

# Interindividual differences in mindfulness are linked to sleep-EEG characteristics.

Wunderlin, M.<sup>1,2\*</sup>, Studler, M.<sup>1\*</sup>, Gianotti, L.R.R.<sup>1</sup>, Züst, M.A.<sup>2</sup>, Knoch, D.<sup>1</sup>

<sup>1</sup>Department of Social Neuroscience and Social Psychology, Institute of Psychology, University of Bern, Fabrikstrasse 8, Bern 3012, Switzerland.

<sup>2</sup>University Hospital of Old Age Psychiatry and Psychotherapy, University of Bern, Bolligenstrasse 111, 3000 Bern 60, Switzerland.

\*Shared first authors

Corresponding

Daria Knoch (daria.knoch@unibe.ch); Marina Wunderlin (marina.wunderlin@unibe.ch)

University of Bern

Institute of Psychology

Department of Social Neuroscience and Social Psychology

Fabrikstrasse 8

3012 Bern / Switzerland

© The Author(s) 2024. Published by Oxford University Press on behalf of Sleep Research Society. This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact [reprints@oup.com](mailto:reprints@oup.com) for reprints and translation rights for reprints. All other permissions can be obtained through our RightsLink service via the Permissions link on the article page on our site—for further information please contact [journals.permissions@oup.com](mailto:journals.permissions@oup.com).

## 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<sub>mean</sub> = 21.5 (SE = 0.28)) in their home 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 REM, but not N1, N2 or SWS. 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.

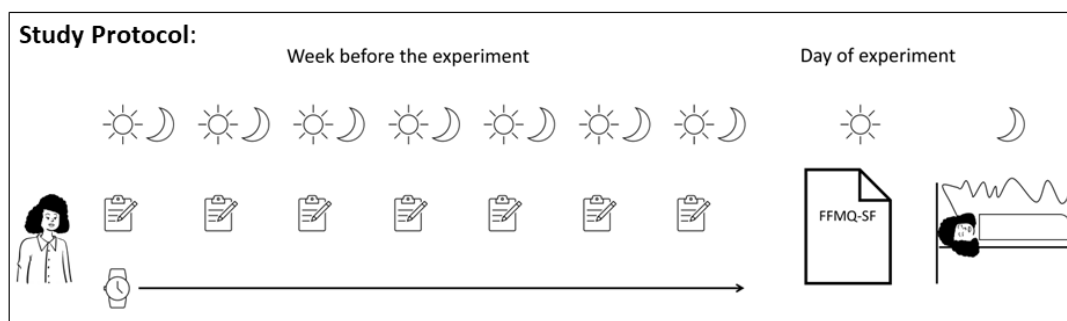
**Conclusions:** REM sleep is pivotal for emotional processing. Decreased REM high-frequency activity was suggested to reflect adrenergic reduction that defuses affective experiences. Increased NREM high-frequency activity is a marker for cognitive hyperarousal in insomnia. We speculate that differences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

Keywords: 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.

Accepted Manuscript

## 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.

Accepted Manuscript

## Introduction

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 in 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 for mental health and social functioning.

## **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), non-compliance 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<sub>mean</sub> = 21.5 (SE = 0.28), 27 female), and 50 participants regarding sleep architecture (age<sub>mean</sub> = 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. On 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 sub-scales (“Observing”, “describing”, “acting with awareness”, “non-judging”, “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 500Hz (third order low pass filter at 131Hz). Impedances were kept below 25 k $\Omega$ . Scoring of sleep stages was performed by trained raters in accordance with standard criteria [34]. During pre-processing, the recorded signal was band-pass filtered offline between 0.5 and 40Hz 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 artefacts were excluded semi-automatically, when power values in the low (0.8-4.6Hz) and high (20-40Hz) 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 (15-30Hz) and gamma (30-40Hz) 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 (4-8Hz) and slow wave activity (0.8-4.6Hz). 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 ( $n_{\text{meditators}} = 6$ ), 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 was correlated with the FFMQ-SF score. Results show that subjective sleep quality was significantly and positively correlated with the FFMQ-SF score ( $\rho = 0.44$ ,  $p < .001$ ,  $p_{\text{adj}} = 0.008$ , 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 one-month time interval [26], revealed a trend-level association: The fewer self-reported issues with sleep in general, the more mindful a person is (see 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 ( $r = 0.34, p = .017, p_{adj} = 0.051$ , see figure 1B), but not the percentage of N1, N2 or SWS (all  $p > 0.47$ , see table 2 for exact  $p$  values). Furthermore, trait mindfulness was negatively correlated at a trend-level with wake time after sleep onset ( $\rho = -0.30, p = .036, p_{adj} = 0.09$ ), but was not correlated with the total sleep time, sleep efficiency or sleep latency ( $p_{adj} > 0.1$ ). 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.

Please insert table 1 here

### **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,  $p_{adj} = 0.025$ , 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 ( $r = -0.27$ ,  $p = .050$ ,  $p_{adj} = 0.10$ , 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:  $r = -0.47$ ,  $p < .001$ ,  $p_{adj} = 0.006$ , figure 1E; gamma:  $r = -0.37$ ,  $p = .007$ ,  $p_{adj} = 0.025$ , 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 ( $r = -0.39$ ,  $p = .005$ ,  $p_{adj} = 0.025$ ). An investigation of subscales of the FFMQ revealed that the data was not driven by specific subscales (see supplementary material, table S2). The here reported results are based on the mean power over Fp1 and Fp2, following previous studies. However, see also the supplementary information 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 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 grey 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 ( $p < .001$ ), REM beta power ( $p = .001$ ) and REM gamma power ( $p = .017$ ) significantly predicted trait mindfulness, while meditation status did not ( $p = 0.292$ ,  $p = 0.198$  and  $p = 0.120$ , 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 (see 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 (4-8Hz) activity. Neither NREM slow wave power nor REM theta power were associated with trait mindfulness (both  $p > 0.13$ , see table 2 for exact  $p$ -values), even when controlling for meditation status ( $p_{slowwave} = 0.146$  and  $p_{theta} = 0.504$ ).

Please insert figure 1 here

Please insert table 2 here

## 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 demonstrating 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 increased 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 the emotional ratings and the amygdala activity. Participants with the lowest REM gamma activity conveyed the largest over-night reduction in both amygdala activity and in 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 level. Trait mindfulness has been

associated with increased emotional regulation and with 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], but 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 within 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 intervention have the potential to increase trait mindfulness – albeit only moderately [46]. With current advances in the field of non-invasive 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 non-invasive 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 that 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.

## **Acknowledgment**

We thank G. Bernasconi, A. Blandenier, A. Cao, J. Forney, F. Hasler, N. Heutschi, N. Luzi, A. Minder, N. Romero, N. Ruch, M. Widmer, J. Wiedmer and R. Wyer for their help in data acquisition.

## **Disclosure Statement**

**Financial Disclosure:** This work was supported by a grant from the Typhaine Foundation awarded to DK.

**Non-financial Disclosure:** none

## **Author Contributions**

DK, LRRG and MS designed the study. MS collected data. MS, LRRG, and MW analyzed the data. MZ provided methodological support. MW 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. MW and MS 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.

## Reference List

- [1] Zandi H, Amirinejad A, Azizifar A, Aibod S, Veisani Y, Mohamadian F. The effectiveness of mindfulness training on coping with stress, exam anxiety, and happiness to promote health. *J Educ Health Promot* 2021;10:177. [https://doi.org/10.4103/jehp.jehp\\_616\\_20](https://doi.org/10.4103/jehp.jehp_616_20).
- [2] Black DS. A brief definition of mindfulness. *Behav Neurosci* 2011;7:109.
- [3] Brown KW, Ryan RM. Perils and Promise in Defining and Measuring Mindfulness: Observations From Experience. *Clin Psychol Sci Pract* 2004;11:242–8. <https://doi.org/10.1093/clipsy.bph078>.
- [4] Kabat-Zinn J. *Full Catastrophe Living: Using the Wisdom of Your Body and Mind to Face Stress, Pain, and Illness*. Delacorte Press; 1990.
- [5] Creswell JD. Mindfulness Interventions. *Annu Rev Psychol* 2017;68:491–516. <https://doi.org/10.1146/annurev-psych-042716-051139>.
- [6] de Vibe M, Bjørndal A, Tipton E, Hammerstrøm K, Kowalski K. Mindfulness Based Stress Reduction (MBSR) for Improving Health, Quality of Life, and Social Functioning in Adults. *Campbell Syst Rev* 2012;8:1–127. <https://doi.org/10.4073/csr.2012.3>.
- [7] Kabat-Zinn J. Mindfulness-Based Interventions in Context: Past, Present, and Future. *Clin Psychol Sci Pract* 2003;10:144–56. <https://doi.org/10.1093/clipsy.bpg016>.
- [8] Brown KW, Ryan RM. The benefits of being present: Mindfulness and its role in psychological well-being. *J Pers Soc Psychol* 2003;84:822–48. <https://doi.org/10.1037/0022-3514.84.4.822>.
- [9] Mesmer-Magnus J, Manapragada A, Viswesvaran C, Allen JW. Trait mindfulness at work: A meta-analysis of the personal and professional correlates of trait mindfulness. *Hum Perform* 2017;30:79–98. <https://doi.org/10.1080/08959285.2017.1307842>.
- [10] Randal C, Pratt D, Bucci S. Mindfulness and Self-esteem: A Systematic Review. *Mindfulness* 2015;6:1366–78. <https://doi.org/10.1007/s12671-015-0407-6>.
- [11] Tomlinson ER, Yousaf O, Vittersø AD, Jones L. Dispositional Mindfulness and Psychological Health: a Systematic Review. *Mindfulness* 2018;9:23–43. <https://doi.org/10.1007/s12671-017-0762-6>.
- [12] Wheeler MS, Arnkoff DB, Glass CR. The Neuroscience of Mindfulness: How Mindfulness Alters the Brain and Facilitates Emotion Regulation. *Mindfulness* 2017;8:1471–87. <https://doi.org/10.1007/s12671-017-0742-x>.
- [13] Black DS, Sussman S, Johnson CA, Milam J. Trait Mindfulness Helps Shield Decision-making From Translating Into Health-risk Behavior. *J Adolesc Health Off Publ Soc Adolesc Med* 2012;51:588–92. <https://doi.org/10.1016/j.jadohealth.2012.03.011>.
- [14] Karyadi KA, VanderVeen JD, Cyders MA. A meta-analysis of the relationship between trait mindfulness and substance use behaviors. *Drug Alcohol Depend* 2014;143:1–10. <https://doi.org/10.1016/j.drugalcdep.2014.07.014>.
- [15] Vilaverde RF, Correia AI, Lima CF. Higher trait mindfulness is associated with empathy but not with emotion recognition abilities. *R Soc Open Sci* 2020;7:192077. <https://doi.org/10.1098/rsos.192077>.
- [16] Donald JN, Sahdra BK, Van Zanden B, Duineveld JJ, Atkins PWB, Marshall SL, et al. Does your mindfulness benefit others? A systematic review and meta-analysis of the link between mindfulness and prosocial behaviour. *Br J Psychol* 2019;110:101–25. <https://doi.org/10.1111/bjop.12338>.
- [17] Colombo SL, Chiarella SG, Raffone A, Simone L. Understanding the Environmental Attitude-Behaviour Gap: The Moderating Role of Dispositional Mindfulness. *Sustainability* 2023;15:7285. <https://doi.org/10.3390/su15097285>.
- [18] Sala M, Rochefort C, Lui PP, Baldwin AS. Trait mindfulness and health behaviours: a meta-analysis. *Health Psychol Rev* 2020;14:345–93. <https://doi.org/10.1080/17437199.2019.1650290>.

- [19] Xie EB, Sedov ID, Sanguino H, Freeman M, Kumari J, Tomfohr-Madsen L. Trait mindfulness and sleep: Interactions between observing and nonreactivity in the association with sleep health. *Health Psychol Open* 2023;10:20551029221149282. <https://doi.org/10.1177/20551029221149282>.
- [20] Garland SN, Campbell T, Samuels C, Carlson LE. Dispositional mindfulness, insomnia, sleep quality and dysfunctional sleep beliefs in post-treatment cancer patients. *Personal Individ Differ* 2013;55:306–11. <https://doi.org/10.1016/j.paid.2013.03.003>.
- [21] Riemann D, Spiegelhalder K, Feige B, Voderholzer U, Berger M, Perlis M, et al. The hyperarousal model of insomnia: A review of the concept and its evidence. *Sleep Med Rev* 2010;14:19–31. <https://doi.org/10.1016/j.smr.2009.04.002>.
- [22] Perlis ML, Smith MT, Andrews PJ, Orff H, Giles DE. Beta/Gamma EEG activity in patients with primary and secondary insomnia and good sleeper controls. *Sleep* 2001;24:110–7. <https://doi.org/10.1093/sleep/24.1.110>.
- [23] Spiegelhalder K, Regen W, Feige B, Holz J, Piosczyk H, Baglioni C, et al. Increased EEG sigma and beta power during NREM sleep in primary insomnia. *Biol Psychol* 2012;91:329–33. <https://doi.org/10.1016/j.biopsycho.2012.08.009>.
- [24] Zhao W, Van Someren EJW, Li C, Chen X, Gui W, Tian Y, et al. EEG spectral analysis in insomnia disorder: A systematic review and meta-analysis. *Sleep Med Rev* 2021;59:101457. <https://doi.org/10.1016/j.smr.2021.101457>.
- [25] Baglioni C, Regen W, Teghen A, Spiegelhalder K, Feige B, Nissen C, et al. Sleep changes in the disorder of insomnia: A meta-analysis of polysomnographic studies. *Sleep Med Rev* 2014;18:195–213. <https://doi.org/10.1016/j.smr.2013.04.001>.
- [26] Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Res* 1989;28:193–213. [https://doi.org/10.1016/0165-1781\(89\)90047-4](https://doi.org/10.1016/0165-1781(89)90047-4).
- [27] Johns MW. A new method for measuring daytime sleepiness: the Epworth sleepiness scale. *Sleep* 1991;14:540–5. <https://doi.org/10.1093/sleep/14.6.540>.
- [28] Roenneberg T, Wirz-Justice A, Meroo M. Life between clocks: daily temporal patterns of human chronotypes. *J Biol Rhythms* 2003;18:80–90. <https://doi.org/10.1177/0748730402239679>.
- [29] Åkerstedt T, Hume K, Minors D, Waterhouse J. The Subjective Meaning of Good Sleep, An Intraindividual Approach Using the Karolinska Sleep Diary. *Percept Mot Skills* 1994;79:287–96. <https://doi.org/10.2466/pms.1994.79.1.287>.
- [30] Görtelmeyer R. SF-A/R und SF-B/R : Schlafragebogen A und B. Göttingen: Hogrefe; 2011.
- [31] Baer RA, Smith GT, Hopkins J, Krietemeyer J, Toney L. Using Self-Report Assessment Methods to Explore Facets of Mindfulness. *Assessment* 2006;13:27–45. <https://doi.org/10.1177/1073191105283504>.
- [32] Bohlmeijer E, ten Klooster PM, Fledderus M, Veehof M, Baer R. Psychometric Properties of the Five Facet Mindfulness Questionnaire in Depressed Adults and Development of a Short Form. *Assessment* 2011;18:308–20. <https://doi.org/10.1177/1073191111408231>.
- [33] Truong QC, Krägeloh CU, Siegert RJ, Landon J, Medvedev ON. Applying Generalizability Theory to Differentiate Between Trait and State in the Five Facet Mindfulness Questionnaire (FFMQ). *Mindfulness* 2020;11:953–63. <https://doi.org/10.1007/s12671-020-01324-7>.
- [34] Berry RB, Albertario C, Harding S. Manual for the Scoring of Sleep and associated Events: Rules, Terminology and Technical Specifications. *Am Acad Sleep Med* 2018;2.5:1689–99.
- [35] Buckelmüller J, Landolt H-P, Stassen HH, Achermann P. Trait-like individual differences in the human sleep electroencephalogram. *Neuroscience* 2006;138:351–6. <https://doi.org/10.1016/j.neuroscience.2005.11.005>.
- [36] Studler M, Gianotti LRR, Koch K, Hausfeld J, Tarokh L, Maric A, et al. Local slow-wave activity over the right prefrontal cortex reveals individual risk preferences. *NeuroImage* 2022;253:119086. <https://doi.org/10.1016/j.neuroimage.2022.119086>.

- [37] van der Helm E, Yao J, Dutt S, Rao V, Saletin JM, Walker MP. REM sleep de-potentiates amygdala activity to previous emotional experiences. *Curr Biol CB* 2011;21:2029–32. <https://doi.org/10.1016/j.cub.2011.10.052>.
- [38] Tinguely G, Finelli LA, Landolt H-P, Borbély AA, Achermann P. Functional EEG topography in sleep and waking: State-dependent and state-independent features. *NeuroImage* 2006;32:283–92. <https://doi.org/10.1016/j.neuroimage.2006.03.017>.
- [39] Chiesa A, Serretti A. A systematic review of neurobiological and clinical features of mindfulness meditations. *Psychol Med* 2010;40:1239–52. <https://doi.org/10.1017/S0033291709991747>.
- [40] Dentico D, Ferrarelli F, Riedner BA, Smith R, Zennig C, Lutz A, et al. Short Meditation Trainings Enhance Non-REM Sleep Low-Frequency Oscillations. *PLoS One* 2016;11:e0148961. <https://doi.org/10.1371/journal.pone.0148961>.
- [41] Ferrarelli F, Smith R, Dentico D, Riedner BA, Zennig C, Benca RM, et al. Experienced Mindfulness Meditators Exhibit Higher Parietal-Occipital EEG Gamma Activity during NREM Sleep. *PLOS ONE* 2013;8:e73417. <https://doi.org/10.1371/journal.pone.0073417>.
- [42] Howell AJ, Digdon NL, Buro K, Sheptycki AR. Relations among mindfulness, well-being, and sleep. *Personal Individ Differ* 2008;45:773–7. <https://doi.org/10.1016/j.paid.2008.08.005>.
- [43] Walker MP, van der Helm E. Overnight therapy? The role of sleep in emotional brain processing. *Psychol Bull* 2009;135:731–48. <https://doi.org/10.1037/a0016570>.
- [44] Glosemeyer RW, Diekelmann S, Cassel W, Kesper K, Koehler U, Westermann S, et al. Selective suppression of rapid eye movement sleep increases next-day negative affect and amygdala responses to social exclusion. *Sci Rep* 2020;10:17325. <https://doi.org/10.1038/s41598-020-74169-8>.
- [45] Léger D, Debellemanniere E, Rabat A, Bayon V, Benchenane K, Chennaoui M. Slow-wave sleep: From the cell to the clinic. *Sleep Med Rev* 2018;41:113–32. <https://doi.org/10.1016/j.smrv.2018.01.008>.
- [46] Kiken LG, Garland EL, Bluth K, Palsson OS, Gaylord SA. From a state to a trait: Trajectories of state mindfulness in meditation during intervention predict changes in trait mindfulness. *Personal Individ Differ* 2015;81:41–6. <https://doi.org/10.1016/j.paid.2014.12.044>.
- [47] Fehér KD, Wunderlin M, Maier JG, Hertenstein E, Schneider CL, Mikutta C, et al. Shaping the slow waves of sleep: A systematic and integrative review of sleep slow wave modulation in humans using non-invasive brain stimulation. *Sleep Med Rev* 2021;58:101438. <https://doi.org/10.1016/j.smrv.2021.101438>.
- [48] Britton WB, Haynes PL, Fridel KW, Bootzin RR. Polysomnographic and subjective profiles of sleep continuity before and after mindfulness-based cognitive therapy in partially remitted depression. *Psychosom Med* 2010;72:539–48. <https://doi.org/10.1097/PSY.0b013e3181dc1bad>.
- [49] Wong KF, Perini F, Lin J, Goldstein M, Ong JL, Lo J, et al. Dissociable changes in sleep architecture with mindfulness and sleep hygiene intervention in older adults: Secondary and exploratory analysis of polysomnography data from the Mindfulness Sleep Therapy (MIST) trial. *Sleep Health* 2022;8:364–72. <https://doi.org/10.1016/j.sleh.2022.02.003>.
- [50] Ohayon MM. Epidemiological Overview of sleep Disorders in the General Population. *Sleep Med Res* 2011;2:1–9. <https://doi.org/10.17241/smr.2011.2.1.1>.

*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 (15-30Hz) during NREM sleep and **E.** REM sleep, **D.** the absolute power in the gamma band (30-40Hz) during NREM sleep and **F.** REM sleep. Participants who are meditators are highlighted in grey. The correlation coefficient is plotted as well as the linear fit with confidence bands. Both uncorrected and FDR-corrected p-values are displayed.*

Accepted Manuscript



	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)

**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.

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.

Accepted Manuscript



	r/rho	p	Adj. p
<b>Subj. sleep quality</b>	0.44	< .001	<b>0.008</b>
N1 (%)	-0.10	0.499	0.567
N2 (%)	-0.10	0.493	0.567
SWS (%)	-0.11	0.466	0.567
<b>REM (%)</b>	0.34	0.017	<b>0.051</b>
Total Sleep Time (min)	0.26	0.069	0.128
<b>Wake time after sleep onset (min)</b>	-0.30	0.036	<b>0.089</b>
Sleep Efficiency (%)	0.23	0.102	0.171
Sleep Latency (min)	-0.05	0.741	0.741
<b>REM-Gamma (log)</b>	-0.37	0.007	<b>0.025</b>
<b>REM-Beta (log)</b>	-0.47	< .001	<b>0.006</b>
REM-Theta (log)	-0.21	0.131	0.197
NREM-Gamma (log)	-0.27	0.050	0.108
<b>NREM-Beta (log)</b>	-0.38	0.005	<b>0.025</b>
NREM SWA (log)	-0.09	0.529	0.567

**Table 2.** Correlation analyses between FFMQ scores and various sleep variables. Both uncorrected as well as FDR-corrected p-values are depicted. Significant and trend-level (FDR-adjusted) p-values and the respective sleep variable are highlighted in bold. The FDR correction was performed on all unadjusted p-values depicted in this table. The high-frequency power and the percentage REM sleep were not associated with the subjective sleep quality (see supplementary material, table S3) and the high-frequency power was not associated with the number/duration of awakenings (see supplementary material, table S4).

Figure 1

