.ion.ucl.ac.UK/SPM) software (Welcome Department of Cognitive Neurology, London, United Kingdom) incorporated in MATLAB 2014a (Math Works Inc., Natick, MA, United States). The images were segmented into gray matter (GM), white matter (WM), and cerebrospinal fluid using the new segmentation tool. Next, we performed registration and normalization by DARTEL in SPM8. All participants' head motion was strictly controlled within 3 mm. The registered images were transformed to MNI space. Finally, the normalized images (GM) were smoothed with a full width at a half-maximum (FWHM) Gaussian kernel of 8 mm.

Behavioral data analysis

The statistical software SPSS 23.0 (SPSS Inc., Chicago, IL, United States) was used to analyze behavioral data. The independent sample *t*-test was carried out to explore the gender and age differences in the global PSQI score.

Voxel-based morphometry analysis

Statistical analyses of white matter volume (WMV) data were performed using SPM8. In the whole-brain analyses, multiple linear regression was used to identify brain regions where the WMV was associated with sleep quality and the scores of each factor of PSQI. The global PSQI score was used as the variable of interest in these analyses. To control for possible confounding variables, age, sex, and global volume were entered simultaneously as the covariates as previous researches (Yin et al., 2019; Zhang et al., 2020). The results were corrected by False Discovery Rate (FDR) correction ($p < 0.01$).

Results

Results of behavioral data

Table 1 shows the mean score, standard deviation (*SD)*, and range of the seven subcomponents (e.g., the subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, daytime dysfunctions, and use of sleep medication) of the PSQI. Figures 1 and 2 shows the distribution of the global PSQI score in males and females, and the independent sample *t*-test revealed that there were no gender differences in the global PSQI score ($t = 1.510$, $p > 0.05$) in the present study. Besides, the P-P plot and frequency histogram with a normal distribution curve of the global PSQI score was shown in Fig. 3. The Skewness of the global PSQI score was 0.581, respectively and the Kurtosis was 0.363, respectively.

Correlations between white matter volume (WMV) and the global PSQI score

To determine regional white matter volume (rWMV), using false-discovery rate (FDR) correction $p < 0.05$ for pairs of voxel. We applied the multiple regression analysis to determine rWMV which was associated with sleep quality. After controlling the effects of age, gender and global brain WMV, the multiple regression analysis showed that WMV in the right middle occipital gyrus ($r = -0.156$, $p < 0.01$), the left superior temporal gyrus ($r = -0.185$, $p < 0.01$), the right precentral gyrus ($r = -0.160$, $p < 0.01$), the left middle frontal gyrus ($r = -0.160$, $p < 0.01$), the left supramarginal gyrus ($r = -0.184$, $p < 0.01$), the left Prcu ($r = -0.164$, $p < 0.01$), and the right superior frontal gyrus ($r = -0.165$, $p < 0.01$) were respectively negatively correlated with the global PSQI score. No other significant associations were found. The information of above brain regions was shown in Table 2.

Table 1
Mean, SD, and range of each factor of PSQI score (N = 352).

	Mean	*SD*	*Range*
age	20.034	1.337	17 – 27
the global PSQI score	5.852	2.630	0 – 16
subjective sleep quality factor of PSQI score	0.997	0.739	0 – 3
sleep latency factor of PSQI score	1.162	0.953	0 – 3
sleep duration factor of PSQI score	1.037	0.780	0 – 3
sleep efficiency factor of PSQI score	0.225	0.534	0 – 3
sleep disturbance factor of PSQI score	0.977	0.385	0 – 2
daytime dysfunctions factor of PSQI score	1.453	0.870	0 – 3
use of sleep medication factor of PSQI score	0.040	0.300	0 – 3
N = number; SD = standard deviation.			

Table 2
Brain regions with a significant association between brain structures and the global PSQI score

Brain regions		**MNI coordinates**			**Cluster size(mm^3)**	***t*-value**
		X	**Y**	**Z**		
Correlation between WMV and the global PSQI score						
Middle occipital gyrus	R	51.0	−76.5	−7.5	84	−2.754
Superior temporal gyrus	L	−64.5	−46.5	7.5	1042	−3.211
Precentral gyrus	R	58.5	−10.5	31.5	461	−3.083
Middle frontal gyrus	L	−31.5	43.5	21.0	119	−2.891
Supramarginal gyrus	L	−43.5	−52.5	31.5	138	−3.295
Precunes	L	−18.0	−55.5	54.0	71	−3.208
Superior frontal gyrus	R	7.5	−6.0	73.5	68	−3.302
Note: PSQI, Pittsburgh Sleep Quality Index Score; L, left; R, right; WMV, white matter volume; MNI, Montreal Neurological Institute. All t-value reflect a VBM threshold of $p < 0.05$ (FDR-corrected).						

Correlation between WMV and the seven dimensions of PSQI score

After controlling for the age, gender, global brain WMV, and the other six factors of the PSQI score, multiple regression analysis revealed that scores on the subjective sleep quality factor of the PSQI significantly and negatively correlated with rWMV in an anatomical cluster that includes the right MOG (r = − 0.165, p < 0.01), the right PostCG (r = − 0.172, p < 0.01), the left IPL (r = − 0.198, p < 0.01) and the left MFG (r = − 0.173, p < 0.01) (see Table.3, Fig. 5A respectively).

Table.3 Brain regions with significant correlations between rWMV and the scores of each factor in the PSQI

Brain regions		MNI coordinates			Cluster size(mm^3)	*t*-value
		X	Y	Z		
Correlation between WMV and subjective sleep quality factor of PSQI score						
Middle occipital gyrus	R	51.0	−70.5	−9.0	61	−3.350
Postcentral gyrus	R	55.5	−25.5	46.5	50	−3.325
Inferior parietal lobule	L	−40.5	−43.5	46.5	276	−3.997
Middle frontal gyrus	L	−30.0	43.5	21.0	29	−3.401
Correlation between WMV and sleep latency factor of PSQI score						
Precentral gyrus	L	−48.0	6.0	9.0	188	−3.784
Superior frontal gyrus	R	15.0	9.0	60.0	47	−3.440
Correlation between WMV and sleep duration factor of PSQI score						
Inferior parietal lobule	L	−37.5	−48.0	58.5	78	−3.848
Precentral gyrus	L	−24.0	−21.0	69.0	6	−3.366
Correlation between WMV and sleep efficiency factor of PSQI score						
Inferior temporal gyrus	R	57.0	−25.5	−28.5	400	−4.720

Note: PSQI, Pittsburgh Sleep Quality Index Score; L, left; R, right; WMV, white matter volume; MNI, Montreal Neurological Institute. All t-value reflect a VBM threshold of p < 0.05 (FDR-corrected).

After controlling for the age, gender, and global brain WMV, and the other six factors of the PSQI score, multiple regression analysis revealed that scores on the sleep latency factor of the PSQI score significantly and negatively correlated with rWMV in the left PreCG (r = − 0.204, p < 0.01) and the right SFG (r = − 0.186, p < 0.01) (see Table.3, Fig. 5B). No positive relations were found between WMV and the sleep latency factor of PSQI score.

After controlling for the age, gender, and global brain WMV, and the other six factor of the PSQI score, multiple regression analysis revealed that scores on the sleep duration factor of the PSQI score significantly and negatively correlated with rWMV in the left PreCG ($r = -0.192$, $p < 0.01$) and in the left IPL ($r = -0.181$, $p < 0.01$). (See Table.3, Fig. 5C). No other significant results were observed.

After controlling the effects of age, gender, and global brain WMV, and the other six factor of the PSQI score, the multiple regression analysis showed that the sleep efficiency factor of PSQI score had significantly and negatively related with WMV in the right inferior temporal gyrus ($r = -0.205$, $p < 0.01$) (See Table.3, Fig. 5D).

No other significant results were observed in sleep disturbance factor, daytime dysfunctions factor, and use of sleep medication factor.

Discussion

In the current study, we examined the relationship between WMV and sleep quality in healthy college students by using voxel-based morphometry analyses. First, behavior results showed that there were no gender differences in the global PSQI score, and the global PSQI score was no significantly correlated with age. Additionally, VBM results showed that the global PSQI score was significantly associated with the WMV in the right MOG, the left STG, the right the PreCG, the left SMG, the left MFG, the Prcu, and the right SFG. More importantly, results also indicated that the brain white matter volume in specific regions could negatively predict the factor of PSQI. These specific brain white matter regions may be replicated in brain areas related to sleep, involving the right MOG, left MFG, and right PostCG (in terms of subjective sleep quality); the right SFG and left PreCG (mainly in terms of sleep latency); and the left IPL and PreCG (mainly in terms of sleep duration).

The present study showed that the global PSQI score was no significantly correlated with age, which was inconsistent with the previous findings (Bian et al., 2020). These discrepancies maybe explained that the mean age was comparably low and the age range was restricted in our sample. In terms of sex disparities in sleep quality, our results were inconsistent with several previous studies (Bian et al., 2020; Neumann et al., 2020; Sa et al., 2020). For example, Bian et al. (2020) found that females had a higher PSQI score than males. Sa et al. (2020) found that females had lower days of getting enough sleep in a week. Becker et al. (2018) also found that females reported more daytime dysfunction than males. They also explained that depression was associated with most aspects of sleep. Thus, it was plausible that differential sex outcomes in sleep quality may be attributed to varying levels of depression, with a higher prevalence of depression in females than in males. In our studies, our sample was selected from healthy college students.

VBM results revealed that the WMV could predict sleep quality, even after we controlled for relevant covariates (i.e., age, gender), which were in line with our hypothesis and previous studies (Eckert et al., 2009; Sridharan et al., 2008). For example, the white matter structure (i.e., frontal, parietal and occipital) was related to short sleep duration (e.g., attention, memory, cognitive control) (Eckert et al., 2009;

Sridharan et al., 2008). Our study differed from earlier studies (Amorim et al., 2018; Takeuchi et al., 2018), which sought to understand white matter microstructure through diffusion tensor imaging (DTI) analysis. Prior several DTI studies (Amorim et al., 2018; Khalsa et al., 2017; Sexton et al., 2017; Takeuchi et al., 2018) indicated that terrible sleep quality was associated with disrupted WM tracts of frontal, temporal, occipital, and subcortical regions. Although this study focused on brain white matter volume using VBM analysis, results similarly revealed that sleep quality was associated with white matter structure in the frontal, temporal and occipital gyrus. To sum up, our findings suggest that variations in specific brain white matter structure may be a predictor of poor sleep.

A significantly negative prediction between WMV and sleep quality was found in the right MOG, the left STG, the right PreCG, the left MFG, the right SFG, the left Prcu, and the left SMG. These brain areas partially belong to the DMN. The DMN included the anterior and posterior DMN. The anterior DMN included the medial prefrontal cortex, anterior cingulate cortex, and SFG. The posterior DMN was consisted of the posterior cingulate cortex (PCC) and Prcu (Zhang et al., 2013). Our results were partially consistent with the previous on sleep-related constructs (Cheng et al., 2020; Choo et al., 2005; Dai et al., 2014; DelRosso & Hoque, 2014; Gong et al., 2019; Yu et al., 2018). For instance, the Prcu had a high metabolic rate during resting wakefulness (Cavanna et al., 2006). Cheng et al. (2020) indicated the volume variation of the brain areas (i.e., prefrontal, temporal cortex, SMG, and Prcu) was correlated with sleep duration. This might be explained by the neurobiological model of insomnia, which assumed that the characteristic of insomnia was that sleep and wake-like activation patterns, used to regulate sleep-wake state, simultaneously existed in specific brain regions (Buysse et al., 2011), involving the DMN (e.g., precuneus, lateral parietal, ventromedial prefrontal, and superior temporal regions). This model showed relatively greater metabolism in the frontoparietal cortex among insomnia subjects, most strikingly in the Prcu. Additionally, Choo et al. (2005) revealed that the right MOG showed a reduction in BOLD response following sleep deprivation. Wang et al. (2016) showed that the increased activity in the bilateral PreCG might be associated with high sensitivity during falling asleep. Moreover, previous studies found that primary insomnia patients showed a significant reduction in left or right dorsolateral prefrontal cortices (i.e. right SFG, and left MFG), left PreCG, bilateral PostCG, and STG compared to normal controls (DelRosso & Hoque, 2014; Joo et al., 2013). As discussed above, we thought that these brain white matter regions (i.e., right MOG, left STG, right PreCG, left MFG, right SFG, left Prcu, and left SMG) were associated with sleep quality.

Then, the global PSQI score consists of seven distinct subcomponents (Buysse et al., 1989). Therefore, it could be possible that significant sleep quality-WMV associations in these studies were driven by one of these subcomponents (e.g., sleep latency). Thus, we further investigated the association of sleep quality with white matter structure separately by using the respective subcomponents of PSQI. Results showed that the right MOG, the right PostCG, the left IPL, and the left MFG were crucial brain regions related to subjective sleep quality. These results were tied with previous studies in sleep (Choo et al., 2005; Tashjian et al., 2018; Zhang et al., 2013). For example, Tashjian et al. (2018) showed that variation in sleep quality was related to a weaker intrinsic DMN. Buckner et al. (2008) revealed that the IPL was regarded as one of the core regions in DMN. The DMN was active when the brain was at rest, while the DMN also played a

crucial role in sleep as well as in other activities (Andrews-Hanna et al., 2014; Liu et al., 2018). Meanwhile, a large number of studies revealed that the DMN was linked not only to sleep problems, but also to other symptoms of sleep problems, including poor cognitive functions (Chen et al., 2018; Santarnecchi et al., 2018). These findings also supported the neurobiological model of insomnia (Buysse et al., 2011) that assumed that the specific brain regions related to sleep include the cortico-limbic circuits, the default mode network, the hypothalamic centers, and the brainstem-hypothalamic arousal centers. Furthermore, in line with our findings, research suggests that the right PostCG was a main receptive region for external stimuli, which was located in the somatosensory network (SSN) (Joo et al., 2013; Sung et al., 2020). A structural MRI study demonstrated a significant reduction in the bilateral PostCG in patients with primary insomnia (Joo et al., 2013), which was related to sleep latency.

Based on the cognitive model of insomnia, individuals who suffer from insomnia tend to be overly worried about thoughts of their sleep and the daytime consequences of not getting enough sleep (Harvey, 2002). These excessively worrying thoughts trigger autonomic arousal, which in turn leads to poor sleep quality. Previous found that excessive anxiety was associated with the decrease of WMV in the left medial and superior frontal gyrus (Moon et al., 2015). Chao et al. (2014) suggested that subjective sleep quality and other measures of sleepiness and wakefulness might have different effects on different regions of the frontal lobe. Öngür et al. (2003) found that frontal lobe volume might also be associated with more inferior sleep quality to be experienced as restorative. In summary, these findings suggest that the neural activity of the right MOG, the left STG, the right the PreCG, the left SMG, the left MFG, the left Prcu, and the right SFG maybe the potential neuroimaging biomarkers of sleep. Therefore, the variations in white matter volume that we could see form the underlying neural mechanism substrate of poor sleep.

Finally, the previous studies revealed that associations with sleep disturbances had decreased volumes in the left IPL (Sung et al., 2020). In contrast, our findings revealed that the WMV in left IPL was negatively associated with subjective sleep quality and sleep duration. We speculate the reason is that subjective sleep quality, sleep duration, and sleep disturbance belong to factors of sleep, which overlaps in the white matter structure of the brain.

Limitations and further directions

Although the present study has several strengths including the healthy college student sample, some limitations have to be mentioned. Firstly, the available sleep-related data was restricted to the Pittsburgh Sleep Quality Index (Buysse et al., 1989), so there were no other questionnaires, polysomnography, or actigraphy data. Secondly, this study was cross-sectional, and therefore it could not determine causal relationships between rWMV and sleep quality. Finally, the current investigation was limited to the group of young, healthy college students and may suffer from restricted generalizability. Poor sleep quality was a heterogeneous construct that includes all different kinds of etiologies for whom distinct neurobiological mechanisms may apply. Moreover, future studies should focus on more objective sleep measures to explore sleep-related neural mechanisms, for example, laboratory measurements.

Conclusions

This study suggested that the brain white matter structure related to sleep quality might overlap with the right MOG, left MFG, and right PostCG (in terms of subjective sleep quality); the right SFG and left PreCG (mainly in terms of sleep latency); and the left IPL and PreCG (mainly in terms of sleep duration). On the one hand, the findings complemented earlier work which indicated that poor sleep quality had been correlated with increased gray matter in the frontal, temporal, and parietal lobes (Joo et al., 2013; Li et al., 2016; Sexton et al., 2014). On the other hand, these findings may not only enrich the neurobiological model of insomnia, lay the foundation for thoroughly revealing the reasons of poor sleep quality, but also provide a reliable path for clinical interventions, particularly in college students. Meanwhile, exploring brain white structure related to sleep could help to shed light on the mechanisms by which sleep quality are associated with brain structure, behaviour and cognition, as well as potentially the neural mechanism responsible for variations in poor sleep.

Declarations

Acknowledgements/Declarations

Author contribution

Youling Bai and Li Zhang conducted the studies, Youling Bai, Li Zhang and Chengwei Liu collected and analyzed the data, Youling Bai, Li Zhang, Chengwei Liu, Xiaobing Cui, Dan Li, and Huazhan Yin prepared and revised the manuscript.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Compliance with Ethical Standards

Informed consent statement. All procedures followed were in accordance with the Helsinki Declaration of1975, and the applicable revisions at the time of the investigation. Informed consent was obtained from all participants included in the study.

Data Availability

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

Code availability

Not applicable

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Figures

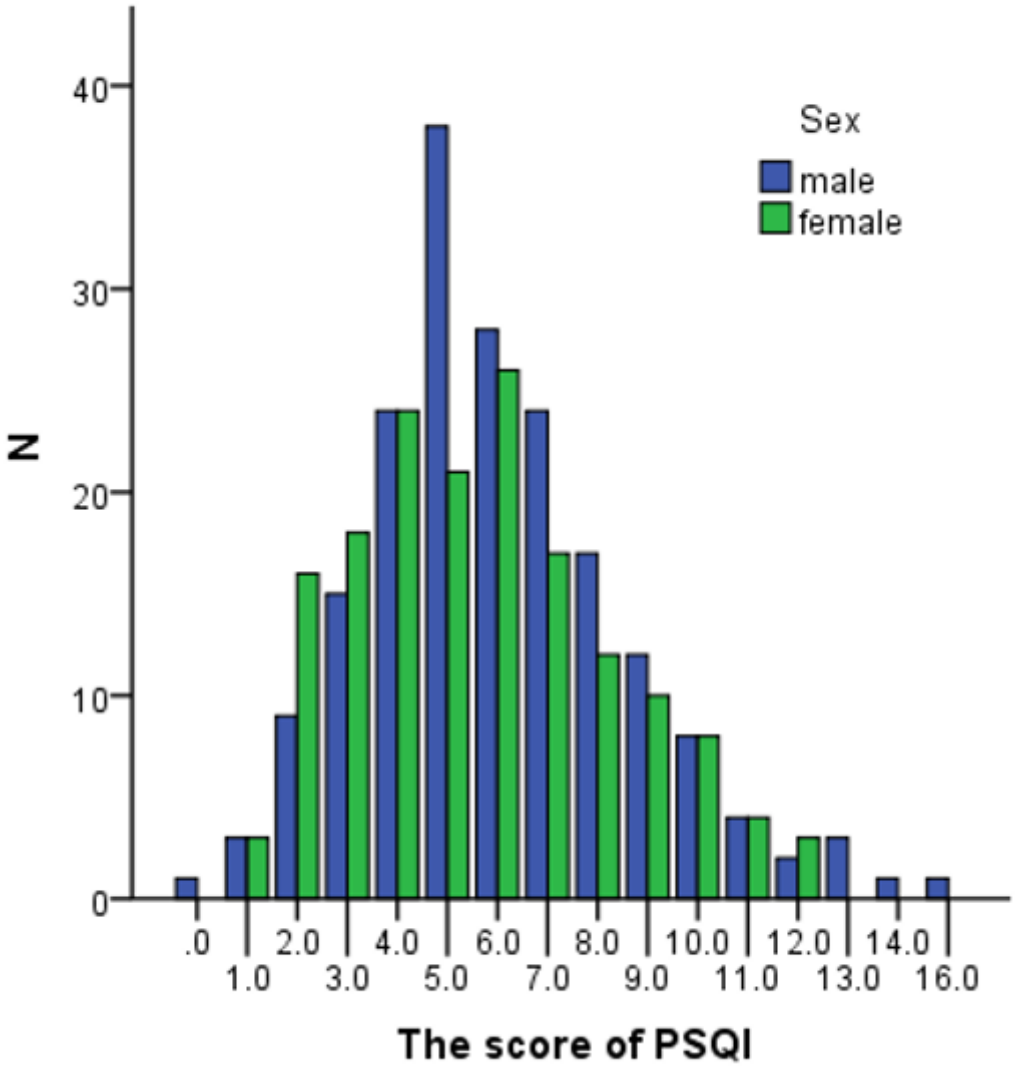

Figure 1

Distribution of PSQI scores in males and females. Histogram showing the distribution of PSQI scores for all subjects.

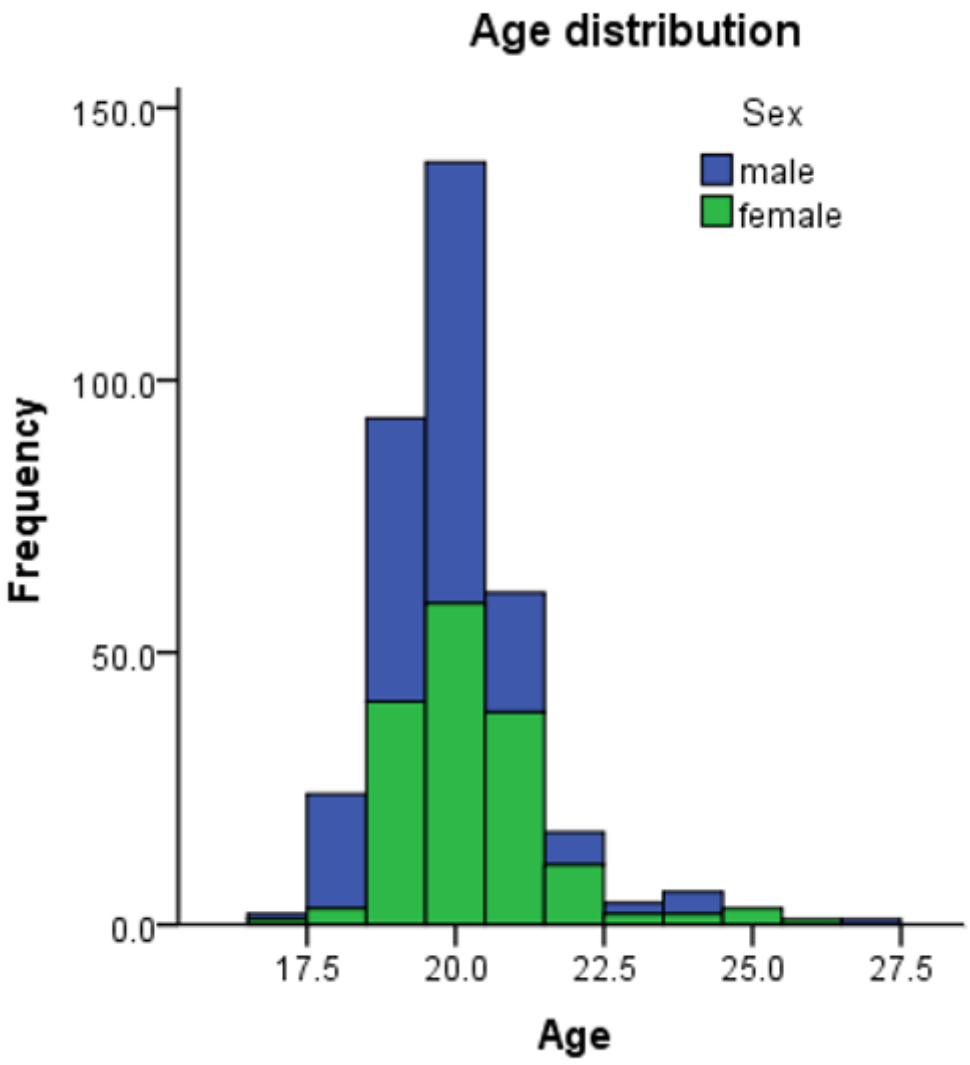

Figure 2

The distribution of the age

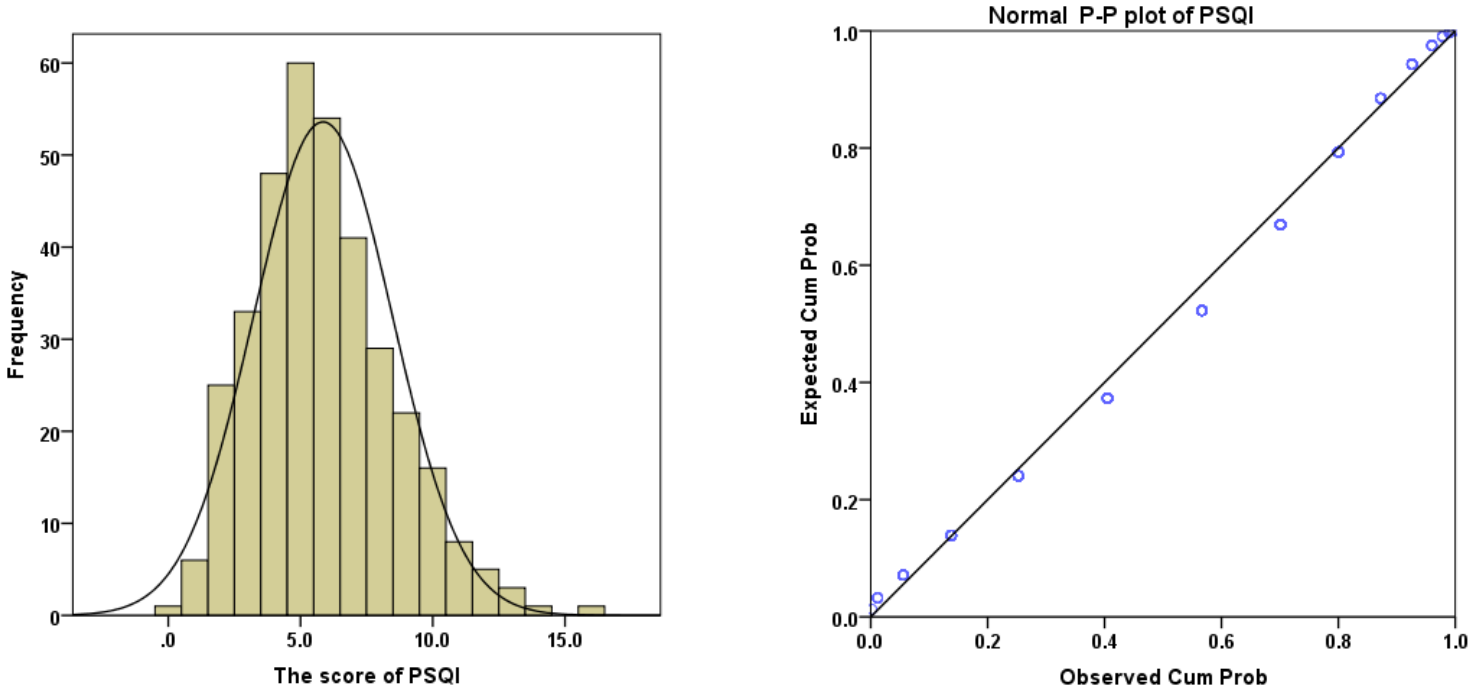

Figure 3

The histogram and P-P plot of the score of PSQI

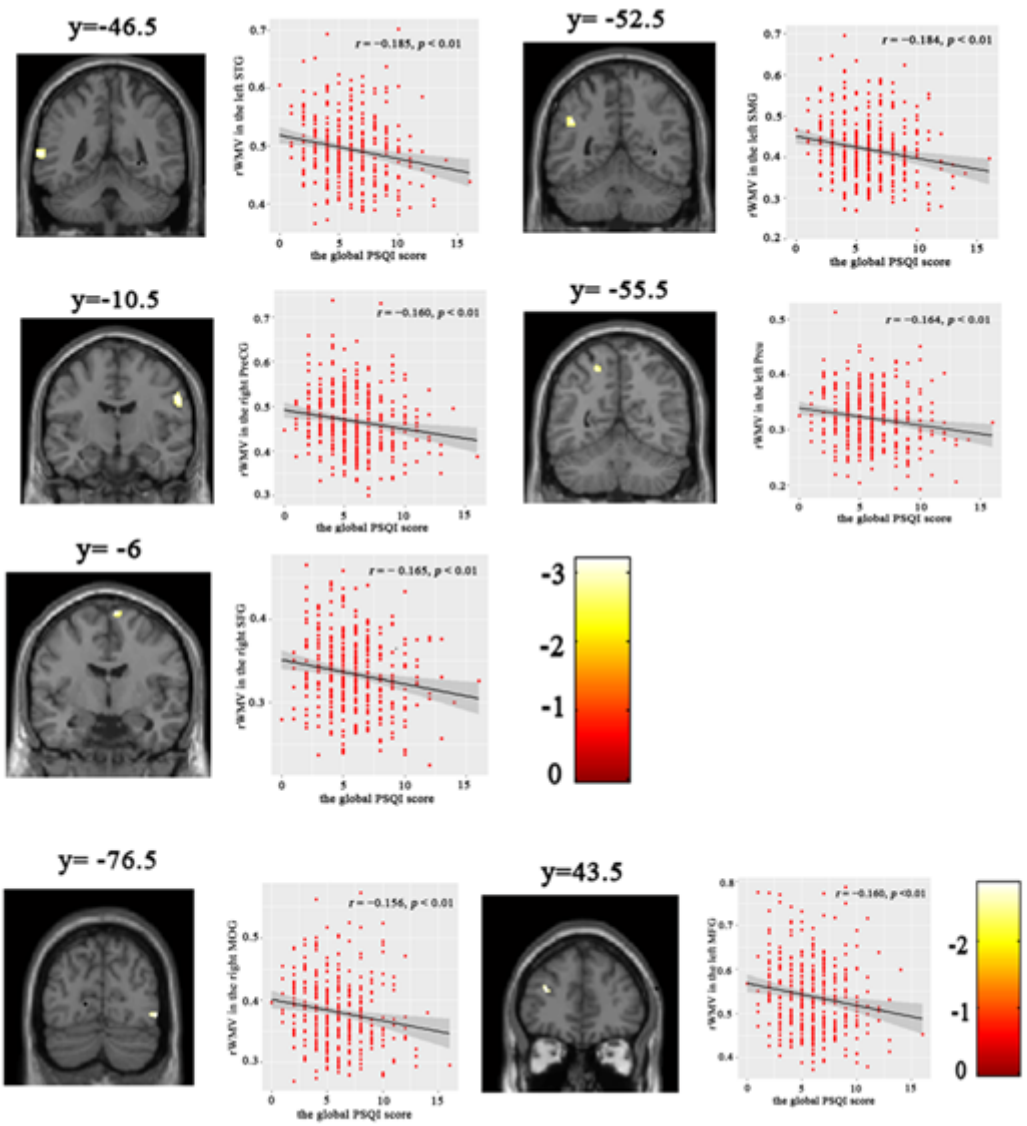

Figure 4

Regions of correlation between WMV and the global of PSQI score. WMV was negatively correlated with PSQI score in the right SFG, the right MOG, the left Prcu, the left STG, the left SMG, the left MFG, and the right PreCG.

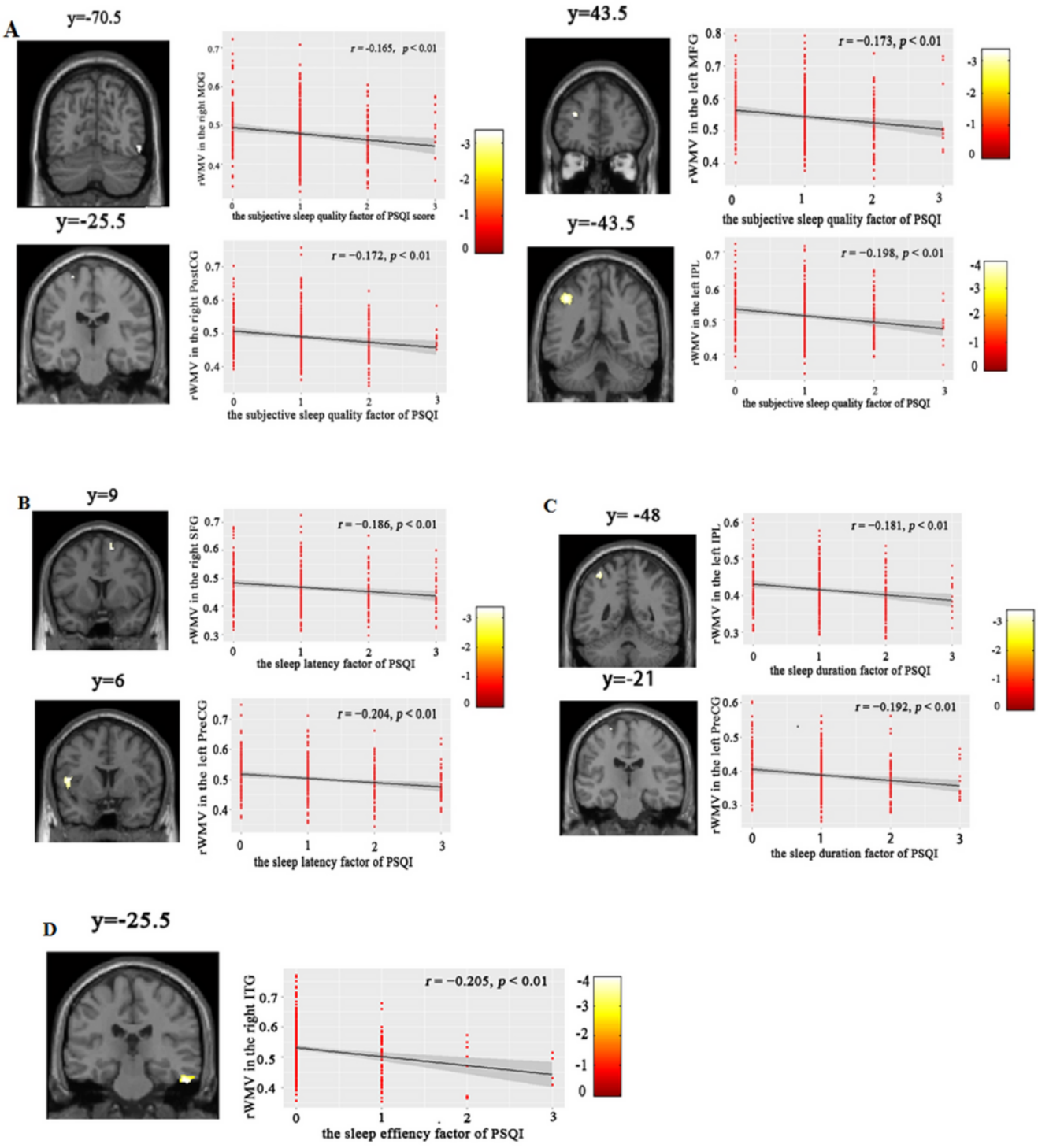

Figure 5

Regions of correlation between WMV and the seven dimensions of PSQI score. WMV was negatively correlated with subjective sleep quality in the right MOG, the right PostCG, the left IPL and the left MFG (A) and negatively correlated with the sleep latency factor of the PSQI score in the left PreCG and the right SFG (B), and negatively correlated with the sleep duration factor of the PSQI score in the left PreCG and in

the left IPL (C) and negatively correlated with the sleep efficiency factor of PSQI score in right inferior temporal gyrus (D).