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Original Article

# Unaltered EEG spectral power and functional connectivity in REM microstates in frequent nightmare recallers: are nightmares really a REM parasomnia?

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ABSTRACT

*Background:* Frequent nightmares show signs of hyperarousal in NREM sleep. Nevertheless, idiopathic nightmare disorder is considered a REM parasomnia, but the pathophysiology of REM sleep in relation to frequent nightmares is controversial. Cortical oscillatory activity in REM sleep is largely modulated by phasic and tonic REM periods and seems to be linked to different functions and dysfunctions of REM sleep. Here, we examined cortical activity and functional synchronization in frequent nightmare recallers and healthy controls, during phasic and tonic REM.
*Methods:* Frequent nightmare recallers ($N = 22$) and healthy controls ($N = 22$) matched for high dream recall spent two nights in the laboratory. Phasic and tonic REM periods from the second nights' recordings were selected to examine differences in EEG spectral power and weighted phase lag index (WPLI) across groups and REM states.
*Results:* Phasic REM showed increased power and synchronization in delta and gamma frequency bands, whereas tonic REM featured increased power and synchronization in the alpha and beta bands. In the theta band, power was higher during tonic, and synchronization was higher during phasic REM sleep. No differences across nightmare and control participants or patterns representing interactions between the groups and REM microstates emerged.
*Conclusions:* Our findings do not support the idea that abnormal REM sleep power and synchronization play a role in the pathophysiology of frequent nightmares. Altered REM sleep in nightmare disorder could have been confounded with comorbid pathologies and increased dream recall, or might be linked to more specific state factors (nightmare episodes).



## 1. Introduction

Frequent nightmares, that is, the weekly experience of highly unpleasant dreams during the night, affect approximately five percent of the general population [1–3], and are associated with a wide range of psychopathological factors [3–5]. The prevalence of frequent nightmares is strikingly high in populations with psychiatric conditions, including psychotic states [6,7], personality disorders [8], suicidal tendencies [9], and most prominently posttraumatic stress disorder (PTSD) [10]. The severity of nightmare complaints are rarely considered in clinical settings [11], despite the observations that nightmare frequency is linked to more adverse psychopathological profiles [12,13], and that targeted treatment of nightmares seems to ameliorate daytime functioning as well [13]. Furthermore, the diagnostic and treatment protocols of nightmare disorder are exclusively based on self-report questionnaires, which consider only the subjective level of abnormal oneiric

*Abbreviations:* PTSD, posttraumatic stress disorder; EEG, electroencephalography; RBD, REM behavior disorder; NM, nightmare; PSG, polysomnography; ICA, independent component analysis; FFT, fast Fourier transformation; WPLI, weighted phase lag index; PLS, partial least squares; LV, latent variable.

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experiences, thereby precluding a more complex understanding of the etiology and neural correlates of nightmare disorder.

Nightmares are also common in patients with different sleep disorders [14], and their frequency correlates with sleep quality in the general population [3,15], suggesting that having frequent nightmares might be linked to altered sleep neurophysiology. In fact, a recent focus on the neurophysiological correlates of frequent nightmares highlighted the relevance of such factors in nightmare disorder regardless the influence of comorbid psychopathologies [16]. For instance, frequent nightmare recallers compared to control participants were characterized by increased arousal-related cortical activity [17] and enhanced high frequency electroencephalographic (EEG) oscillations during NREM sleep [18,19]. Altered arousal-related activity was more pronounced during state transitions between NREM to REM sleep [18,20,21], indicating that transitory sleep periods facilitating microarousals, micro-awakenings, and sleep interruptions might be specifically disrupted in individuals with frequent nightmares. Other studies revealed altered sleep spindling in frequent nightmare recallers compared to healthy controls, suggesting abnormalities in thalamocortical networks supporting memory processes during NREM sleep [22].

Interestingly, neurophysiological REM sleep features associated with frequent nightmares are less consistent than those reported for NREM sleep. Nevertheless, a few studies indicate that altered neurophysiological activity might also take place during the REM phase. Individuals with frequent nightmares showed increased REM spectral power between 10–14.5 Hz and 3–4 Hz, termed as "high-alpha" and "high-delta" activity, respectively [23]. Only the latter was replicated, however. Still, this increase in high delta power was observed in NREM sleep and wakefulness as well, and interpreted as a sign of increased emotional memory processing in frequent nightmare recallers [19].

Nevertheless, one possible confounder in these studies is dream recall, which is usually higher in participants with frequent nightmares [24], and is associated with a partially overlapping set of EEG features both during NREM and REM sleep [25–27]. Interestingly, a recent study that took the confounding factor of dream recall into consideration detected pronounced differences across the nightmare and control group respect to NREM EEG power, but no differences emerged for REM sleep [18]. Our aim here was to examine potential REM sleep features of cortical oscillatory activity associated with frequent nightmares in more detail, by reanalyzing this dataset [18] while taking into account the microstructure (ie phasic and tonic microstates) of REM sleep.

Phasic and tonic REM periods exhibit marked differences in spontaneous oscillatory activity in healthy individuals showing increased (1.5–4 Hz) delta and (30–48 Hz) gamma activity (indexed by spectral power and functional synchronization) during phasic, and relatively increased high alpha and beta (~12–29 Hz) EEG activity in tonic REM (for an extensive review see Ref. [28]). Previous studies suggest that awakening thresholds are reduced, and environmental alertness is partially reinstated during tonic REM [29,30], whereas during phasic periods the brain temporarily decouples from the surroundings and exhibits functionally isolated, internally focused cognitive and emotional activity that is supposedly experienced in the form of intense dreams [29]. The two most abundantly studied REM parasomnias, narcolepsy and REM behavior disorder (RBD), appear to further accentuate the differences between phasic and tonic REM microstates. For instance, phasic REM activity is abnormally high in narcolepsy [31], and nocturnal behaviors in RBD patients are also more frequent during phasic than tonic REM [32]. In addition, spectral power and functional synchronization showed more pronounced differences between phasic and tonic states in RBD compared to healthy controls, indicating abnormal motor activity, specifically during phasic REM periods in RBD [33]. These findings suggest that pathological processes in narcolepsy and RBD seem to have a distinct impact on REM microstates. Moreover, intense dream experiences and frequent nightmares are commonly observed in both conditions [34–36].

Although nightmare disorder is considered to be a REM parasomnia [37], to the best of our knowledge, no previous studies examined spontaneous cortical activity of frequent nightmare recallers in phasic and tonic REM microstates. Therefore, we examined EEG spectral power and functional connectivity during phasic and tonic REM in participants experiencing frequent nightmares and healthy controls. Intense emotional activity during REM sleep, which can be expected to a higher degree in participants with frequent nightmares based on the phenomenology of nightmare disorder, might be reflected by altered cortical activity in phasic REM. On the other hand, since tonic REM is more susceptible to arousals and micro-awakenings, increased arousal-related activity in nightmare recallers might lead to increased wake-like high alpha and beta EEG activity [38–40] in tonic REM. Therefore, we expected a more pronounced contrast of cortical activity across phasic and tonic REM sleep in our group of nightmare participants compared to healthy controls.

## 2. Methods

### 2.1. Participants

Participants were recruited from two Hungarian Universities and through social media. In order to participate, they had to fill out an online screening questionnaire with questions regarding sleep quality, dream recall frequency, bad dream frequency, nightmare frequency, alcohol and drug consumption and previous psychiatric and neurological disease history (for the complete list of acquired and analyzed questionnaires see Ref. [18]). Inclusion criteria were the following: 1) Remembering dreams at least 2–3 times/month; 2) Either 2–3 nightmares/months (nightmare (NM) group) or 2–3 nightmares/year (control group); 3) More than 1 bad dream/week (NM group) or less than 1 bad dream/months (control group); 4) No previous psychiatric, neurological or chronic somatic disease history; 5) Moderate alcohol intake (1 or less drink/week); 6) No regular medication intake (except contraceptives). Based on their answers, potential participants were invited for a face-to-face interview with a psychologist to further exclude individuals with recent trauma experience (last 5 years) and/or acute stress related nightmares.

After the screening process, 49 individuals (25 control, 24 NM participants) were invited to participate in this study. During the experiment, one participant did not return for the second night of measurement and was excluded from the analysis. Five additional participants had to be excluded due to bad data quality ($N = 3$), reporting having frequent night terrors ($N = 1$), and insufficient amount of sleep on the experimental night (sleep efficiency < 60%, $N = 1$). Ultimately the data of 21 control participants ($M_{age} = 21.46$, $Std_{age} = 1.43$, 6 male) and 22 NM participants ($M_{age} = 22.91$, $Std_{age} = 3.1$, 8 male) was analyzed. Compensation for participation was either in partial class credits (for university students) or in 45€ worth of Hungarian forints. The experimental protocol was approved by the United Ethical Review Committee for Research in Psychology, Hungary (EBKEB 2016/077), in line with the Declaration of Helsinki and written informed consent was collected.

### 2.2. Procedure

Participants spent two consecutive nights in the sleep laboratory monitored by polysomnography (PSG). Arrivals to the lab and

bed times were personally adjusted between 9.30 pm and 11:30 pm based on participant preferences. Awakenings were initiated after at least 7 h of sleep between 7 am and 8 am. The first night was used as habituation night. Sleep architecture of the first night was evaluated in order to ensure that the preceding night's sleep did not influence our results of the study (second) night. Participants from the two groups spent the same amount of time in bed in the first night, had to follow the same instructions (no caffeine intake after noon, no afternoon naps) and showed no REM sleep related differences. PSG recordings of the second night were analyzed in more detail and are reported below.

### 2.3. Recordings and preprocessing

Following the 10–20 electrode placement guidelines [41], all participants were fitted with 17 EEG scalp electrodes (F7, F8, F3, F4, Fz, T3, T4, C3, C4, Cz, T5, T6, P3, P4, Pz, O1, and O2), which were referenced to the mathematically linked mastoids (A1, A2). Additionally, muscle activity was measured by bipolar electromyography (EMG) placed on the chin, eye movements were measured by electrooculography (EOG) and heartrate was monitored by electrocardiography (ECG) during both nights. Gold coated Ag/AgCl EEG cups were fixed on the scalp with EC2 Grass Electrode Cream (Grass Technologies, Natus Manufacturing Ltd., Galway, Ireland). The data was recorded with Micromed SD LTM 32 Bs (Micromed S.p.A., Mogliano Veneto, Italy) and visualized by SystemPLUS 1.02.1098 software (Micromed Srl, Roma, Italy). All impedances were kept below 8 kΩ and the signal was collected pre-filtered (0.33–1500 Hz; 40 db/decade anti-aliasing hardware input filter), amplified and digitized with 4096 Hz sampling rate with 16-bit resolution and down-sampled to 512 Hz.

Phasic and tonic REM segments were selected manually through visual inspection of the EOG channel, based on the presence or absence of bursts of eye movements using the Fieldtrip open source toolbox [42] of MATLAB (version 9.3.0.713579, R2017b, The MathWorks, Inc., Natick, MA). Four second-long segments were coded as phasic REM when the EOG channel showed at least two consecutive eye movements during REM sleep periods (scored previously in the database [18]). Four-second long segments without significant bursts of eye movements (EOG deflection of less than 25 μV) were categorized as tonic REM. The selection of segments was carried out by research assistants trained in sleep scoring, and the selected four seconds long periods were visually inspected by a trained sleep researcher in order to exclude segments with inaccurate categorizations, as well as to discard trials showing movement-related and technical artifacts. In order to increase the stationarity of the data, we further segmented the four-second phasic and tonic epochs into 2 s long trials with 50% overlap.

Independent component analysis (ICA) was applied to identify and remove eye-movement related artifacts in EEG channels. Large potentials produced by eye-movements can contaminate the EEG signal inflating low frequency activity [43], whereas muscular activity related to microsaccades confounds oscillations in the gamma frequency range [44]. Tonic and phasic trials were appended for each participant, and EOG, EMG and reference channels were removed from the data before running the analysis. Components were identified as reflecting eye movement related artifacts if they showed a dominantly frontal topography and EOG-like time course. For most participants, one or two (maximum three) components showed this pattern and were therefore removed.

### 2.4. Spectral power analysis after Laplace transformation

As EEG data, and therefore the spectral power calculated from it, are sensitive to volume conduction, a Laplace transformation was applied to the artifact-free, phasic and tonic segments before calculating spectral power. In essence, this transformation acts as a spatial filter, and therefore attenuates the influence of volume conduction. Specifically, the data was transformed using spherical spline interpolation based on the second order spatial derivative of the signal, as first described by Perrin and colleagues [45]. The parameters were left at the default values for data with less than 32 channels in the Fieldtrip toolbox (order of splines = 4, degree of Legendre polynomials = 10, $\lambda = 10^{-5}$). Spectral power was calculated for each electrode and frequency bin (2–48 Hz, 0.5 Hz bins resolution) using the fast Fourier transformation (FFT) algorithm from the open source Fieldtrip toolbox [42] in MATLAB. Power was extracted separately for low (2–30 Hz) and high (30.5–48 Hz) frequencies, using a Hanning taper for the low frequencies and a multitaper using the DPSS (discrete prolate spheroidal sequences) method with 2 Hz smoothing for the high frequencies [46]. The average power spectral densities were extracted for phasic and tonic trials, separately.

### 2.5. Functional connectivity: weighted phase lag index

Connectivity was estimated using the weighted phase lag index (WPLI) [47], which is a modified version of the phase lag index (PLI), first introduced by Stam and colleagues [48]. The PLI quantifies connectivity by considering the consistency of the phase angle differences (ie phase lag) between the frequency-specific signal recorded from two channels over time. In essence, PLI values are high (max. 1) when the difference between phase values extracted from the two channels stays similar over time, while it is small (min. 0) when this difference changes randomly over time. By disregarding any phase lags close to zero and $\pi$, PLI attenuates the influence of volume conduction [48]. The WPLI additionally gives greater weight to phase lags closer to 0.5 $\pi$ and 1.5$\pi$ and lower weight to phase lags close to zero and $\pi$, thereby reducing the influence of small disturbances in phase lags (ie a phase lag turning into a lead and vice versa). Power and phase information were extracted for all trials by Fourier transformation, and WPLI values were calculated at each 0.5 Hz frequency bin between 2 and 48 Hz for each unique combination of electrode pairs using the connectivity function from the Fieldtrip toolbox. Considering the relative insensitivity of the WPLI to volume conduction, the cleaned, but not Laplace transformed EEG data were used to calculate connectivity.

### 2.6. Statistical analysis with partial least squares (PLS)

Partial least squares (PLS) is a multivariate statistical method that allows one to test for differences between experimental groups and/or conditions across the whole brain and multiple frequencies at once [49–51]. PLS decomposes the data into patterns of group and/or condition differences and similarities, which are called latent variables (LVs), that explain the most variance in the data. Each LV consists of three components. The first is the singular value, which indicates the strength of the pattern represented by the LV, and is used to test the statistical significance of the pattern. The second component holds the condition loadings, which specify how each condition within each group is associated with the pattern identified by the LV. These condition loadings essentially show the contrast between groups and conditions as identified by the LV. The third component contains the element loadings, which highlight the spatiotemporal pattern, ie at which electrodes/electrode pairs and frequencies the contrast found by the LV is expressed. Together, these three components indicate if and where statistical differences and/or interaction effects in spectral power and connectivity between participants with frequent nightmares

and controls (group factor), and between tonic and phasic REM sleep microstates (condition factor) are present.

Statistical testing is performed at two levels for PLS analyses. First, the overall significance of the LVs is determined through permutation testing [52]. In essence, permutation testing involves repeatedly shuffling the data randomly between conditions and groups (but within participants), and then conducting the analyses with these shuffled data for a number of iterations. The statistical significance of an LV is determined by comparing the singular value obtained from the non-shuffled data to the distribution of singular values found with the shuffled data. When the observed singular value is more extreme that 95% of the values in the distribution, the LV is considered significant at an alpha level of 0.05. Fundamentally, such permutation testing determines the probability of the observed data pattern being found due to chance. In this study, 500 permutations were used for each analysis. The second level of testing involves bootstrap resampling. This consists of rerunning the PLS analysis with a different subsample of the participants several times, to determine how consistently the pattern is found across the full sample. A distribution of the element loadings estimated from different subsamples is created and used to calculate bootstrap ratios (actual element loadings divided by the standard error of the element loadings distribution for each element). Bootstrap ratios of 3.1 or higher correspond roughly to a 99% confidence interval (ie they are similar to z-scores). Data was resampled 200 times for each analysis in this study. No correction for multiple comparisons is needed for PLS analyses, as both statistical tests are performed in one computational step. To highlight the statistical significance of and the amount of crossblock covariance explained by each LV, *p*-values and percentage of crossblock covariance explained (PCCE), respectively, are reported for the LVs of interest. Two PLS analyses were performed, one for spectral power and one for connectivity. Both groups (frequent nightmare recallers and controls) and both conditions (tonic and phasic REM microstates) were included in each analysis, to test for any group and condition differences and interactions.

## 3. Results

### 3.1. Sleep architecture

The main parameters of sleep architecture of the present sample have been presented elsewhere [18]. In brief, differences across nightmare and control participants emerged only in case of NREM sleep, showing reduced slow wave sleep, and a nominally significant increase in Stage 1 sleep, as well as more awakenings during NREM sleep in nightmare recallers compared to controls. Measures

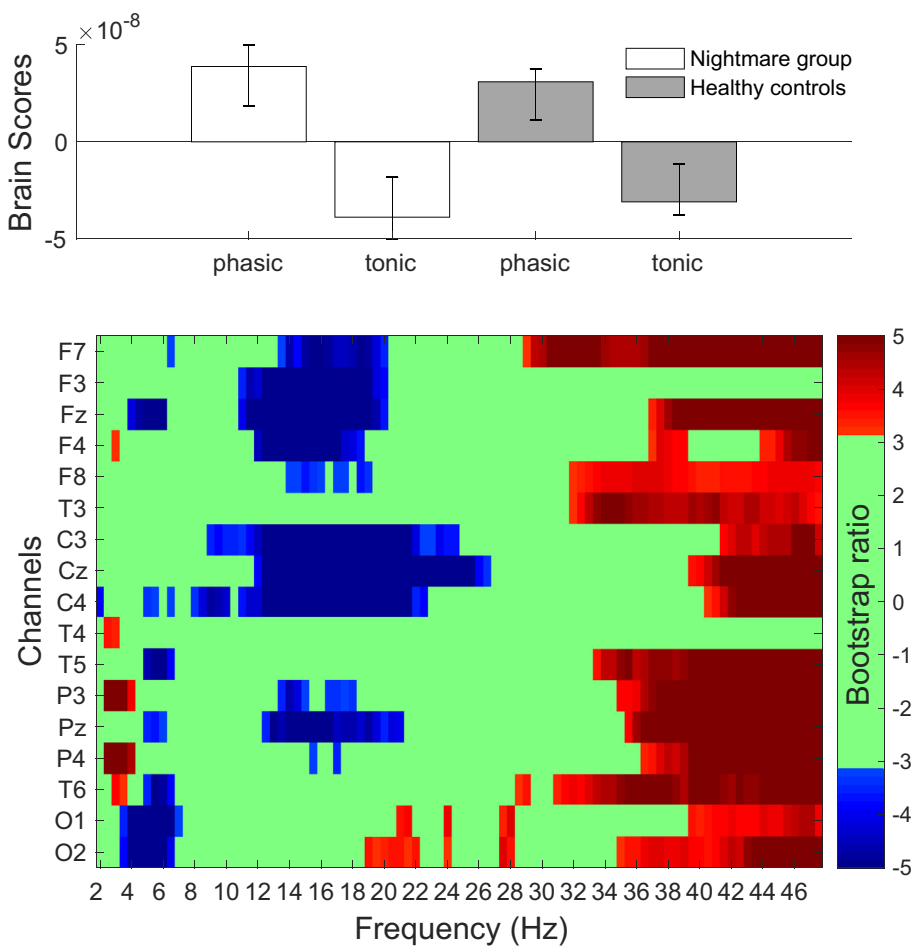


**Fig. 1.** Contrast in spectral power between phasic and tonic REM sleep microstates in participants with frequent nightmares and healthy controls, as identified by partial-least squares (PLS) analysis. The bar graph shows the differences and similarities between conditions and groups (in this case, a difference between phasic and tonic REM microstates which is similar across groups). The statistical image plot depicts the spatiotemporal pattern of this contrast in bootstrap ratio values across frequencies (rows) and electrodes (columns). Elements with bootstrap ratios ≥3.1 (roughly falling within a 99% confidence interval) are colored to highlight where the effect was most reliable across individuals as established through bootstrap resampling. Positive values (red) indicate increased spectral power during phasic REM, while negative values (blue) indicate increased spectral power during tonic REM sleep. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

related to REM sleep (REM %, REM latency, REM awakenings) were not different across the groups (see Ref. [18] for more details).

### 3.2. Spectral power

The PLS analysis comparing the two groups (nightmare and control group) and conditions (phasic and tonic REM) in terms of spectral power identified one significant LV ($p = 0.002$, PCCE = 71.2%). This LV revealed a contrast between phasic and tonic REM conditions, which was similar for the two groups (see top of Fig. 1). This contrast was most consistently expressed in a widespread increase in gamma throughout the scalp during phasic REM sleep. Increased phasic gamma power was present at all electrodes except F3 and T4 and spanned between 30 and 48 Hz. In addition, a relative increase in occipital beta (between ~19 and 28 Hz) and temporo-parietal (T4, P3, P4, T6) delta power emerged in phasic REM. Moreover, we observed an increase in alpha and beta power that ranged between 8 and 26 Hz and appeared at frontal, central, and parietal electrodes, and an increase in theta power (4–8 Hz; Fz, C4, T5, Pz, T6, O1, O2), during tonic compared to phasic REM in these frequency ranges (see bottom of Fig. 1).

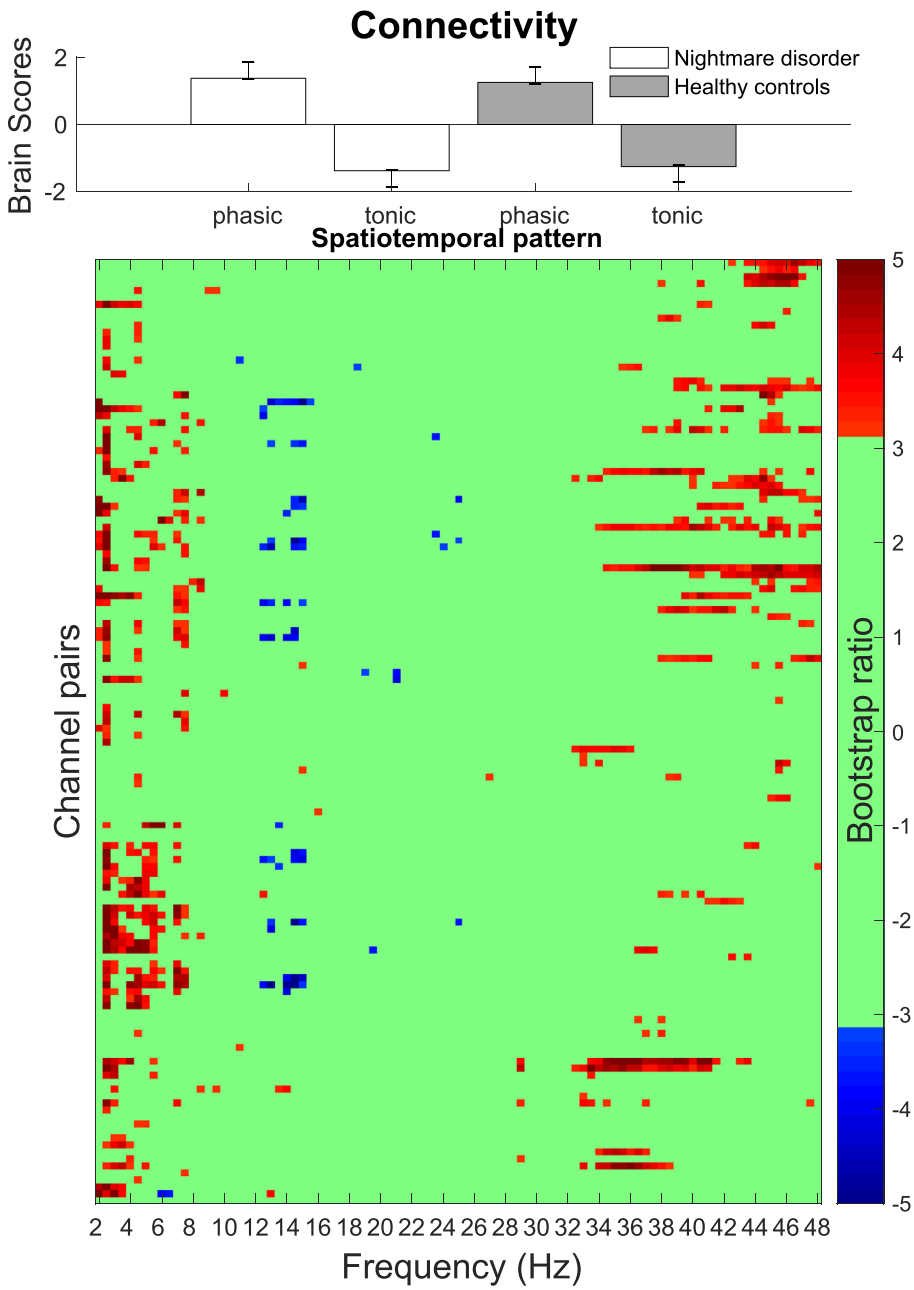


**Fig. 2.** Contrast in connectivity (as quantified by the weighted phase lag index – WPLI) between phasic and tonic REM sleep microstates in participants with frequent nightmares and healthy controls, as identified by partial-least squares (PLS) analysis. The bar graph shows the differences and similarities between conditions and groups (in this case, a difference between phasic and tonic REM microstates which is similar across groups). The statistical image plot depicts the spatiotemporal pattern of this contrast in bootstrap ratio values across frequencies (rows) and electrode pairs (columns). Elements with bootstrap ratios ≥3.1 (roughly falling within a 99% confidence interval) are colored to highlight where the effect was most reliable across individuals as established through bootstrap resampling. Positive values (red) indicate higher connectivity during phasic REM, while negative values (blue) indicate higher connectivity during tonic REM sleep. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Absolute power can be influenced by multiple participant- and measurement-related factors, and can therefore confound comparisons across groups, potentially explaining why we found no group differences. Therefore, we calculated relative power for each individual and channel separately and performed a PLS analysis, again including both groups and conditions, for relative spectral power as well. The results similarly highlighted only one significant LV ($p = 0.002$, PVE = 85.4%), which distinguished between phasic and tonic REM sleep, but not participants with frequent nightmares and healthy controls (see Fig. S1). The spatiotemporal pattern expressed by this LV was comparable to that reported above, but more spatially contained, especially in the gamma frequency band.

### 3.3. Connectivity

The PLS analysis comparing connectivity across the two groups and conditions, similarly identified one significant LV ($p < 0.001$, PCCE = 77.4%). Again, this LV highlighted a contrast between phasic and tonic REM sleep microstates that did not differ between the two groups (see top of Fig. 2). This contrast involved an increase in WPLI values at delta and theta (2–8 Hz) and gamma (32–48 Hz) frequency bands in phasic compared to tonic REM. In contrast, a decrease in WPLI values in the high alpha/low beta range (12–16 Hz) during phasic compared to tonic REM emerged, indicating increased connectivity in tonic compared to phasic REM sleep in this range of frequencies (see bottom of Fig. 2). The topographic location of the electrode pairs that most consistently showed this contrast (ie with a bootstrap ratio ≥3.1, roughly translating to a 99% confidence interval), are presented in Fig. 3 for the four frequency ranges separately. The higher delta and theta connectivity during phasic REM sleep was widespread, involving posterior, central and temporal areas of the brain. Lower alpha/beta connectivity was predominantly found in central areas, as well as at some parietal and right temporal electrodes. The increase in gamma connectivity was most notably expressed in long-range connections from posterior to central and left to right electrodes.

## 4. Discussion

The aim of our study was to examine oscillatory activity during phasic and tonic REM microstates in a group of frequent nightmare recallers and healthy controls by examining spectral power and functional synchronization. Our analyses revealed pronounced differences across phasic and tonic REM conditions in a wide range of frequencies in case of spectral power and functional synchronization. Nevertheless, nightmare recallers and healthy controls did not exhibit different oscillatory activity during phasic and tonic microstates, and no interaction for group × REM states emerged, indicating that phasic and tonic microstates do not differentially modulate EEG oscillations in nightmare recallers compared to control participants.

Phasic periods showed increased delta (2–4 Hz) and gamma (~30–48 Hz) frequency power compared to tonic periods. Moreover, low frequency power within the delta and theta frequency bands and high frequency power involving the gamma range showed increased and widespread functional synchronization during phasic when compared to tonic REM sleep (see Fig. 4). These findings are in line with previous studies [53–56], and provide the first robust replication that is based on a larger ($N = 43$) sample, in contrast with previous studies that involved a much lower number of individuals (varying between 12 and 20 participants).

Contrary to our expectations, frequent nightmare recallers did not show altered oscillatory activity in phasic REM periods, neither for slow, nor for high frequency power or synchronization.

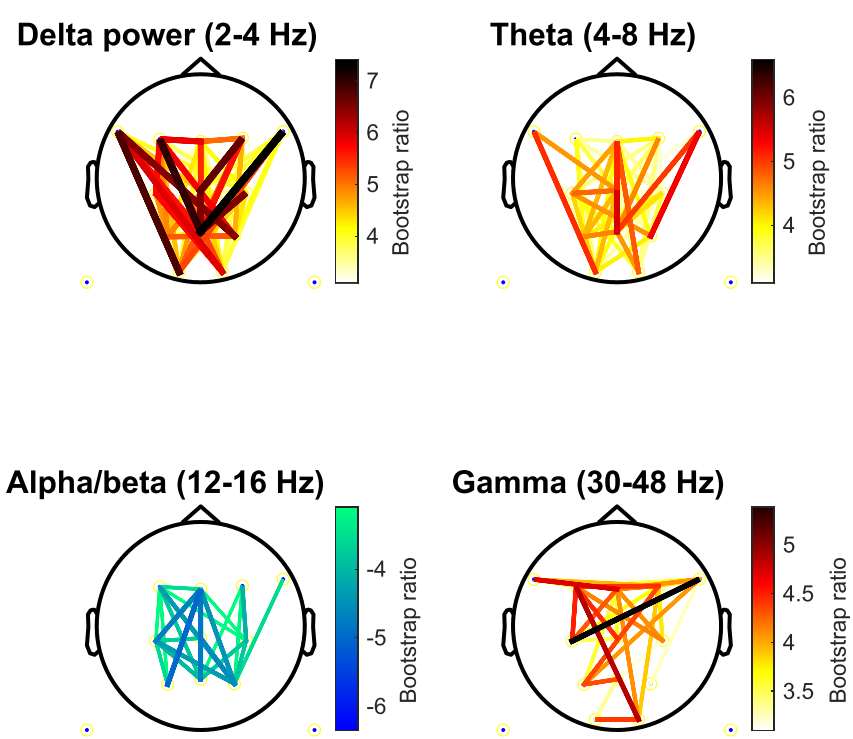


**Fig. 3.** Topographical representation of channel pairs showing the most consistent difference in connectivity (as quantified by the weighted phase lag index) between phasic and tonic REM sleep in both the frequent nightmares and healthy control group. Specifically, channel pairs with a bootstrap ratio ≥3.1, roughly corresponding to a 99% confidence interval, are illustrated separately for the delta (top left), theta (top right), high alpha/low beta (bottom left) and gamma (bottom right) frequency bands. Positive values (ie red/yellow lines) represent higher connectivity during phasic compared to tonic REM, while negative values (blue/green lines) indicate higher connectivity during tonic REM sleep. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

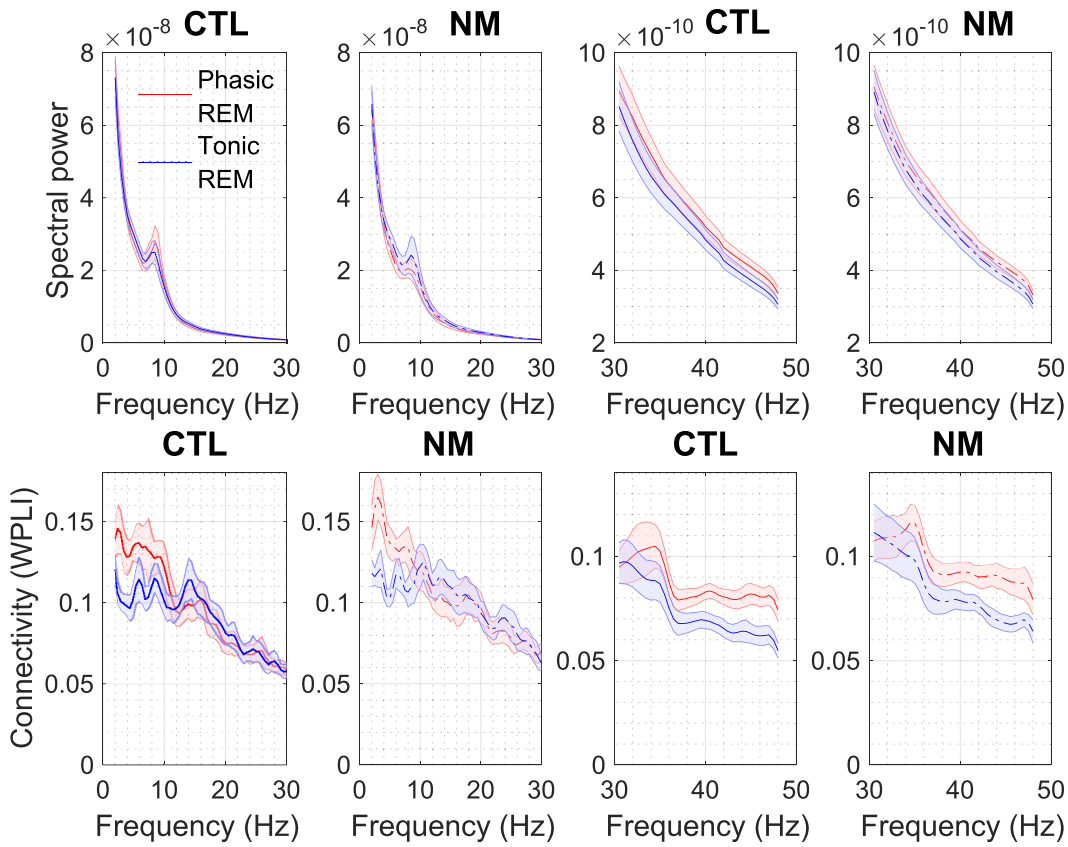


**Fig. 4.** Average spectral power (top) and connectivity (bottom) across all electrodes during phasic and tonic REM sleep in the healthy controls (CTL) and frequent nightmare group (NM), graphed separately for lower (2–30 Hz) and higher (30.5–48 Hz) frequency bins. The shaded areas mark the standard error around the average. 2 Hz smoothing was applied to the connectivity graphs for illustration only. WPLI = weighted phase lag index.

Interestingly, whereas nightmares are considered to occur primarily in REM sleep, the EEG correlates of nightmare disorder in REM sleep are far from being conclusive. Two studies identified relatively increased fronto-central low frequency activity (in the delta and theta ranges between 2 and 5 Hz) in frequent nightmare recallers compared to controls; however, this activity was not specific to REM sleep, but also appeared to some extent in NREM sleep and wakefulness [19,23]. Furthermore, previous studies that examined the REM-EEG correlates of nightmare complaints did not control for the confounding factor of high dream recall frequency. Increased dream recall is a necessary but not sufficient condition for increased nightmare frequency; therefore, EEG comparisons between frequent nightmare recallers and controls might be confounded with differences in dream recall. In fact, experiments on the neural correlates of dream recall suggest that enhanced REM theta activity, particularly at frontal derivations, predicts successful dream recall after awakening [26,57]. Although we took into consideration the potentially confounding effect of dream recall by including control participants that scored high in dream recall, further studies might systematically disentangle the EEG correlates of nightmare and dream recall frequency.

Since we did not collect dream reports throughout the night by forced awakenings, here we focused on the trait-like EEG correlates of nightmare frequency, regardless the presence of actual nightmares. Therefore, it is feasible that altered physiological activity in REM sleep could only be uncovered during nightmarish experiences. Such state-like physiological correlates of nightmares were observed recently in a study that contrasted the last five minutes of REM periods in which participants did or did not experience nightmares [58]. Nightmarish experiences within the nightmare group were associated with increased autonomic activity and REM density compared to non-dysphoric dreams of the nightmare group, and compared to the dream experiences of control participants [58]. As increased autonomic activity and REM density are prominent features of phasic REM states [28,59,60], it is possible that nightmarish experiences would be associated with abnormal cortical activity in phasic REM periods in a state-like manner.

In line with earlier findings [53–56,61], tonic in comparison with phasic REM periods exhibited relatively increased power in the high-alpha and beta frequency range (~10–28 Hz), and increased synchronization between 12 and 16 Hz, resembling the findings of a previous study reporting increased inter-and intra-hemispheric synchronization in an overlapping frequency range [62] (see Fig. 4). Relative increases in tonic REM power however, were not limited to the high alpha and beta frequency range, but included lower frequencies involving the theta band (4–7 Hz). Increased power in a wider frequency range involving the theta band during tonic REM is not at odds with previous data, as it was also observed at the level of the scalp [53] and the motor cortex [61].

Interestingly, we did not detect any alterations in tonic REM power and synchronization in our nightmare participants compared to controls. Tonic REM periods are characterized by increased environmental processing [29,63,64] and are more susceptible to micro-awakenings [30,65,66]. Based on previous findings indicating abnormal arousal processes in frequent nightmare recallers, we anticipated altered cortical activity in tonic REM states in the nightmare compared to the control group. Our findings do not support this hypothesis, and cast further doubts on the notion of nightmare disorder as a parasomnia specifically linked to REM

sleep. The assumption that nightmare disorder is a REM parasomnia may partly stem from the early observations reporting that dreaming is more intense during REM sleep [67], as well as from neurobiological models linking REM sleep to emotional information processing [5,68]. Nevertheless, there is no solid evidence indicating that nightmares occur more frequently during REM sleep than during NREM sleep. For instance, nightmares in PTSD patients are evenly distributed across NREM and REM periods [69]. Accordingly, dreaming also occurs during NREM sleep, and patterns of specific cortical activity appear to be involved in oneiric processes during the NREM state [25,27,70]. Regarding the trait-like aspects of dream recall, individuals with high dream recall showed enhanced neural responses to relevant stimuli (eg their own names) compared to individuals that rarely remember their dreams, but these differences were not limited to REM sleep, and were even more consistently observed in wakefulness and NREM sleep [71,72]. In addition, in a more recent study, awakenings from NREM sleep did, but awakenings from REM sleep did not differentiate high versus low dream recallers [73], pointing to the critical role of altered NREM sleep in dream recall. Likewise, numerous studies indicating the influence of NREM sleep on emotional memory processing urged to update the exclusive role of REM sleep in emotional reprocessing [74–78].

Our study was not without limitations. Most importantly, our nightmare group included individuals who experience frequent nightmares, but were not diagnosed with nightmare disorder, therefore we cannot dismiss the possibility that group differences might exist between healthy controls and patients with nightmare disorder. In addition, the coarse categorization of participants as either experiencing frequent nightmares or not might have prevented the detection of more subtle effects associated with the frequency of nightmares. Nonetheless, frequent nightmares are the defining feature of nightmare disorder.

In conclusion, we found no evidence to suggest that individuals who experience frequent nightmares show trait-like alterations in power and synchronization during phasic and tonic REM sleep microstates compared to healthy controls. Overall, our findings suggest that in order to understand the neurobiological background of frequent nightmares, researchers need to extend the analyses beyond REM-related processes, and explore neurophysiological processes of NREM sleep in relation to the phenomenology, comorbidity, and trait-and state-like aspects of nightmare disorder.

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## CRediT authorship contribution statement

**Gwen van der Wijk:** Conceptualization, Data curation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Borbála Blaskovich:** Data curation, Investigation, Writing - review & editing. **Yeganeh Farahzadi:** Data curation, Formal analysis, Writing - review & editing. **Péter Simor:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing - original draft, Writing - review & editing.

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## Conflict of interest

None declared.

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: https://doi.org/10.1016/j.sleep.2020.07.014.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sleep.2020.07.014.

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