Original Article

Interindividual differences in mindfulness are linked to sleep-electroencephalographic characteristics

Marina Wunderlin[1,2,*], [iD] Mirjam Studler[1], Lorena R. R. Gianotti[1], Marc A. Züst[2], [iD] and Daria Knoch[1,*]

[1]Department of Social Neuroscience and Social Psychology, Institute of Psychology, University of Bern, Bern, Switzerland and
[2]University Hospital of Old Age Psychiatry and Psychotherapy, University of Bern, Bern, Switzerland

*Corresponding authors: Daria Knoch, Department of Social Neuroscience and Social Psychology, Institute of Psychology, University of Bern, Fabrikstrasse 8, 3012, Bern, Switzerland. Email: daria.knoch@unibe.ch; Marina Wunderlin, Department of Social Neuroscience and Social Psychology, Institute of Psychology, University of Bern, Fabrikstrasse 8, 3012 Bern, Switzerland. Email: marina.wunderlin@unibe.ch.

Abstract

Study Objectives: Mindfulness describes the ability to focus on the presence, including one's thoughts and feelings. Trait mindfulness—a person's inherent tendency to be mindful—has been connected to increased subjective sleep quality, but evidence from objective EEG-based sleep measures is lacking. Here, we investigate whether objective EEG-based sleep parameters explain interindividual differences in trait mindfulness.

Methods: Whole-night polysomnographic data were gathered from 52 healthy adults (27 females; age_{mean} = 21.5 [SE = 0.28]) in their homes using a portable high-density EEG device. Trait mindfulness was assessed using the Five Facet Mindfulness Questionnaire short form (FFMQ-SF).

Results: Trait mindfulness was positively correlated at trend level with the percentage of rapid eye movement (REM), but not N1, N2, or slow wave sleep. Additionally, those exhibiting less REM beta/gamma power and NREM beta power displayed higher trait mindfulness and vice versa. Lastly, we replicated findings connecting higher trait mindfulness to better subjective sleep quality.

Conclusions: REM sleep is pivotal for emotional processing. Decreased REM high-frequency activity was suggested to reflect adrenergic reduction that defuses affective experiences. Increased NREM high-frequency activity is a marker for cognitive hyperarousal in insomnia. We speculate that differences in trait mindfulness might be explained by differences in REM- and NREM-sleep functions that promote ideal emotional regulation and prevent hyperarousal.

Key words: REM sleep; high-frequency power; hyperarousal; emotion regulation; mindfulness

Graphical Abstract
Trait Mindfulness and Sleep

Aim: Investigate the association between trait mindfulness (TM) measured with the short form of the Five Facet Mindfulness Questionnaire (FFMQ-SF) and sleep-EEG characteristics.
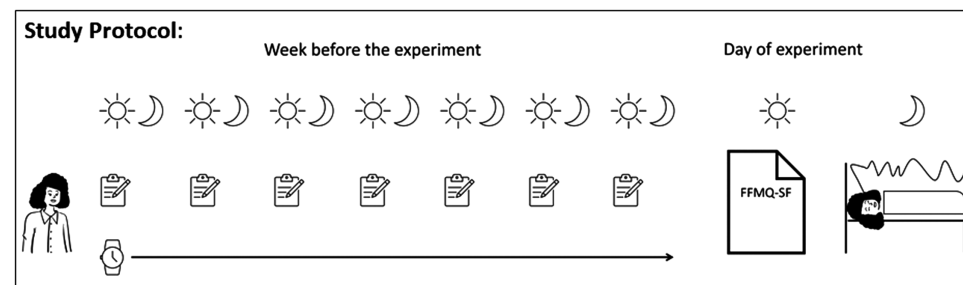
Main Results:

- TM is positively correlated with REM sleep duration.
- TM is negatively correlated with high-frequency power during REM and NREM sleep.

Statement of Significance

Research on mindfulness has increased dramatically over the past two decades, with studies linking trait mindfulness to various cognitive, emotional, and social functions. However, the role of sleep in trait mindfulness has not been clear. While some studies have suggested a clear link to subjective sleep quality, evidence from objective EEG-based sleep markers is lacking. Here, we found that interindividual differences in trait mindfulness can be attributed to interindividual differences in sleep-EEG characteristics that play a functional role in achieving optimal emotional regulation and balanced states of arousal during sleep. Our findings emphasize the importance of sleep in shaping mindfulness and highlight the potential benefits of interventions targeting specific sleep functions for fostering mental health and social functioning.

In a society characterized by increasing demands and stressors, the concept of mindfulness has gained substantial attraction regarding psychological well-being [1]. Mindfulness is defined as the ability to pay attention to and be aware of what is occurring in the present moment in a nonreactive and nonjudgmental manner [2–4]. While there is an abundant body of literature showing that mindfulness-based interventions have great health benefits [5–7], a relatively younger field of research focuses on how mindfulness as a trait—rather than a state—impacts various aspects of living. Trait mindfulness—referring to a person's inherent disposition to be mindful—has recently emerged as a crucial factor in a range of cognitive, emotional, and social functions. Those with higher trait mindfulness display increased life satisfaction and better mental health [8, 9], have more self-esteem [10], and enhanced emotion regulatory control [11, 12], whereas those with lower trait mindfulness demonstrate lower job satisfaction and performance [9] as well as increased health risk behaviors, such as smoking [13] or substance abuse [14]. In the social domain, higher trait mindfulness has been associated with increased empathy [15], prosocial behavior [16], and pro-environmental behavior [17]. This growing body of evidence is illuminating the broad and multifaceted benefits of trait mindfulness, suggesting that it is an essential skill for individuals navigating the challenges of contemporary life.

A meta-analysis demonstrated that better subjective sleep quality was linked to higher trait mindfulness [18]. The authors further investigated objective sleep parameters—measured via actigraphy—and found no significant association with trait mindfulness. However, recently, it was shown that a sleep health score, as quantified by six domains including two subjective measures and four actigraphy-based measures of sleep, namely sleep regularity, duration, timing, and efficiency, was positively associated with trait mindfulness [19]. While actigraphy offers a convenient method for tracking sleep patterns, the more reliable gold standard to measure objective sleep is polysomnography, which depends on electroencephalographic (EEG) measures of brain waves. The sleep EEG enables the determination of sleep architecture—referring to the structural organization of sleep by different sleep stages (rapid eye movement [REM] sleep and non-REM stages N1, N2, and slow wave sleep [SWS]) as well as differences in spectral power in a wide range of frequency bands. Currently, evidence connecting such objective sleep parameters to trait mindfulness is lacking.

In this study, we investigate whether objective EEG-based sleep parameters explain interindividual differences in trait mindfulness. Given that this study represents the first investigation of EEG-based sleep parameters and trait mindfulness, we refrain from formulating strong a priori hypotheses. Nonetheless, drawing upon clinical research conducted on individuals with insomnia, there are inferences we can make to postulate potential directions. These inferences are based on findings linking decreased insomnia symptoms [20] as well as higher subjectively perceived sleep quality

[18] to higher trait mindfulness. Models of insomnia suggest that hyperarousal plays a key role as a physiological mechanism in the development and persistence of sleep disturbances [21]. Studies investigating EEG spectral power in insomnia patients showed that compared to healthy controls, individuals with insomnia display increased high-frequency power in the beta and gamma range during non-REM (NREM) sleep, which has been interpreted as a biomarker of cognitive hyperarousal [22, 23]. Although most studies focus on NREM sleep, there is some evidence suggesting that REM sleep also displays increased high-frequency power in individuals with insomnia [24]. Hence, trait mindfulness might be associated with decreased high-frequency power during both REM and NREM sleep, reflecting less hyperarousal during sleep. Furthermore, with regard to sleep architecture, there is evidence for decreased REM and SWS in individuals with insomnia compared to healthy controls [25]. Hence, trait mindfulness might be associated with the duration of REM sleep and SWS, as well as their main underlying frequencies theta and slow wave activity, respectively.

In this study, we investigated whether interindividual differences in trait mindfulness as measured via a short form of the five-facet mindfulness questionnaire (FFMQ-SF) can be explained by subjective and objective measures of sleep in a homogenous group of healthy, good sleepers ($n = 52$). Polysomnographic data were recorded in participants own homes using a portable high-density EEG device. The FFMQ-SF was filled in preceding the recording. Building upon the literature in clinical populations, we explore the relationship between trait mindfulness and subjective sleep quality, sleep architecture as well as high-frequency activity and the underlying main frequencies during both REM and NREM sleep. This study expands on the previously established link between subjective sleep quality and trait mindfulness [18] by investigating underlying functions reflected in sleep EEG measures. Deepening the understanding of how sleep and mindfulness are connected might further provide new insights into mental health and social functioning.

Materials and Methods
Sample
A total of 62 healthy, right-handed participants were recruited to participate in this study. Ten participants were excluded due to insufficient quality of EEG data ($n = 6$), noncompliance to the study protocol ($n = 2$), and missing items in the Five-Facet Mindfulness Questionnaire ($n = 2$). Two additional participants were excluded from the sleep architecture analyses as interruptions in the whole-night recordings hindered the determination of exact sleep stage percentages. The final sample for analyses consisted of 52 participants (age$_{mean}$ = 21.5 (SE = 0.28), 27 female), and 50 participants regarding sleep architecture (age$_{mean}$ = 21.5 (SE = 0.29), 26 female). We specifically recruited a homogenous sample of good sleepers to maximize the chance of measuring people's normal, characteristic sleep patterns (trait), rather than sleep patterns underlying temporary conditions (state). The inclusion criteria involving sleep habits included the following requirements: good general sleep quality (Pittsburgh Sleep Quality Index [PSQI] < 5 [26]);, sleep duration of 7–8 hours/night, normal daytime sleepiness (Epworth Sleepiness Scale < 10 [27],), neutral or moderate chronotypes (Munich Chronotype Questionnaire > 2 & < 7 [28];), no history of sleep disorders, no traveling across > 2 time zones 30 days prior to the experiment, none or moderate intake of caffeine (< 5 units/day), nicotine (< 5 units/day) and alcohol (< 7 drinks/week). Women with natural hormonal cycles only participated in the study outside of their fertile phases and not within the first 2 days of their menstrual cycle. Women taking hormonal contraception only participated outside of their hormone-free interval (e.g. pill break). Other inclusion criteria encompassed right-handedness, absence of past or current neurological, psychiatric or substance abuse disorders, no regular medication intake, and normal weight. This study, which is part of a larger project, was approved by the local ethics committee and informed consent was obtained from all study participants. Full participation was rewarded with 155 Swiss francs.

Procedure
Whole-night polysomnographic data were gathered at the participants' own homes by means of a portable high-density EEG device. Participants were asked to adhere to a regular sleep–wake rhythm at their habitual bedtimes one week prior to the polysomnographic recording. They were instructed to refrain from napping during the day and to limit their caffeine and alcohol consumption to one unit per day. Adherence to this pre-experimental protocol was monitored by means of sleep diaries, consumption diaries as well as actigraphy (tri-axial accelerometer, GENEActiv, activinsights Ltd., Kimbolton, Huntingdon, UK), a device placed on the non-dominant hand of participants, measuring sleep and wake phases via motion interpretation. Prior to the recording night, participants were asked whether they regularly meditate and if so, which form of meditation they practice and at what frequency per week. To get familiar with the feeling of sleeping in their own home wearing a high-density EEG system, participants were given a mock EEG system to take home and test on their own terms prior to the recording night. In the early evening of the polysomnographic recording, participants met with members of the research group at the laboratory where they were connected to the portable high-density EEG system. While the EEG system was set up, participants filled in the FFMQ-SF. Participants were then sent home wearing the device. Shortly before their bedtime—which was determined according to the participants habitual sleep schedule—a member of the research team was tasked with visiting the participants home to ensure that the EEG signal was of good quality, to increase signal quality if needed and to start the recording. Subjective sleep quality (perceived calmness [29] and depth [30]) was assessed the following morning on a 5-point Likert scale as part of a sleep diary. Participants stopped the recordings independently in the morning and brought the EEG system back to the lab.

Assessment of trait mindfulness
Trait mindfulness was assessed via a validated 24-item short form of the Five Facet Mindfulness Questionnaire (FFMQ-SF [31, 32],). The FFMQ-SF measures average mindfulness based on 24 items belonging to one of five subscales ("Observing," "describing," "acting with awareness," "non-judging," and "non-reactivity"). The FFMQ is widely considered to be a measure of trait mindfulness [33], referring to a person's disposition to be more or less mindful.

EEG system and preprocessing
Recordings were obtained from a portable high-density EEG system (LiveAmp64, Brain Products) containing 64 channels, including three electrodes for the electrooculogram and two submental electrodes for the electromyogram measurements (actiCAP, EASYCAP). Two additional channels served as reference (Cz) and ground (AFz) electrodes. The signal was sampled at 500 Hz (third-order low pass filter at 131 Hz). Impedances were kept below 25 kΩ. Scoring of sleep stages was performed by trained

raters in accordance with standard criteria [34]. During preprocessing, the recorded signal was band-pass filtered offline between 0.5 and 40 Hz and bad channels were individually identified through visual inspection of time-frequency plots and spectrograms of the whole night. After bad channels were excluded, the remaining signals were then re-referenced to the average of all good channels. To obtain power density spectra, fast Fourier transformations were performed for each channel on continuous 5-second segments (no overlap) using Hanning tapers. For each 30-second epoch, the average over all segments was calculated. Epochs containing artifacts were excluded semi-automatically, when power values in the low (0.8–4.6 Hz) and high (20–40 Hz) frequency ranges exceeded a moving-average threshold [35, 36]. Furthermore, individual topographies for frequency ranges of interest were plotted to identify additional bad channels.

Data analysis

To analyze sleep architecture, the percentage of each sleep stage was calculated by dividing the minutes per stage by the total sleep time. The stages of interest were N1, N2, SWS, and REM. For the subjective sleep quality, the mean rating of the two sleep diary items measuring perceived sleep depth and calmness of sleep was calculated. The EEG spectral power was extracted separately for REM sleep and NREM sleep. As common in the field, we refer to stages N2 and SWS as NREM sleep, without including N1 in our analyses. Log-transformed absolute power in the beta (15–30 Hz) and gamma (30–40 Hz) range were extracted from frontal channels (mean over Fp1 and Fp2), following previous studies [24, 37, 38]. The association between trait mindfulness (FFMQ-SF score) and the sleep parameters was assessed using Pearson or Spearman correlations, depending on normal distribution or lack thereof, respectively. The Shapiro–Wilk test statistic was used to determine normal distribution. We further extracted REM and NREM-power for their respective predominant frequencies, theta (4–8 Hz) and slow wave activity (0.8–4.6 Hz). A false discovery rate (FDR) correction was applied for the correlation analyses. The FDR correction was performed on all unadjusted p-values for the analyses of interest, involving sleep architecture, high-frequency power as well as slow wave and theta power. For the Supplementary Analyses, FDR corrections were applied to the uncorrected p-values of each additional analysis separately. Lastly, since evidence suggests that meditation practice might influence sleep parameters [39–41], we additionally calculated linear regression models with meditation practice status (yes/no) as a covariate: trait mindfulness ~ sleep parameter * meditation status. As the number of meditators was relatively low ($n_{meditators} = 6$), we did not further investigate the type or frequency of meditation.

Results

Subjective sleep quality and sleep architecture

To investigate associations between subjective sleep quality and trait mindfulness, participants' subjectively perceived sleep depth and calmness of sleep were correlated with the FFMQ-SF score. Results show that subjective sleep quality was significantly and positively correlated with the FFMQ-SF score (rho = 0.44, $p < .001$, $p_{adj} = .008$, see Figure 1A), indicating that the more mindful participants are, the better they perceive their own sleep quality. We have investigated subjective sleep quality of a specific night; however, our Supplementary Analyses including the PSQI score, which assesses a more global variable of sleep quality over a 1-month time interval [26], revealed a trend-level association: The fewer self-reported issues with sleep in general, the more mindful a person is (Supplementary Information, Table S1). With regard to objective measures of sleep quality, we first investigated sleep architecture. Table 1 displays the average durations of sleep stages as a percentage of the total sleep time, as well as the sleep efficiency (= percentage of time spent asleep while lying in bed), the wake time after sleep onset and the total sleep time. Trait mindfulness was positively correlated with the percentage of REM sleep at a trend level, barely missing significance ($r = 0.34$, $p = .017$, $p_{adj} = .051$, see Figure 1B), but not the percentage of N1, N2, or SWS (all $p > .47$, see Table 2 for exact p values). Furthermore, trait mindfulness was negatively correlated at a trend level with wake time after sleep onset (rho = –0.30, $p = .036$, $p_{adj} = .09$), but was not correlated with the total sleep time, sleep efficiency, or sleep latency ($p_{adj} > .1$). See Table 2 for an overview of the results of the correlation analyses. The results suggest a trend that individuals who are more mindful may display more REM sleep as well as shorter periods spent awake during the night.

High-frequency power during REM and NREM sleep

Next, we investigated absolute spectral power in the high-frequency beta (15–30 Hz) and gamma (30-40Hz) bands for REM and NREM sleep (stages N2/SWS only) separately. During NREM sleep, beta power negatively correlated with trait mindfulness ($r = –0.38$, $p = .005$, $p_{adj} = .025$, see Figure 1C and Table 2). For NREM gamma power, we observed a similar negative association at a trend level, which did however not withstand FDR correction ($r = –0.27$, $p = .050$, $p_{adj} = .10$, see Figure 1D and Table 2). For REM sleep, we found that trait mindfulness was significantly and negatively associated with both beta and gamma power (beta: $r = –0.47$, $p < .001$, $p_{adj} = .006$, Figure 1E; gamma: $r = –0.37$, $p = .007$, $p_{adj} = .025$, Figure 1F; see Table 2). As the visual inspection of the correlation plot for REM beta power (Figure 1E) displayed a potential outlier, the analysis was repeated without the outlier and the effect remained stable ($r = –0.39$, $p = .005$, $p_{adj} = .025$). An investigation of subscales of the FFMQ revealed that the data was not driven by specific subscales (Supplementary Table S2). The here reported results are based on the mean power over Fp1 and Fp2, following previous studies. However, see also Supplementary Figure S1 for a topographic representation of correlations indicating that the results are not exclusive to local frontal channels but rather represent a global phenomenon. Overall, the results suggest that individuals with high trait mindfulness display less high-frequency power during both REM and NREM sleep—for

Table 1. Mean and SE for the Total Sleep Time, Sleep Efficiency, Sleep Latency, Wake After Sleep Onset, the Duration of Each Sleep Stage (as a Percentage of Total Sleep Time), and Subjective Sleep Quality

	Total sleep time [min]	Sleep efficiency [%]	Sleep latency [min]	Wake time after sleep onset [min]	% N1 sleep	% N2 sleep	% SWS	% REM sleep	Subjective sleep quality
Mean (SE)	435.8 (3.9)	93 (0.4)	10.2 (0.9)	22.2 (1.7)	7.8 (0.5)	46.4 (0.8)	24.5 (0.8)	21.3 (0.6)	3.1 (0.13)

Sleep efficiency refers to the time spent asleep while lying in bed. Subjective sleep quality is measured on a 5-point Likert scale where 5 indicates good sleep and 1 indicates bad sleep.
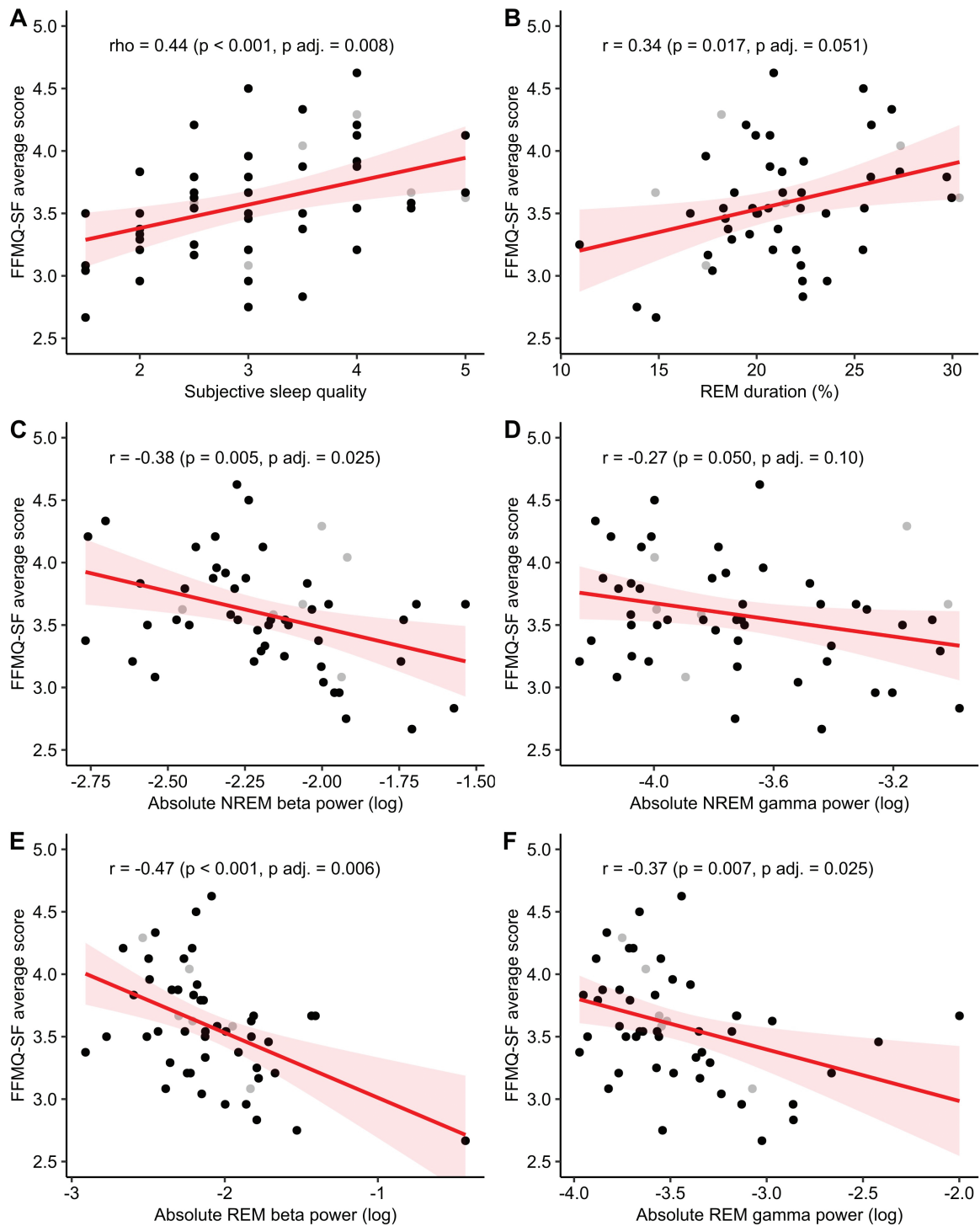
Figure 1. Correlations between trait mindfulness and various sleep measures. Trait mindfulness is depicted on the y-axis as the average score from the FFMQ-SF. The x-axis represents (**A**). the subjective sleep quality as measured on a 5-point Likert scale, (**B**) the percentage of REM sleep duration, (**C**) the absolute power in the beta band (15–30 Hz) during NREM sleep and (**E**) REM sleep, (**D**) the absolute power in the gamma band (30–40 Hz) during NREM sleep and (**F**) REM sleep. Participants who are meditators are highlighted in gray. The correlation coefficient is plotted as well as the linear fit with confidence bands. Both uncorrected and FDR-corrected P-values are displayed.

NREM sleep, this effect seems to be reduced to the lower beta band, whereas for REM sleep, both beta and gamma bands are affected.

In order to control for potential influences of meditation practice on high-frequency power during sleep [41], we re-calculated all high-frequency-based analyses using linear regression models with meditation practice status (yes/no) as a covariate. Participants who are meditators are marked in gray in the correlation plots in Figure 1. The overall models were significant for all power bands (NREM beta: F (3,48) = 3.62, $p = .020$; NREM gamma: F (3,48) = 2.81, $p = .049$; REM beta: F (3,48) = 5.58, $p = .002$; REM gamma: F (3,48) = 3.77, $p = .017$). NREM beta power ($p < .001$),

Table 2. Correlation Analyses Between FFMQ Scores and Various Sleep Variables

	r/rho	P	Adj. P
Subjective sleep quality	0.44	< .001	.008
N1 (%)	−0.10	.499	.567
N2 (%)	−0.10	.493	.567
SWS (%)	−0.11	.466	.567
REM (%)	0.34	.017	.051
Total sleep time (min)	0.26	.069	.128
Wake time after sleep onset (min)	−0.30	.036	.089
Sleep efficiency (%)	0.23	.102	.171
Sleep latency (min)	−0.05	.741	.741
REM-gamma (log)	−0.37	.007	.025
REM-beta (log)	−0.47	< .001	.006
REM-theta (log)	−0.21	.131	.197
NREM-gamma (log)	−0.27	.050	.108
NREM-beta (log)	−0.38	.005	.025
NREM SWA (log)	−0.09	.529	.567

Both uncorrected as well as FDR-corrected *p*-values are depicted. Significant and trend-level (FDR-adjusted) *p*-values and the respective sleep variables are highlighted in italics. The FDR correction was performed on all unadjusted *p*-values depicted in this table. The high-frequency power and the percentage of REM sleep were not associated with the subjective sleep quality (*Supplementary Material, Table S3*) and the high-frequency power was not associated with the number/duration of awakenings (*Supplementary Material, Table S4*).

REM beta power (*p* = .001) and REM gamma power (*p* = .017) significantly predicted trait mindfulness, while meditation status did not (*p* = .292, *p* = .198 and *p* = .120, respectively*). NREM gamma power also significantly predicted trait mindfulness (*p* = .011) but here, meditation status exhibited a trend-level influence as well (*p* = .063), partially masking the effect of NREM gamma power on mindfulness in a simple correlation (Figure 1D).

To investigate whether trait mindfulness was exclusively associated with the high-frequency bands > 15 Hz, we next analyzed NREM and REM sleep according to their respective predominant frequency bands. For NREM sleep the predominantly occurring frequency band is slow wave activity (0.8–4.6Hz) while for REM sleep it is theta (4–8 Hz) activity. Neither NREM slow wave power nor REM theta power were associated with trait mindfulness (both *p* > .13, see Table 2 for exact *p*-values), even when controlling for meditation status (*p*_slowwave = .146 and *p*_theta = .504).

Discussion

In this paper, we set out to explain interindividual differences in trait mindfulness by interindividual differences in objective sleep parameters. We showed that in a homogenous group of healthy good sleepers, individuals with higher trait mindfulness display better subjective sleep quality, a trend towards more REM sleep, as well as significantly lower high-frequency power during both NREM and REM sleep. We have replicated previous findings connecting higher trait mindfulness to better subjective sleep quality [18, 42] and we provide evidence linking differences in EEG-based objective sleep parameters to interindividual differences in trait mindfulness.

High-frequency power during sleep has been described as a reflection of cortical hyperarousal in insomnia disorder [21]. Our finding that trait mindfulness was negatively associated with high-frequency power during NREM and REM sleep is in line with the hyperarousal hypothesis, suggesting that particularly mindful individuals might express sleep that is less disturbed by hyperarousal. We did not observe any relationship between trait mindfulness and slow wave power during NREM sleep—a proxy for sleep depth. This suggests that NREM sleep might not per se be deeper, but that more mindful individuals display mechanisms that potentially prevent the brain from over-stimulating. Our results suggest that even among healthy, good sleepers without overt disturbances, subtle variations in hyperarousal exist. Unlike in individuals with insomnia, the presence of hyperarousal in this context does not imply concrete sleep disruptions. Instead, it suggests a continuum of sleep hyperarousal that can be explained by differences in trait mindfulness.

Our finding demonstrates that more mindful individuals tend to display more REM sleep links to the function of REM sleep in emotional regulation [43]. Selectively depriving participants of REM sleep has been shown to heighten negative affect following sleep and increase amygdala responses to stressful situations [44], indicating that REM sleep enables optimal emotional control. Studies investigating potential mechanisms revealed that high-frequency power during REM sleep was a proxy for central adrenergic activity, commonly connected to stress or arousal [43]. In one study, participants rated the intensity of emotional stimuli while in an fMRI scanner, both prior to and post-sleep [37]. The authors found a correlation between REM gamma activity and overnight changes in emotional ratings and amygdala activity. Participants with the lowest REM gamma activity conveyed the largest overnight reduction in both amygdala activity and the ratings of emotional intensity [37]. This indicates that a decrease in REM gamma power might display a mechanism to defuse affective experiences on both the neuronal and behavioral levels. Trait mindfulness has been associated with increased emotional regulation and decreased amygdala activity during emotionally salient tasks [11, 12]. In our data, those who are more mindful expressed the least amount of REM high-frequency power. Hence, interindividual differences in trait mindfulness might be explained by differences in emotional regulation—particularly mediated through sleep functions.

The literature on high-frequency power during NREM sleep shows a somewhat paradoxical finding that increased high-frequency power can both be an indicator of hyperarousal in individuals with insomnia [21], and also of increased sustained cognitive control in extremely trained meditators [41]. Hence, in both cases, NREM sleep displays high-frequency power, but whether this is assessed as adaptive arousal (cognitive control in expert meditators) or maladaptive hyperarousal (agitation in individuals with insomnia) might be determined by other mediating factors. In the data analyzed here, we did not observe any marked differences in effects when adding meditation status ($n = 6$) as a covariate, but the shift in the NREM gamma band from a strong trend (uncorrected $p = .05$) to a significant effect in the regression analysis corrected for meditation status ($p.=011$) indicated that meditation practice might indeed mask the strength of the effect in the NREM-gamma band. Overall, the number of meditators in our sample is too small to sensibly investigate differences in how trait mindfulness and high-frequency power might be differentially associated between non-meditators and meditators.

SWS is considered to have a significant impact on the brain's restorative functions [45]. It was suggested that meditation—as a mindfulness-related concept—can increase slow-wave activity through plastic changes associated with the utilization of mental training and focused attention [39, 40]. Here, we found that trait mindfulness was not associated with slow wave activity or SWS duration. In our analyses on slow wave power, we controlled for meditation practice and the model remained insignificant. Although the underlying concepts of meditation and mindfulness might be linked, it is important to note that we investigated mindfulness as a trait, which is different from (although not unrelated to) mindfulness or meditation practice (state). While mindfulness as a trait might be exclusively associated with REM sleep, mindfulness as a state ("applied mindfulness") might impact SWS and slow wave power through use-dependent plastic changes.

An important limitation of this study is that our analyses are of correlational nature. This means that we cannot establish the causality of the observed effects. It is possible that superior REM and NREM functions have contributed to the development of higher trait mindfulness. Conversely, it could also be the case that individuals with higher trait mindfulness have improved REM and NREM functions due to their inherent disposition to be mindful. Although we investigated mindfulness as a trait, research suggests close links to mindfulness as a state. For instance, long-term mindfulness-based interventions have the potential to increase trait mindfulness—albeit only moderately [46]. With current advances in the field of noninvasive brain stimulation during sleep [47], future research might gain more insight into the causality of the relationship between mindfulness and sleep functions. For instance, one might use noninvasive brain stimulation to modulate REM sleep, or high-frequency power and investigate how mindfulness assessments change. In the opposite direction, it could be investigated how moderate changes in trait mindfulness over a period of time might relate to changes in sleep architecture or in the sleep power spectrum. However, the literature on the effects of mindfulness-based interventions on EEG-based sleep markers is limited and yields inconsistent results [48, 49]. It poses an intriguing avenue for future research to explore whether mindfulness as a state and trait mindfulness exert interacting effects on sleep, potentially explaining some of the inconsistencies from previous studies. It could be the case for instance, that mindfulness-based interventions improve sleep more in those who already display high trait mindfulness. The opposite is also possible, that those with lower trait mindfulness might exhibit more potential to increase their subjective and objective sleep quality by means of mindfulness-based interventions. However, at this point, these ideas remain speculative. Lastly, future research could explore the potential mediating role of mindfulness-related concepts, such as self-control.

The findings of this study contribute to an emerging field of research demonstrating the link between trait mindfulness and various aspects of living. Here, we expand on the link between subjective sleep quality and trait mindfulness [18] by demonstrating how interindividual differences in objectively measured sleep parameters and functions account for interindividual differences in trait mindfulness. This novel link between objective sleep markers and trait mindfulness highlights the potential significance of sleep functions in shaping trait mindfulness. We speculate that optimized REM and NREM functions enable ideal emotional regulation and balanced states of arousal, which opens emotional and cognitive capacities to be more mindful. As sleep-related issues are becoming exceedingly common in the general population [50], prioritizing sleep health is of considerable importance. Optimizing REM and NREM sleep functions to better regulate emotions and arousal may have a beneficial impact on promoting mindfulness and might exert a transformative influence on mental health and social functioning.

Supplementary material

Supplementary material is available at *SLEEP* online.

Acknowledgment

Disclosure statement

Author contributions

D.K., L.R.R.G., and M.S. designed the study. M.S. collected data. M.S., L.R.R.G., and M.W. analyzed the data. M.Z. provided methodological support. M.W. drafted the outline and first version of the manuscript. All of the authors discussed the results and provided critical revision of the manuscript and final approval. M.W. and M.S. contributed equally to this work.

Data availability

The dataset analyzed in the present study as well as scripting and plotting code are available from the corresponding authors via email on reasonable request.

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