Title: Subjective sleep quality in healthy young adults moderates associations of sensitivity to punishment and reward with functional connectivity of regions relevant for insomnia disorder

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Abstract

Chronic unhealthy sleeping behaviours are a major risk factor for the emergence of mood and anxiety disorders. Nevertheless, we are still lacking understanding why some individuals are more prone than others to affective dysregulation caused by sleep disruption. With preliminary evidence suggesting that brain activity during positive and negative emotional processing might play an important modulating role, we conducted whole-brain resting-state functional connectivity analyses in a large cohort of healthy young adults (N = 155). Using regions consistently affected in insomnia disorder as seeds, we investigated sleep quality-related neural connectivity patterns that were both insensitive and sensitive to the interactions with individual measures of reward and punishment processing, additionally assessing the links with indices of emotional health. Majority of the findings reflected interactions between sleep quality and reinforcement sensitivity, with the opposite associations reported in the good and poor sleepers. One of such connections, the coupling between precentral gyrus and posterior insula, was additionally negatively linked to trait anxiety, with the lowest connectivity values observed in poor sleepers with higher sensitivity to punishment. In turn, the only finding associated solely with sleep quality, i.e. coupling between subgenual anterior cingulate cortex and thalamus, was also related to the habitual use of emotion suppression strategies. As such, the present study provides evidence that affective functioning plays an essential role in determining the effects of poor sleep quality on brain connectivity and emotional health, providing a plausible mechanism for why certain individuals are more susceptible to sleep-related affective dysregulation than others.

Keywords

Sleep quality; fMRI; functional connectivity; sensitivity to punishment; sensitivity to reward; emotion regulation; anxiety

Highlights

- Functional connectivity of insomnia-related brain regions is altered in poor sleepers
- Sleep quality interacts with reinforcement sensitivity for most of such effects
- Distinct sleep-related mechanisms are linked to trait anxiety and emotion suppression
- Poor sleep and high punishment sensitivity increase the risk of affect dysregulation.

1. Introduction

During adolescence and early adulthood we undergo a shift towards later hours of waking up and falling asleep (Pifer et al., 2024). As the societal norms demand early hours of schooling and work, the youth are particularly susceptible to suffer from the circadian rhythm and sleep disturbances, with adverse consequences affecting them on immediate and lifespan time scales. Within hours to days, sleep deprivation causes deterioration of attention and executive functions (Killgore, 2010), leading to worse academic performance (Owens et al., 2021) on one hand, and dysregulated emotional processing on the other (Tempesta et al., 2020). Persistent inadequate sleep timing and sleep debt can eventually contribute to the emergence of mood and anxiety disorders in susceptible individuals (Meyer et al., 2024). Chronic unhealthy sleeping behaviours are further related to structural brain differences (Zareba et al., 2024b), accelerated brain ageing (Liu et al., 2022) and increased prevalence of neurodegenerative diseases (Cullell et al., 2021). With increasing amount of evidence suggesting that mental health issues experienced during youth can increase the risk of pathological brain aging (Hedges et al., 2024), understanding the mechanisms through which sleep quality affects one's emotional functioning may help inform interventions that will improve the quality of life not only when one is young, but may also save the day in the future.

Studies have found partially convergent patterns of functional alterations in the affective brain circuitry in short-term and chronic insomnia patients (Ma et al., 2021), with some works extending such characteristics to non-diagnosed individuals experiencing sleeping difficulties (Prather et al., 2013; Baglioni et al., 2014), suggesting that processes responsible for affective dysregulation may start well before one meets diagnosis criteria. Previous functional connectivity works linking sleep-related alterations in neural circuitry with emotion regulation and mental health indices were, however, limited in their scope only to specific canonical resting-state networks (Yin et al., 2024; Chen et al., 2024; Shen et al., 2024). Importantly, the more complex mental processes, such as regulation of one's affective state, typically require cooperation between associative areas belonging to more than one such network (Morawetz et al., 2020), which previously has not been the focus of research in the context of sleep.

Furthermore, we are still lacking understanding why some individuals are more prone than others to affective dysregulation caused by sleep disruption (Chen et al., 2017; Minkel et al., 2012; Vargas and Lopez-Duran, 2017; Wright et al., 2007). One study reported that higher levels of reward-related activity could act as a buffer against depressive symptoms associated with poor sleep (Avinun et al., 2017). Similarly, the activity of anterior insula was found to moderate the associations between negative life stress, sleep disturbances and mood symptomatology, with stronger links identified at higher levels of insular activation (Kim et al., 2022). These two studies therefore point out to a possibility that the individual sensitivity to reward and punishment may play an essential role in determining the impact of poor sleep quality on affective functioning.

Therefore, the current work aims to fill this important gap in the literature, comparing for the first time sleep quality-related neural connectivity patterns, potentially within and across canonical resting-state networks, that are both insensitive and sensitive to the interactions with individual indices of reward and punishment processing. Focusing on a set of regions consistently affected in insomnia disorder (Wu et al., 2020), we conducted whole-brain resting-state functional connectivity analysis in a large cohort of healthy young adults (N = 155) with approximately half of them reporting sleeping problems. We assessed whether such neural connectivity patterns would also be related to indices of emotional well-being: the habitual use of adaptive (cognitive reappraisal) and maladaptive (suppression) emotion regulation strategies, and trait-anxiety. Given the evidence outlined above, we expected to see differences in functional connectivity that would be dependent solely on sleep quality, as well as its interactions with indices of

reinforcement sensitivity. For both types of connectivity results, we additionally hypothesised to observe links with emotion regulation and trait-anxiety. In the case of neural patterns associated solely with poor sleep quality, we expected them to be additionally correlated with higher levels of trait-anxiety and emotion suppression, and lower levels of emotion reappraisal. As for the connectivity patterns linked to the interactions between sleep quality and reinforcement sensitivity, the combined effects of these measures were difficult to predict a priori due to the potential buffering effects of positive and negative emotion processing strength (Avinun et al., 2017; Kim et al., 2022).

2. Methods

2.1. Participants

The study was performed using the data of 155 healthy volunteers (22.23 ± 2.75 years, 61 males) recruited mainly from the university community via local announcements and word of mouth. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected to normal vision, no history of neurological and psychiatric disorders, and were drug-free. Self-reported sleep quality during the past month was assessed with the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989). Using the original criteria of PSQI scores higher than 5 indicating sleep disturbances, the sample was divided into the good (N = 86) and poor (N = 69) sleepers groups. Individual differences in the negative and positive reinforcement sensitivity were assessed using the Behavioral Inhibition and Behavioral Activation System (BIS/BAS; Carver and White, 1994), and Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ; Torrubia et al., 2001). Trait-anxiety was measured with the State-Trait Anxiety Inventory (STAI; Spielberger, 1989), while the use of reappraisal and suppression strategies for emotion regulation was tested with Emotion Regulation Questionnaire (ERQ; Gross and John, 2003; Cabello et al., 2013). All behavioural data were collected online via Qualtrics XM. The comparison of the demographic and psychological characteristics of the two groups is presented in Table 1. The poor sleepers reported higher anxiety levels and increased use of emotion suppression strategy.

Table 1. Demographic and psychological characteristics of the good and poor sleeper groups. Unless specified otherwise, the significance values come from independent samples t-tests. Bolded values represent significant group differences.

Variable	**Good sleepers (n = 86) mean ± SD**	**Poor sleepers (n = 69) mean ± SD**	**p value**
Gender	37 males, 49 females	24 males, 45 females	0.297 [a]
Age	22.43 (2.61)	21.97 (2.91)	0.302
PSQI	3.70 (1.15)	8.58 (2.65)	**< 0.001**
BIS	21.62 (3.33)	21.96 (3.42)	0.533
BAS	41.62 (5.03)	40.91 (5.16)	0.394
SP	10.90 (5.36)	11.87 (5.20)	0.257
SR	9.56 (3.91)	10.16 (3.97)	0.346
STAI	21.16 (9.37)	26.54 (12.22)	**0.002**

ERQ reappraisal	29.94 (6.14)	28.36 (6.49)	0.123
ERQ suppression	13.74 (5.81)	16.17 (5.76)	**0.01**

[a] Chi-squared test.

Abbreviations: SD, standard deviation; PSQI, Pittsburgh Sleep Quality Index; BIS, Behavioral Inhibition System; BAS, Behavioural Activation System; SP, sensitivity to punishment; SR, sensitivity to reward; STAI, State-Trait Anxiety Inventory; ERQ, Emotion Regulation Questionnaire.

2.2. MRI data acquisition and preprocessing

Two types of images were collected for each participant using a 3 Tesla scanner (SIGNA Architect, GE Healthcare, Chicago, Illinois, United States) and a 24-channel head coil. High-resolution anatomical image was obtained with T1 BRAVO sequence (384 sagittal slices; 0.5 × 0.47 × 0.47 mm voxel size; TR = 8.516 ms; TE = 3.276 ms). The resting-state fMRI data was collected with a T2*-weighted gradient echo planar imaging sequence (27 axial slices acquired in the interleaved bottom-up order; 3.75 × 3.75 × 4.5 mm voxel size; TR = 2000 ms; TE = 30 ms; flip angle = 70°; 210 volumes resulting in 7 mins of data). During the functional scan, the participants were instructed to keep their eyes open and concentrate on the fixation cross without thinking about anything in particular.

Preprocessing of the data was performed using CONN release 21.a (Whitfield-Gabrieli and Nieto-Castanon, 2012) and SPM release 12.7771 (Penny et al., 2011). The modular preprocessing pipeline (Nieto-Castanon, 2020) included realignment with correction of susceptibility distortion interactions, slice timing correction, outlier detection, direct segmentation and MNI-space normalisation, and smoothing. Functional data were realigned using SPM realign and unwarp procedure (Andersson et al., 2001), where all scans were coregistered to a reference image (first scan of the first session) using a least squares approach and a 6 parameter (rigid body) transformation (Friston et al., 1995), and resampled using b-spline interpolation to correct for motion and magnetic susceptibility interactions. Temporal misalignment between different slices of the functional data was corrected following SPM slice-timing correction procedure (Sladky et al., 2011), using sinc temporal interpolation to resample each slice BOLD time series to a common mid-acquisition time. Potential outlier scans were identified using ART (Whitfield-Gabrieli et al., 2011) as acquisitions with framewise displacement above 0.9 mm or global BOLD signal changes above 5 standard deviations (Power et al., 2014), and a reference BOLD image was computed for each subject by averaging all scans excluding outliers. Functional and anatomical data were normalised into standard MNI space, segmented into grey matter (GM), white matter, and cerebrospinal fluid (CSF) tissue classes, and resampled to 3 mm isotropic voxels following a direct normalisation procedure (Calhoun et al., 2017) using SPM unified segmentation and normalisation algorithm (Ashburner and Friston, 2005; Ashburner, 2007) with the default IXI-549 tissue probability map template. Subsequently, functional data were smoothed using spatial convolution with a Gaussian kernel of 4 mm full width half maximum (FWHM). Lastly, functional data were denoised using a standard denoising pipeline including the regression of potential confounding effects characterised by white matter timeseries (5 CompCor noise components), CSF timeseries (5 CompCor noise components), motion parameters and their first order derivatives (12 factors; Friston et al., 1996), outlier scans (below 52 factors; Power et al., 2014), and linear trends (2 factors), followed by bandpass frequency filtering of the BOLD time series (Hallquist et al., 2013) between 0.008 Hz and 0.09 Hz. CompCor (Behzadi et al., 2007; Chai et al., 2012) noise components within white matter and CSF were estimated by computing the average BOLD signal as well as the largest principal components orthogonal to the BOLD average, motion parameters, and outlier scans within each subject's eroded segmentation masks. From the number of noise terms included in this denoising strategy, the effective degrees of freedom of

the BOLD signal after denoising were estimated to range from 40.7 to 57.7 (average 57.2) across all subjects.

2.3. Regions of interest and seed-based connectivity analysis

Regions of interest (ROIs) for the seed-based functional connectivity analyses were selected based on the results of the recent meta-analyses on the structural and functional brain changes in insomnia disorder (Wu et al., 2020). ROIs were defined as 4 mm-radius spheres centred on the peak coordinates of reported differences in GM volume, glucose metabolism, amplitude of low frequency fluctuations (ALFF) and regional homogeneity (ReHo). The only exception from this rule was made for anterior cingulate cortex (ACC) as the meta-analysis results partially mapped onto the border between subgenual (sgACC) and pregenual ACC (pgACC), which are known to engaged more in the processing of, respectively, positive and negative reinforcement (Rolls, 2019). In this case, we decided to use larger, atlas-based ROIs, distinguishing between the ACC subregions (Fan et al., 2016). The ROIs with their mass centre coordinates are presented in Table 2. If more than one ROI was present in a given anatomical location in one hemisphere, the corresponding Brodmann areas (BA) were added for easier discrimination.

Table 2. Regions of interest (ROIs) for the seed-based functional connectivity analyses.

Location	MNI coordinates
L cuneus	-3, -90, 21
L fusiform gyrus BA 20	-44, -34, -18
L fusiform gyrus BA 37	-36, -48, -12
L middle temporal gyrus	-57, -3, -27
L orbital gyrus *	-21, 33, -21
L parahippocampal gyrus	-42, -39, 9
L posterior cingulate cortex	-6, -48, 6
L precentral gyrus	-30, -6, 54
L precuneus	3, -45, 36
L pregenual anterior cingulate cortex	-6, 34, 20
L subgenual anterior cingulate cortex	-4, 38, -2
R amygdala	36, 0, -24
R anterior lobe of cerebellum	15, -42, -30
R middle cingulate gyrus	9, -9, 36
R middle frontal gyrus	52, 15, 32
R middle temporal gyrus	57, -63, -3
R posterior cingulate cortex	12, -40, 22
R precentral gyrus	33, -12, 48
R pregenual anterior cingulate cortex	4, 28, 28
R subgenual anterior cingulate cortex	6, 42, 6

Abbreviations: L, left; R, right; BA, Brodmann area.

* In the original meta-analysis (Wu et al., 2020), the area was reported as L middle frontal gyrus, however, according to the Brainnetome atlas (Fan et al., 2016), it mapped more closely on the currently disclosed area.

Seed-based connectivity analyses were performed in AFNI (Cox, 1996). For every ROI in each participant, we extracted the mean blood-oxygen-level-dependent (BOLD) signal time series, and computed the Pearson correlations with the time courses of all other brain voxels. The distribution of the correlation coefficients was normalised with the Fisher's z transform. Whole-brain functional connectivity maps created in this manner were used as the input to the statistical analyses.

2.4. Statistical analysis

All neuroimaging analyses were performed with the 3dMVM (Chen et al., 2014) package available as a part of AFNI (Cox, 1996). For each ROI, we tested an ANCOVA-style design in which its functional connectivity was predicted by the subjective sleep quality (good or poor sleeper group), sensitivity to reward (SR) and sensitivity to punishment (SP), modelling the main effects, as well as the two- and three-factor interactions. Biological sex and age of participants were controlled as covariates. Multiple comparisons correction was achieved through cluster-level family-wise error rate correction (FWE < 0.05) after the initial voxel-level thresholding at the level of $p < 0.001$.

To test the replicability of the reported effects across the psychometric scales, this time using BIS/BAS (Carver and White, 1994), we extracted the connectivity patterns successfully predicted in the whole-brain models and used them as the dependent variables in permutation-based linear regressions (10000 permutations). The decision to use a non-parametric approach was guided by the lack of normal distribution of the BIS data. The calculations were run using the *lmperm* function from the *permuco* library (Frossard and Renaud, 2021) in R (version 4.2.1; R Core Team, 2022), including biological sex and age as covariates, akin to the original analyses.

Last but not least, we additionally tested whether the highlighted connectivity patterns were associated with trait anxiety and the use of emotion reappraisal and suppression strategies. This analysis was meant to elucidate whether the same neural patterns that were associated with sleep quality and its interactions with reinforcement sensitivity measures were also related to negative emotionality and maladaptive emotion regulation. Multiple comparison correction across the replication and associative analyses were achieved with the false discovery rate (FDR < 0.05) approach.

3. Results

3.1. Effects of sleep quality and reinforcement sensitivity on neural connectivity

The whole-brain analyses yielded five significant findings, one for the main effect of subjective sleep quality and four others for the interactions with SP and SR (Table 3). Poor sleepers were found to have lower functional connectivity between the right sgACC and left prefrontal thalamus (Figure 1A). In turn, interactions between the sleep quality and SP predicted the connectivity of the left precentral gyrus with posterior insula (Figure 2A), and supramarginal and superior temporal gyri of the same hemisphere (Figure 3B). Similarly, the functional connectivity of the left fusiform gyrus BA 20 and bilateral supplementary motor area was dependent on the interaction between the sleep quality and SR (Figure 3A). In all the cases, the reinforcement sensitivity measures were positively linked to the functional connectivity in the good sleepers, while the opposite relationships were observed for the poor sleepers. Three-way interactions between sleep quality, SP and SR were observed for the functional connectivity of the right middle temporal gyrus and the left lateral prefrontal cortex (Figure 4). Poor sleepers with lower SP had a positive association between SR and the connectivity, whereas in poor sleepers with

higher SP the relationship was negative. The direction of the associations was reversed in the group without sleeping problems.

Table 3. Results of the seed-based functional connectivity analyses. Multiplication sign (×) indicates interactions between the factors.

Seed	Factors	MNI	Location	Voxels	F-stat
R subgenual anterior cingulate cortex	Sleep quality	-12, -16, 8	L prefrontal thalamus	37	19.66
L fusiform gyrus BA 20	Sleep quality × SR	10, 8, 56	B supplementary motor area	46	21.59
L precentral gyrus	Sleep quality × SP	-56, -22, 14	L supramarginal gyrus L superior temporal gyrus	80	24.86
L precentral gyrus	Sleep quality × SP	-42, -10, 0	L posterior insula	69	31.64
R middle temporal gyrus	Sleep quality × SP × SR	-32, 50, 12	L lateral prefrontal cortex	86	23.99

Abbreviations: L, left; R, right; B, bilateral; BA, Brodmann area; SR, sensitivity to reward; SP, sensitivity to punishment.

The analysis performed with the BIS/BAS data replicated the effects of interactions between sleep quality and SR on the functional connectivity between the left fusiform gyrus BA 20 and bilateral supplementary motor area ($t = 2.74$; $p_{FDR} = 0.03$; Supplementary Figure 1). As for the main effects of SR and SP, they were observed for 5 functional connectivity patterns each, and were characterised by higher replicability (80%) than the interaction effects. As these associations were not the primary focus of the paper, they are provided in the Supplementary Material (Supplementary Table 1 and Supplementary Figure 2) for the sake of transparency and to facilitate their reusability for meta-analytic purposes.

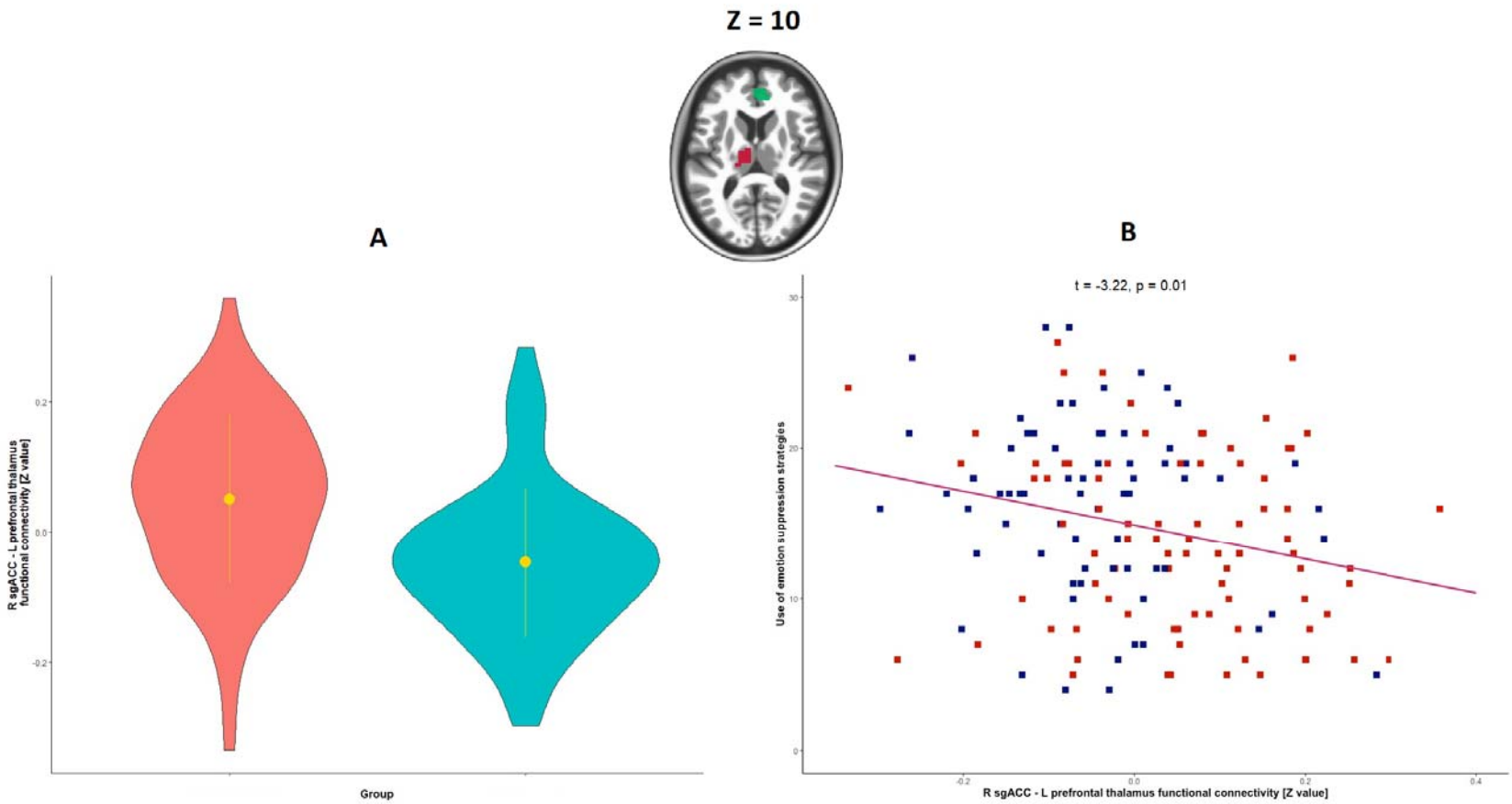

Figure 1. (A) Poor sleepers (blue) were found to have lower functional connectivity between the right subgenual anterior cingulate cortex (R sgACC) and the left prefrontal thalamus compared to the good sleepers (red). (B) Functional connectivity between the two areas was additionally negatively associated with the habitual use of emotion suppression strategies. For illustrative purposes, we used the average of connectivity values from the voxels within the thalamus cluster. R sgACC seed is presented in green, while the left prefrontal thalamus cluster is shown in magenta.

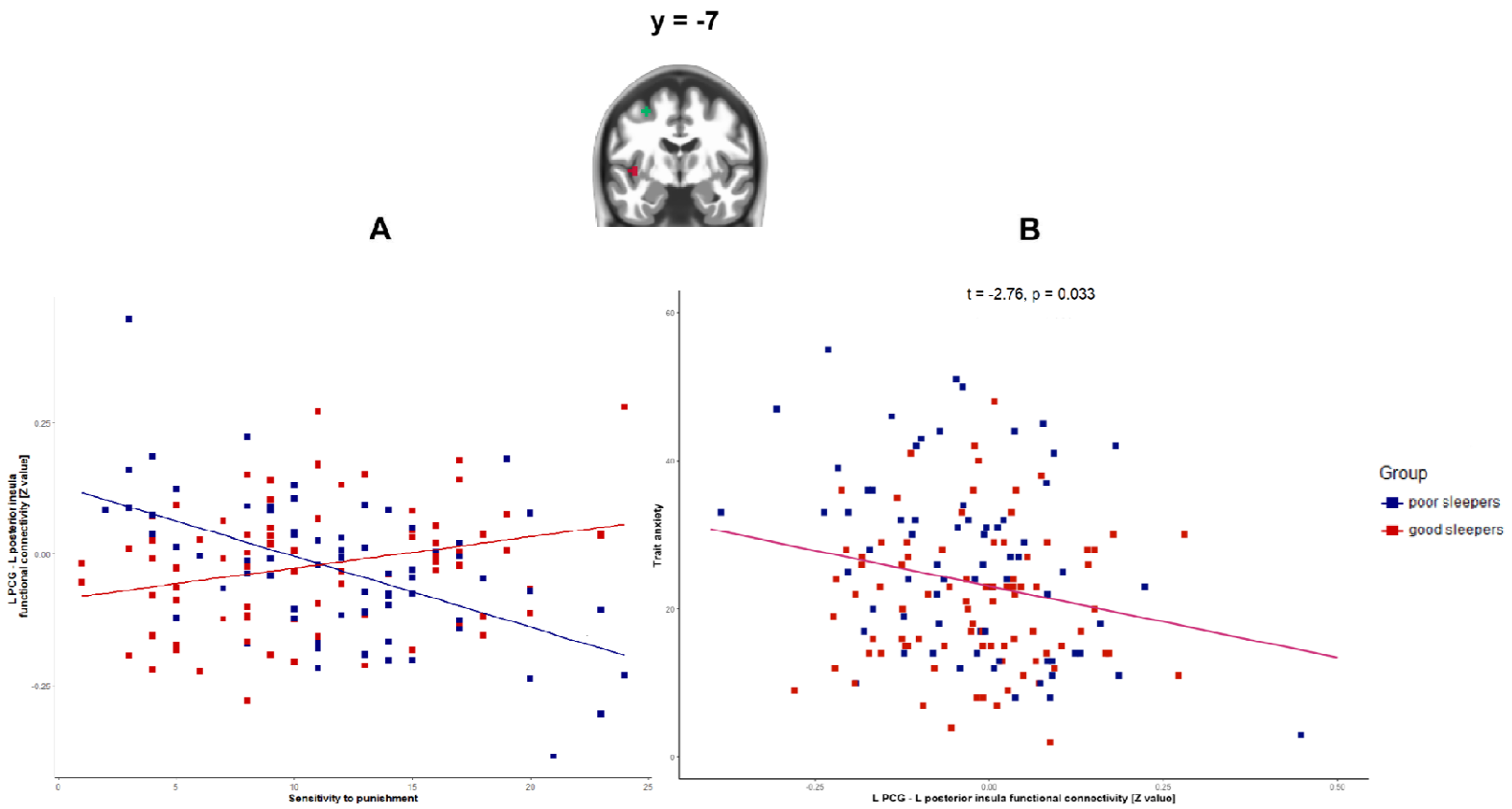

Figure 2. The functional connectivity of the left precentral gyrus (L PCG) with the left posterior insula was sensitive to the interactions of individual sleep quality with negative reinforcement sensitivity (A). The strength of the coupling between the areas was additionally negatively correlated with trait anxiety (B). For illustrative purposes, we used the average of connectivity values from the voxels within the insula cluster. L PCG seed is presented in green, while the left posterior insula cluster is shown in magenta.

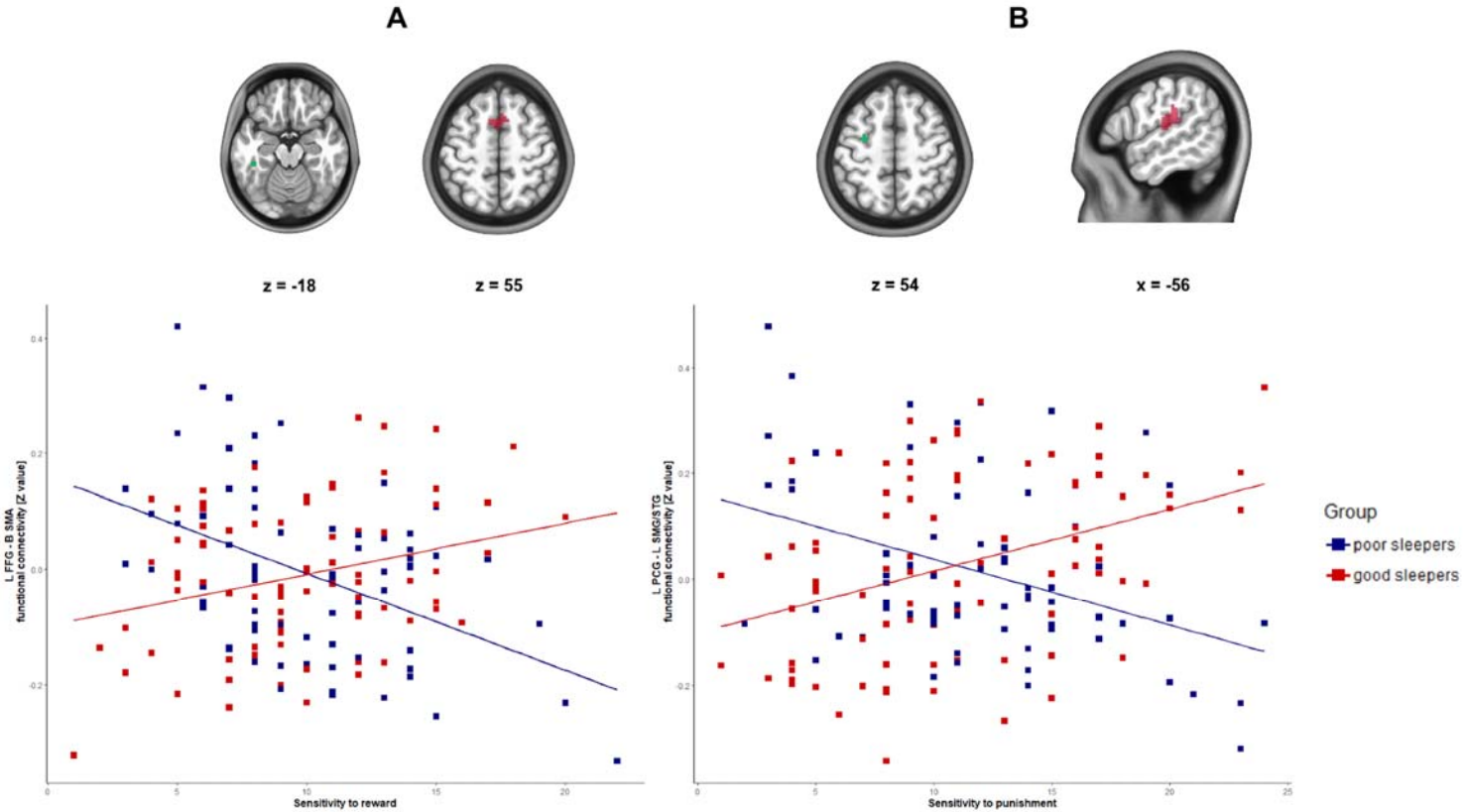

Figure 3. The associations between reinforcement sensitivity measures and functional connectivity patterns were moderated by individual sleep quality. Significant findings for the positive reinforcement (A) were observed for the connectivity between the left fusiform gyrus (L FFG) and bilateral supplementary motor area (B SMA). As for the negative reinforcement (B), such associations were found for the connectivity of the left precentral gyrus (L PCG) with the left supramarginal and superior temporal gyri (L SMG/STG). For illustrative purposes, we used the average of connectivity values from the significant voxels in each cluster. Seeds are presented in green, and the areas highlighted by the whole-brain analyses are shown in magenta.

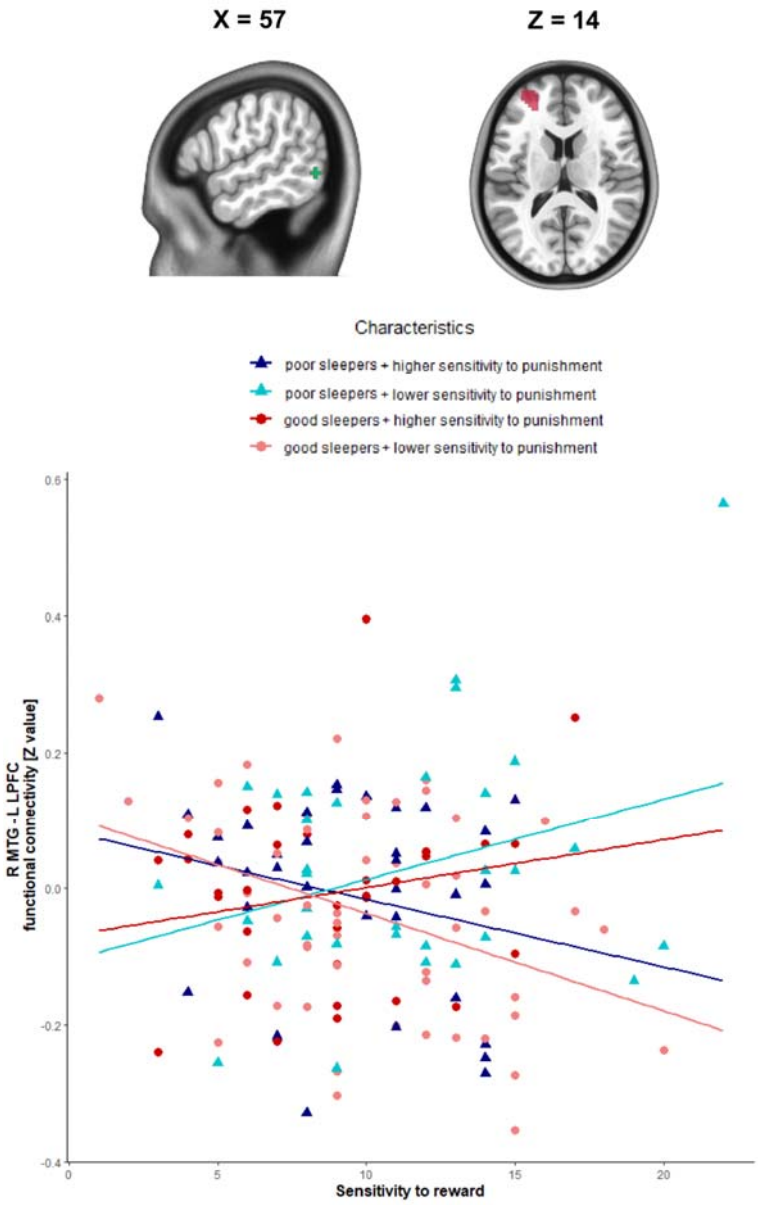

Figure 4. Three-way interactions between sleep quality, positive and negative reinforcement sensitivity were found for the functional connectivity between the right middle temporal gyrus (R MTG) and the left lateral prefrontal cortex (L LPFC). Poor sleepers with lower sensitivity to punishment had a positive association between sensitivity to reward and the connectivity, whereas in poor sleepers with higher sensitivity to punishment the relationship was negative. The direction of the associations was reversed in the good sleepers. For illustrative purposes, the good and poor sleepers groups were divided into subgroups with higher and lower sensitivity to punishment, with the cut-off based on the median of the entire sample (i.e. 11). Plots were drawn using average connectivity values from the voxels in the L LPFC cluster. R MTG seed is shown in green, and the frontal area in magenta.

3.2. Associations of the highlighted connectivity patterns with anxiety and emotion regulation

Two of the highlighted functional connectivity patterns were also related to indices of emotional health. The strength of the coupling between the right sgACC and left prefrontal thalamus was negatively related to the use of emotion suppression strategies ($t = -3.22$; $p_{FDR} = 0.01$; Figure 1B), while the functional connectivity between the left precentral gyrus and posterior insula was negatively associated with trait anxiety ($t = -2.76$; $p_{FDR} = 0.033$; Figure 2B). All the other associations were not significant (Supplementary Table 2). The links with anxiety and emotion regulation for the connectivity patterns related to the main effects of positive and negative reinforcement measures are provided in Supplementary Table 3.

4. Discussion

In line with the hypotheses, the current work highlights a fact that a deterioration of sleep quality over a period of a month in a sample of healthy young adults is related to altered functional connectivity of brain areas implicated in insomnia disorder (Wu et al., 2020). In more detail, poor sleep quality was negatively related to the connectivity between sgACC and thalamus, with a similar association observed for the use of emotion suppression strategies. In turn, functional connectivity patterns of the left precentral and fusiform gyri, and the right middle temporal gyrus were dependent on the interactions between sleep quality and reinforcement sensitivity, with the opposite associations found in the good and poor sleepers. One of such connections, the coupling between the left precentral gyrus and posterior insula, was additionally negatively linked to trait anxiety.

Mounting evidence pinpoints the pivotal role of sgACC in the emotional dysregulation observed across different levels of sleep debt and in clinical populations (Motomura et al., 2013; Chai et al., 2023; Reimann et al., 2023). Given its role as an interface between emotional and cognitive processes (Reiman et al., 2023), the involvement of this area in emotional suppression comes as no surprise (Motomura et al., 2013). Interestingly, the results of the current study suggest that different sgACC-related pathways might be responsible for this phenomenon at different stages of emotion processing. For instance, accumulating sleep debt over 5 consecutive days was found to increase reactivity of amygdala to the emotional faces, a finding that was proportional to the decrease in amygdala's connectivity to sgACC (Motomura et al., 2013). Similarly, enhanced connectivity between these two areas after a night of total sleep deprivation was associated with better mood in healthy participants and antidepressant effects in depressed patients (Chai et al., 2023). Therefore, decreased connectivity between sgACC and amygdala appears related to an increase of the latter's emotion-generating activity. As the thalamic region identified in the current work is involved in sensorimotor functions (Fan et al., 2016), its lower connectivity with sgACC might reflect decreased propensity to act as a result of experienced emotions, providing a mechanism that could potentially partially counterbalance the increased amygdala reactivity (Goldin et al., 2008; Palmer and Alfano, 2017).

Intriguingly, the previously discussed connectivity pattern was the only one that differed between the groups based solely on sleep quality. The prevalence of the results associated with individual affective functioning speaks to the crucial role it plays in determining the impact of poor sleep on one's well-being. The connections of the right middle temporal gyrus with the left lateral prefrontal cortex, and the left fusiform gyrus with bilateral supplementary area reflect functional links between higher-order visual cortices and areas playing key role in emotion regulation (Fan et al., 2016; Morawetz et al., 2020). In turn, the coupling of the left precentral gyrus with ipsilateral posterior insula, and supramarginal and superior temporal gyri maps onto areas co-belonging to the pericentral somatosensory network (Uddin et al., 2019).

Previous neuroimaging studies have shown that the anatomy of the discussed sensory cortices mediated associations of stress and negative emotionality with worsened sleep quality (Zhang et al., 2022; Wang et al., 2021), additionally linking it with circadian phenotypes at risk of experiencing sleep problems (Zareba et al., 2022, Vulser et al., 2023). Nevertheless, higher-order cognitive processes also appear to play a vital role in the phenomenon. Through introducing deficits in attentional modulation, one night of sleep deprivation can lead to reduced visual processing capacity (Kong et al., 2011; Poh and Chee, 2017). Interestingly, in individuals with chronic poor sleep quality, the visual capabilities appear preserved, however, through compensatory reliance on other brain networks (Abdolalizadeh and Nabavi, 2022). The attentional decrements after a night of sleep deprivation have also been linked to increased subjective pain ratings with a concurrent decrease of neural reactivity to painful stimuli (Tiede et al., 2010), a pattern mirroring our functional connectivity findings (i.e., lower coupling associated with higher sensitivity to punishment). Several studies probing visual affective processing have similarly pinpointed dysregulated relationships between different components emotions and impaired brain-behavior associations following sleep deprivation (Franzen et al., 2008; Mao et al., 2024). With short-term and chronic sleep restriction sharing their effects on some aspects of emotional processing (Tempesta et al., 2015), the presented mechanisms could therefore contribute to the differential associations between neural connectivity and reinforcement sensitivity observed in good and poor sleepers in the current study.

One such connectivity pattern, the coupling of the left precentral gyrus with the left posterior insula, was negatively associated with trait anxiety. The link was clearly driven by the poor sleepers (Figure 2), in line with the previous evidence for moderating effects of sleep quality on brain-behaviour associations (Prather et al., 2013). Posterior insula is responsible for basic mapping and integration of proprioceptive information, relaying it later to the anterior insula for more advanced conscious perception (Kuehn et al., 2016). Previous studies have highlighted the particular role of both divisions of insula in emotion processing circuitry across subclinical and clinical anxiety (Zareba et al, 2024a; Wang et al., 2019; Pico-Perez et al., 2017). Higher trait anxiety has also been linked to greater increase in the reactivity of anterior insula to emotional cues following sleep deprivation (Goldstein et al., 2013). The current work extends the links between anxiety and sleep quality to the context of posterior insula. More importantly, it complements the previous research by providing evidence that the elevated levels of anxiety might be encountered predominantly in individuals with chronic sleep problems and co-occurring high sensitivity to punishment, identifying them as a group at a particularly high risk of developing mental health issues, suggesting an underlying neural mechanism.

As such, it is tempting to propose that psychological interventions altering the functioning of the insula might be an effective preventive measure for individuals at increased risk of chronic sleep disruption, for example due to shift work or inflexible school timings. Indeed, the activity of this region has recently been found to be predictive of the outcome of cognitive-behavioural therapy in anxiety-related disorders (Pico-Perez et al., 2023). Nevertheless, in the context of the current cross-sectional study, we cannot disentangle whether individual sensitivity to punishment changed as a result of poor sleep quality, or whether the baseline reinforcement sensitivity affected the sleep-related alterations in functional connectivity, posing a potential limitation to the clinical usability of the current findings. Additionally, the present work used subjective ratings of sleep quality, with previous literature suggesting discrepancies in the neural correlates between objective and subjective sleep measures (Grumbach et al., 2020). Nevertheless, due to interindividual variability in the dissipation of homeostatic sleep pressure, quantitatively similar sleep might lead to completely different levels of qualitative subjective vigourness (Mongrain et al., 2006), yielding subjective ratings a valuable and useful tool. Last but not least, it needs to be stressed out that the replicability of connectivity effects associated with interactions between sleep quality and reinforcement sensitivity was lower than for the latter's main effects. One potential explanation for such a finding might be the difference in how single

items are scored in the used questionnaires. While SPSRQ (Torrubia et al., 2001) has a binary scoring system, the approach deployed in BIS/BAS (Carver and White, 1994) permits a broader range of responses (from 1 to 4). As such, while the total scores in both measures are highly correlated with each other, the more nuanced interactions might be more difficult to observe across the two scales.

5. Conclusions

With the majority of the findings involving interactions with individual differences in positive and negative reinforcement sensitivity, the present study makes an invaluable contribution by providing evidence that affective functioning plays an essential role in determining the effects of poor sleep quality on brain connectivity and emotional health. Importantly, the discussed connectivity patterns are also separately linked to trait anxiety and the use of emotion suppression strategies, indicating that different emotional facets associated with worsened sleep quality may have distinct underlying mechanisms. This is particularly underlined by the modulating effect of sensitivity to punishment on the connection between the precentral gyrus and insula, with its coupling strength additionally associated with trait anxiety. As such, the current work increases our understanding of the links between sleep and mental health, providing a plausible mechanism for why certain individuals are more susceptible to sleep-related affective dysregulation than others (Chen et al., 2017; Minkel et al., 2012; Vargas and Lopez-Duran, 2017; Wright et al., 2007).

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Data availability

Binary masks showing the areas significantly associated with each contrast will be made available on NeuroVault after the manuscript acceptance.

CRediT author statement

MRZ: Conceptualization, Formal analysis, Writing - Original Draft, Visualisation. TD: Investigation, Writing - Review & Editing. MAPG: Investigation, Writing - Review & Editing. JAV: Investigation, Writing - Review & Editing. VC: Conceptualisation, Formal analysis, Supervision, Writing - Review & Editing. MV: Conceptualisation, Supervision, Writing - Review & Editing.

Disclosure statement

The authors report there are no competing interests to declare.

Ethical statement

All the procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Declaration of Helsinki (1975), and the applicable revisions at the time that this research was underway. Informed consent to be included in the study was obtained from all the participants. The study protocol was approved by the Universitat Jaume I Ethics Committee.

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