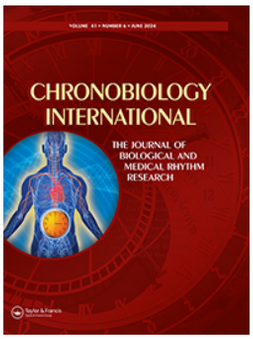

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The Journal of Biological and Medical Rhythm Research

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/icbi20

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To cite this article: Vladimir B. Dorokhov, Alexandra N. Puchkova, Dmitry E. Shumov, Eugenia O. Gandina, Anton O. Taranov, Natalya V. Ligun, Dmitry S. Sveshnikov, Elena B. Yakunina, Olga V. Mankaeva & Arcady A. Putilov (15 Jul 2024): The yin and yang of two opponent processes of sleep-wake regulation: Sex-associated differences in the spectral EEG markers of the drives for sleep and wake, Chronobiology International, DOI: 10.1080/07420528.2024.2378007

To link to this article: https://doi.org/10.1080/07420528.2024.2378007

CHRONOBIOLOGY INTERNATIONAL
https://doi.org/10.1080/07420528.2024.2378007

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ORIGINAL ARTICLE

The yin and yang of two opponent processes of sleep-wake regulation: Sex-associated differences in the spectral EEG markers of the drives for sleep and wake

Vladimir B. Dorokhov[a], Alexandra N. Puchkova[a], Dmitry E. Shumov[a], Eugenia O. Gandina[a], Anton O. Taranov[a], Natalya V. Ligun[a], Dmitry S. Sveshnikov[b], Elena B. Yakunina[b], Olga V. Mankaeva[b], and Arcady A. Putilov[a]

[a]Laboratory of Sleep/Wake Neurobiology, Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences, Moscow, Russia; [b]Department of Normal Physiology, Medical Institute of the Peoples' Friendship University of Russia, Moscow, Russia

ABSTRACT

Although objectively measured characteristics of sleep efficiency and quality were found to be better in women than men, women more frequently than men suffer from poor or insufficient or non-restorative sleep. We explored this apparent paradox by testing the sex-associated differences in electroencephalographic (EEG) indicators of two opponent processes of sleep-wake regulation, the drives for sleep and wake. We tried to provide empirical support for the hypothesis that a stronger women's sleep drive can explain better objective characteristics of sleep quality in women than men, while a stronger women's wake drive can be an explanation of a higher frequency of sleep-related complaints in women than men. To our knowledge, this was the first attempt to examine the associations of sex with scores on the 1st and 2nd principal components of the EEG spectrum that can serve as objective spectral EEG markers of the opponent drives for sleep and wake, respectively. The particular prediction was that, in women compared to men, not only the 1st principal component score but also the 2nd principal component score could be higher (i.e. both drives could be stronger). In a sample of 80 university students (40 females), the EEG signals were recorded during 160 afternoon napping attempts (50 min or longer). The difference between male and female students in sleep latencies did not reach a statistically significant level. In accordance with our prediction, both principal component scores were found to be higher in female than in male students irrespective of sleep stage. It is likely that the influence of the wake drive is entirely overlooked in the polysomnographic studies due to the predominant contribution of the indicators of the sleep drive to the conventional objective characteristics of sleep quality. Therefore, a stronger women's sleep drive can be an explanation of women's better sleep quality in the results of polysomnographic studies. On the other hand, if a stronger women's wake drive can influence the perception of their sleep quality, this can explain their more frequent sleep-related complaints.

ARTICLE HISTORY
Received 18 December 2023
Revised 24 June 2024
Accepted 4 July 2024

KEYWORDS
Sleep-wake regulation; slow-wave activity; EEG spectrum; principal component analysis; sex-related difference

Introduction

Sleep in women differs from sleep in men in several respects. On the one hand, polysomnographically measured characteristics of sleep efficiency and quality were consistently found to be better in women than men (Bixler et al. 2009; Fukuda et al. 1999; Redline et al. 2004; Unruh et al. 2008; Voderholzer et al. 2003; Walsleben et al. 2004). These characteristics include shorter sleep latencies, fewer nocturnal awakenings, less stage 1 sleep, and deeper sleep (Ehlers and Kupfer 1997; Goel et al. 2005; Hume et al. 1998; Redline et al. 2004; Roehrs et al. 2006). On the other hand, subjective sleep reports of women suggested that, in contrast to the objective characteristics, they have a higher need for sleep (Groeger et al. 2004; Jean-Louis et al. 2000; Reyner et al. 1995; Ursin et al. 2005), more frequently suffer from insufficient or non-restorative sleep (Mai and Buysse 2008, Soares and Murray 2008; van den Berg et al. 2009), and more often diagnosed with insomnia and hypersomnia (Ohayon 1996, 2002; Pajėdienė et al. 2024; Young et al. 1993; Zhang and Wing 2006).

The EEG slow-wave activity during non-rapid-eye-movement (NREM) sleep (e.g., the EEG power density in the frequency range between 1 Hz and 4 Hz) serves as the major conventional indicator of strength of the drive for sleep or, in other terms, as the major quantitative measure of deep sleep and homeostatic sleep pressure (Borbély 1982; Daan et al. 1984). This slow-wave activity was consistently shown to be higher in healthy women than men thus indicating that objective sleep quality is

CONTACT Arcady A. Putilov arcady.putilov@gmail.com Laboratory of Sleep/Wake Neurobiology, Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences, 11 Nipkowstr., Berlin 12489, Germany

better in women than men (Carrier et al. 2001; Dijk et al. 1989; Fukuda et al. 1999; Svetnik et al. 2017).

Slow-wave activity can also be interpreted in the light of the opponent process model of sleep-wake regulation (Dijk and Czeisler 1995; Edgar et al. 1993) as reflecting the combined influence of the two drives, the drive for sleep and the drive for wake, on the EEG spectrum. Our previous results suggested that the conventional measure of sleep pressure, delta power, reflects the combined influence of two drives on the EEG spectrum, i.e., not only the influence of the drive for sleep but also the opposing influence of the drive for wake (Putilov 2011; Putilov et al. 2013). The influence of the sleep drive can be separated from the influence of the wake drive by calculating scores on the 1st and 2nd principal components of the EEG spectrum (Putilov 2011; Putilov et al. 2013). Previously, we compared the effect of age on these scores and concluded that the aging process is associated not only with a weaker sleep drive as indicated by both lower levels of NREM slow-wave activity and lower score on the largest (1st) principal component of the EEG spectrum but also with a relative strong wake drive as indicated by a higher score on the 2nd principal component (Putilov 2015; Putilov and Donskaya 2016; Putilov et al. 2013). The superposition of the effect of these weaker sleep drive and stronger wake drive was suggested to underlie the age-related deterioration of sleep quality, e.g., unwanted awakenings, difficulty of falling asleep, "lightened" sleep, sleep fragmentation, decreased duration of nighttime sleep, etc. Additionally, a stronger wake drive was proposed to explain why, paradoxically, older adults better than younger adults tolerate sleep deprivation (e.g., Dijk et al. 2010; Duffy et al. 2009; Landolt et al. 2012; Putilov and Donskaya 2016).

To the best of our knowledge, the sex-associated differences in the strengths of the drives for sleep and wake have not yet been examined. Here, we tried to explore the apparent paradox of sex-associated differences in objective vs. subjective measures in the light of hypothesis of sex-associated differences in the principal component structure of the EEG spectrum. We tested the hypothesis that a stronger women's sleep drive can explain their better objective characteristics of sleep quality, while a stronger women's wake drive can be an explanation of their higher frequency of sleep-related complaints. We predicted to find that a stronger sleep drive in women than men is reflected in their elevated score on the 1st principal component. Since, during NREM sleep, a higher level of slow-wave activity is the major contributor to a higher 1st principal component score, the elevation of both these indexes (i.e., a higher level of this activity and a higher 1st score) could point to the sex-associated difference in the sleep drive. Therefore, a stronger sleep drive would underlie a better objective sleep quality in women than men, but such a stronger women's sleep drive cannot be a reasonable explanation of their self-reports on lower sleep quality and non-restorative sleep. To propose the explanation of this paradox, we hypothesized that a stronger opposing drive for wake would explain a higher frequency of self-reports of low sleep quality and symptoms of insomnia in women than men. Consequently, we predicted to find that 1) men and women are also different in score on the 2nd principal component of the EEG spectrum, a marker of the strength of the wake drive, and that 2) this score is also elevated in women thus indicating that the drive for wake would be stronger in women than in men.

Methods

Participants of the nap study

All procedures of the present study were performed in accordance with the ethical standards laid down by the 1964 Helsinki Declaration and its later amendments. The Ethics Committee of the Institute of Higher Nervous Activity and Neurophysiology approved the experimental protocols in June 2019 (Approval#12402-02-7112). The participants were informed in detail about all procedures, and informed written consent was obtained from each participant of the study. The nap study was conducted in 2020–2023 during October, November, and December. Unpaid volunteers of this study were 40 male and 40 female university students with a mean age ± standard deviation of 20.40 ± 1.56 and 20.25 ± 1.14 years, respectively.

The structured interview with a sleep researcher preceded the invitation to participate in the study and to choose the dates for three afternoon naps. The interview was focused on the following exclusion criteria: age either younger than 18 or older than 23 years, history of mental or sleep disorder, any complaints about poor physical condition and functioning, current mild cold and missing classes due to any sickness in two previous weeks, involvement in shift or night work and crossing several time zones in the previous month, irregularity of sleep-wake schedule exemplified by more than 1-h difference in weekday bedtimes, frequent sleep reduction exemplified by, at least, one night of partial sleep deprivation in the previous week. The exclusion criteria for female students additionally included pregnancy or breastfeeding, and they were also asked about the day of last menstruation and the usual cycle length.

Study protocol

Each visit to a sleep laboratory was preceded and followed by attending classes in the same university building. During 1 month, each study participant was invited to have three napping attempts. The intervals between them varied from 3 days to 3 weeks. Each visit to the sleep laboratory was scheduled at the same afternoon hour (not earlier than 12:30 and not later than 15:30). Usually, the visit lasted approximately 1 h in the case of three 50-min napping attempts (n = 27) and approximately 1 h and 40 min in the case of three 90-min napping attempts (n = 53). The first napping attempt was regarded as an adaptation nap, while, for the current study, the analysis of the polysomnographic records was limited to Nap 2 and Nap 3 (Figure 1a).

Polysomnographic recordings

During the preparation of polysomnographic recordings and during these recordings, a participant was lying in bed in a room of the sleep laboratory. He/she was instructed to try to relax, to fall asleep after light off, and to sleep for the next 50 or 90 min. The recordings were performed using a Neurovisor BMM-36 (Medical Computer Systems LLC, Moscow), the MCScap Sleep electrode helmet, and the NeoRec 1.4 software. The electrodes were applied in accordance with the standard monitoring montage known as the International 10–20 system of electrode placement. The EEG signals were obtained from 19 channels connected by a monopolar 10–20 scheme with two reference electrodes on the mastoid bones. Among other recorded polysomnographic signals were the signals from two electrooculogram channels, one electromyogram channel, and one electrocardiogram channel. The signals were conditioned by the high-pass, low-pass, and notch filters (0.5 Hz, 35 Hz, and 50 Hz frequencies, respectively). The sampling frequency was 1000 Hz.

Sleep scoring

In accordance with the conventional scoring procedure (Iber et al. 2007), visual scoring on 30-s epochs of each record was performed independently by two experienced scorers. The initial disagreement, depending upon the stage, varied from 10% (N1) to 2% (N3). In order to finally produce consensus scores, the scorers reexamined together all intervals with discrepant scores. They were uninformed about names and sex of the study participants. The 30-s epochs were classified into 5 stages: wake stage (W), three stages of NREM sleep (N1, N2, N3), and rapid-eye-movement (REM) sleep (R).

Spectral analysis of the EEG signals

The spectral EEG power densities were calculated from data on the EEG signals recorded from electrodes placed at 5 derivations (Fz, F4, Cz, Pz, and O2 referenced to the ear mastoid sites, M1/M2). The records of the signals from each of these derivations were visually inspected on 1-s epochs to remove all epochs containing artifacts from further analysis. Spectral power densities for the artifact-free epochs were computed using the FFTW (Fastest Fourier Transform in the West) package (Frigo and Johnson 2005; see also www.fftw.org for more detail). With few exceptions, mean spectra for each 30-s epoch were obtained by averaging over as many as 20–30 1-s spectra.

Further analysis of spectra was limited to the first 16 single-Hz frequency bandwidths, between 1 Hz and 16 Hz (i.e., 0.50–1.49 Hz for 1 Hz, 1.50–2.49 Hz for 2 Hz, 2.50–3.49 Hz for 3 Hz, . . ., 15.50–16.49 Hz for 16 Hz). These sets of 16 single-Hz power densities were averaged within each 30-s interval of EEG records, ln-transformed, and assigned to one of the 5 stages. For statistical analysis, the individual sets of spectral powers (100 or 180 per derivation of each napping attempt) were further averaged, e.g., over derivations and/or within each nap (Figure 2b) and/or within each stage (Figure 1b), etc. Moreover, these 16 ln-transformed single-Hz power densities were averaged after averaging over derivations (Figure 3) within four 4-Hz frequency ranges, delta (1 Hz-4 Hz), theta (5 Hz-8 Hz), alpha (9 Hz-12 Hz), and sigma (13 Hz-16 Hz). Analysis of the EEG indexes within each of the 5 stages was performed for 28 study participants, and epochs were assigned to all 5 rather than a smaller number of stages (Figure 1b).

Analysis of principal component structure of the EEG spectrum

The $SPSS_{23.0}$ statistical software package (IBM, Armonk, NY, USA) was applied for all further analyses including principal component analysis of the sets of 16 ln-transformed single-Hz power densities (1 Hz-16 Hz) from each of 5 derivations. Scores on the 1st and 2nd principal components of variation in the EEG power spectra were calculated and averaged (Figure 4) in a similar way as the sets of 16 ln-transformed single-Hz powers and spectral powers in 4 frequency ranges (Figure 3).

Depending upon derivation, the variation explained by the 1st and 2nd principal components varied from 50%

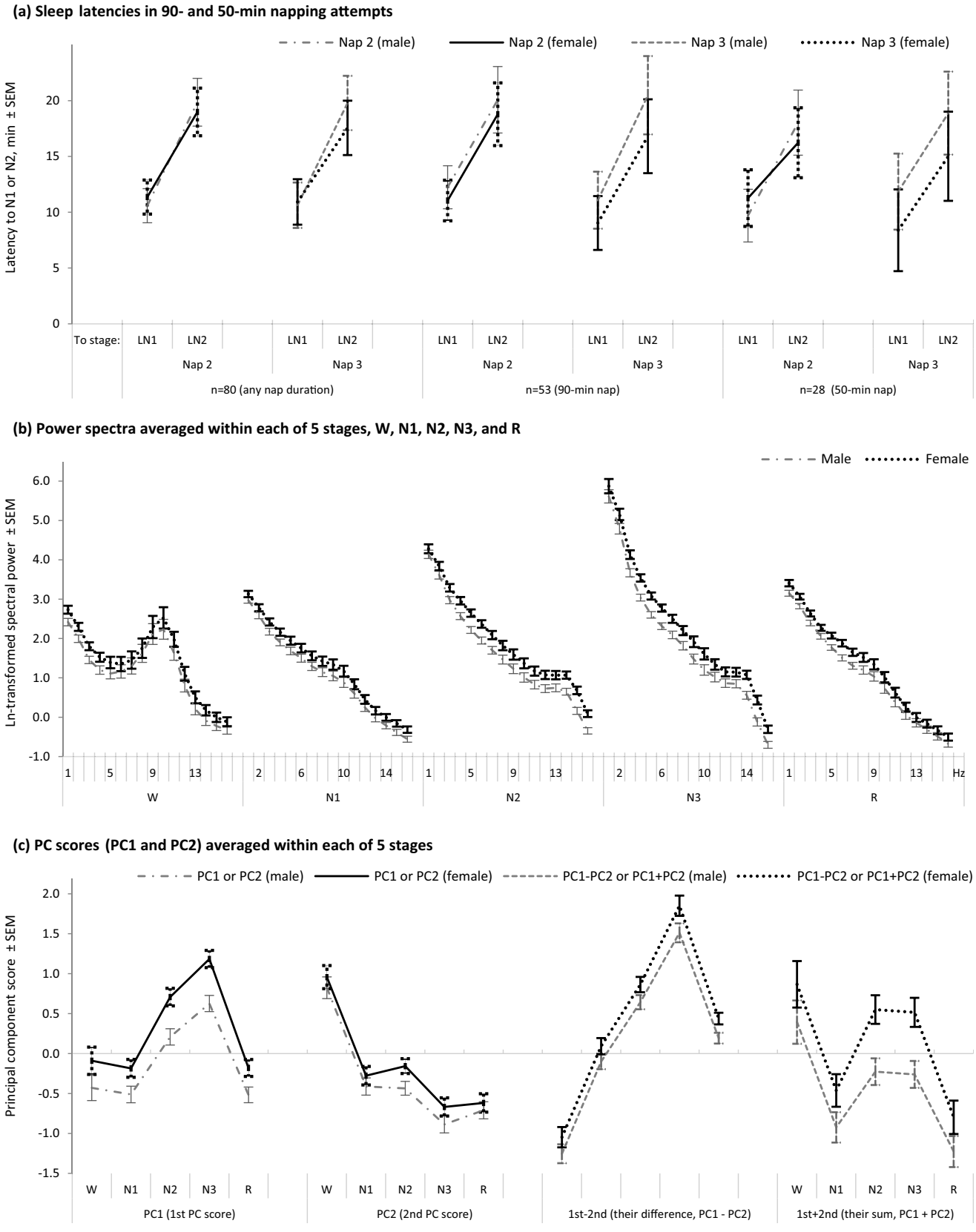

Figure 1. Two sleep latencies and power spectra and principal component scores for 5 stages. (a) Sleep latencies for the whole sample, only 90-min napping attempts, and only the subsample with all 5 stages. LN1 and LN2: Latencies to stages N1 and N2, respectively. (b) Power spectra in the range 1–16 Hz for each of the 5 stages. (c) Principal component scores, their difference, and sum for each of the 5 stages.

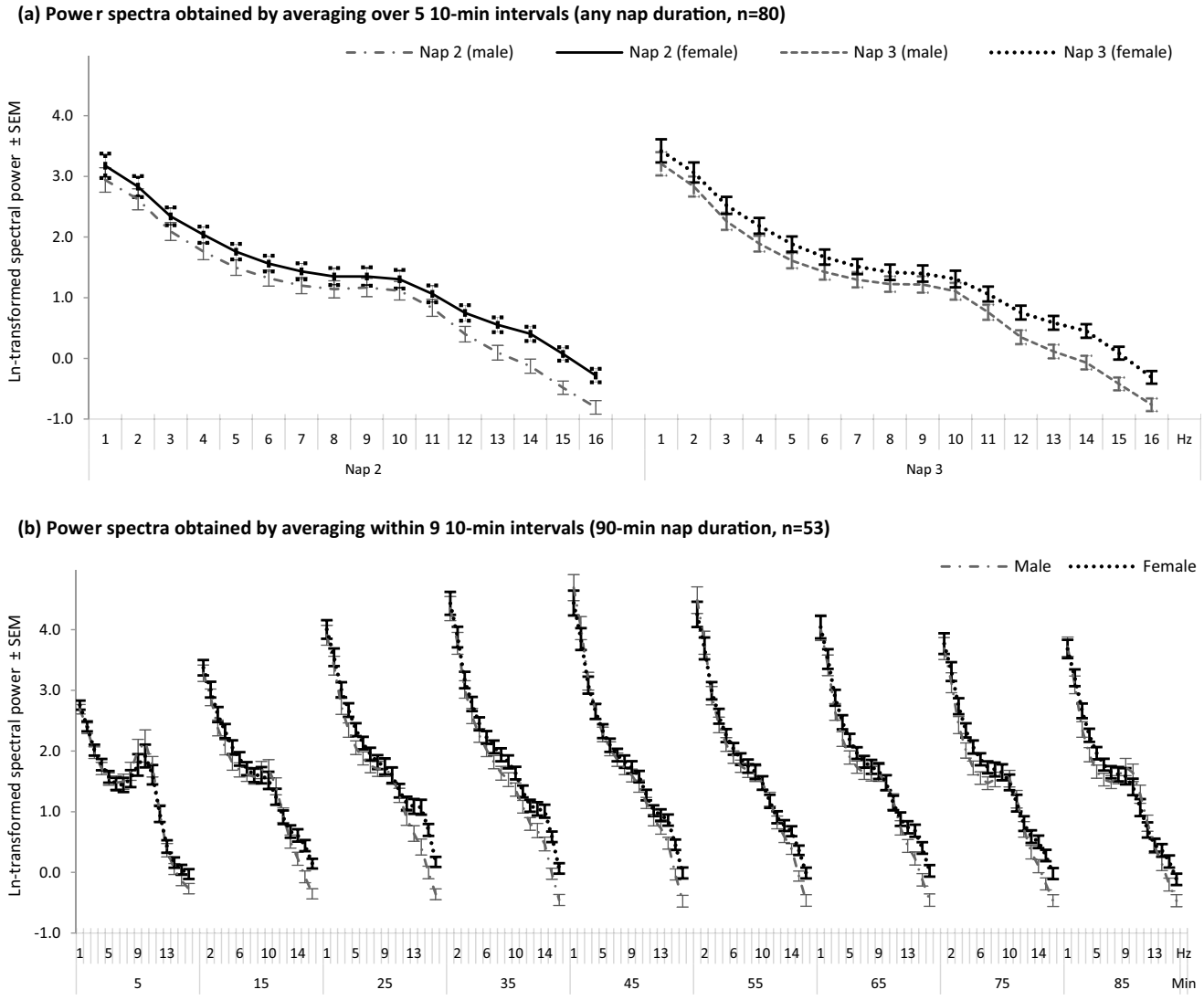

Figure 2. Power spectra in the range 1–16 Hz for two naps and 9 10-min intervals. (a) Averaged within two naps and over 5 10-min intervals for the whole sample. (b) Averaged over two naps and within 9 10-min intervals (only 90-min napping attempts).

to 55% and from 19% to 32%, and their eigenvalues varied from 7.9 to 8.8 and from 3.1 to 5.1, respectively. The pattern of loadings of 16 single-Hz spectral powers on each of the principal components was almost identical for 5 derivations. Loadings of alpha frequencies on both components were positive, loadings of delta frequencies on either the 1st or the 2nd principal component were either positive or negative, respectively, loadings of sigma and theta frequencies on the 1st principal component were, similarly to delta loadings, positive, and loadings of sigma frequencies on the 2nd principal component were, similarly to alpha loadings, positive.

Participants of the preceding online survey

An online survey of the same student population (n = 633) preceded the nap study (December 2019). The major purpose of this survey was to explore daytime sleepiness, chronotype, sleep-wake behavior, and habits in university students. In the present study, the results of this survey were used to confirm the significance of the association of being female with lower subjective sleep quality. When attending classes, students were invited by the lecturers to voluntarily participate in this survey. The mean age and standard deviation of male and female students were 19.0 and 1.5 years and 19.1 and 1.5 years, respectively. The students were asked to anonymously respond from their smartphones to the questions about their sleep and sleepiness. To collect their responses, the web page was designed (https://docs.google.com/forms/d/e/1FAIpQLSdIEeg00XFqmoULmKjXMqGI9rtMwpPD4HVwv5ZqYtH-BDMd3A/viewform). The questionnaires included:

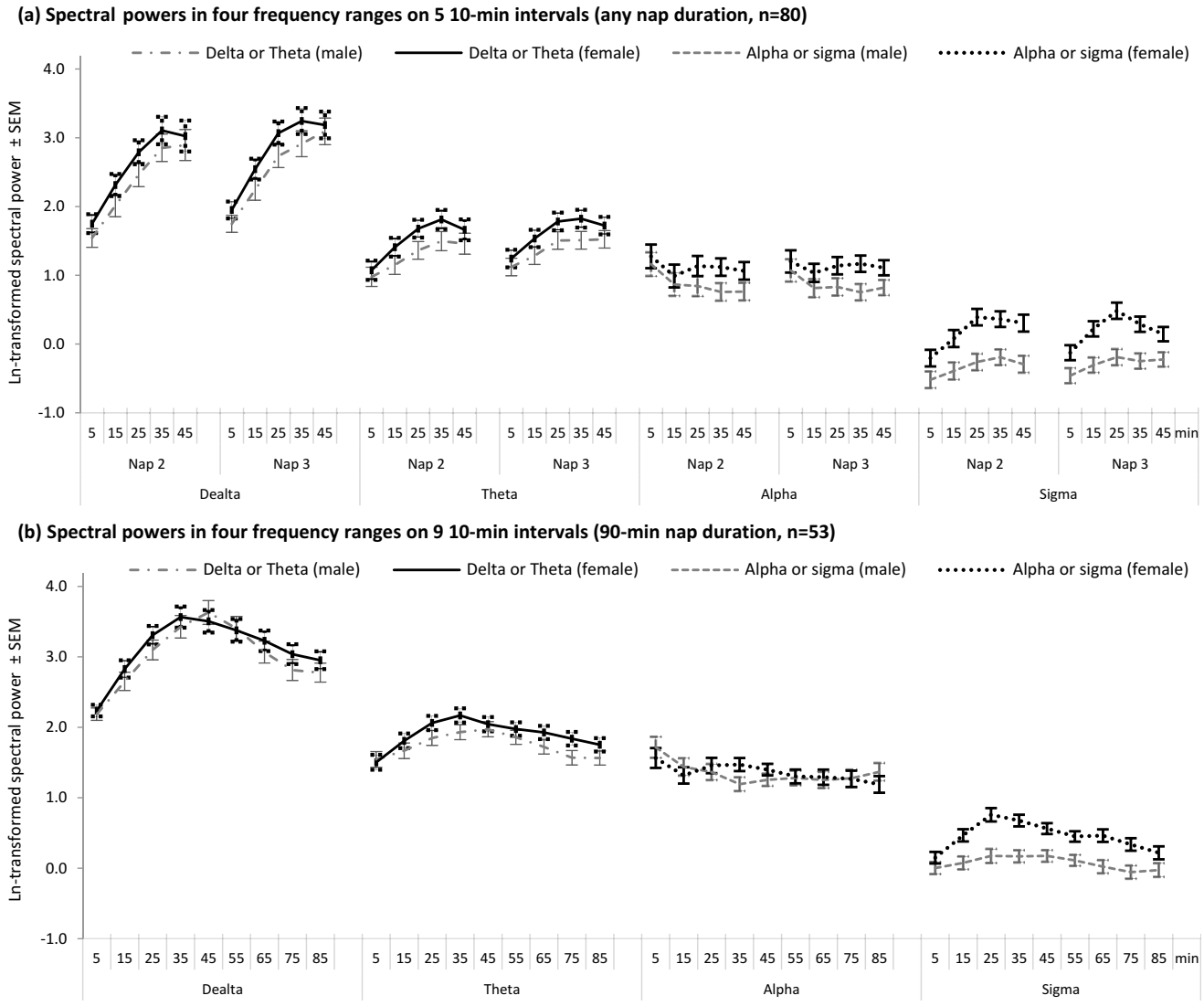

Figure 3. Time courses of spectral powers in 4 frequency rangers across 10-min intervals. (a) Averaged within 5 10-min intervals of each of two naps. (b) Averaged over two naps and within 9 10-min intervals (only 90-min napping attempts).

1) The 8-item Epworth Sleepiness Scale (ESS) for the determination of level of daytime sleepiness, and

2) The Pittsburgh Sleep Quality Index (PSQI) for self-reporting monthly averaged sleep onset latency, sleep duration, hours slept, sleep efficiency, and subjective sleep quality score.

The ESS (Johns 1991) quantifies the likelihood to fall asleep in each of 8 different daily life situations with a scale ranging from 0 to 3, where 0 corresponds to none and 3 to the situation when dozing off is the most likely. The total score ranges from 0 to 24. In the samples collected in this survey ($n = 633$), Cronbach's Alpha attained the value of 0.698.

To obtain self-reports of monthly averaged latency to sleep onset, sleep duration (time between sleep onset and offset), hours slept, percentage of sleep (sleep efficiency, %), and subjective sleep quality score, the responses to several questions 1–4 and 9 of the PSQI (Buysse et al. 1989) were used.

Statistical analysis

In the nap study, two-, three- and four-way repeated measure ANOVAs (rANOVAs) were run to test the significance of the main effect of the independent factor "Sex" (male vs. female students). The major results obtained for this effect are summarized in (Table 1) and illustrated in Figures 1a–c, 2 a–c, 3 a–c, 4 a–c and 5a–c.

Pearson's correlation coefficients were computed to illustrate the association of principal component scores with delta power, the conventional index of sleep pressure (Table 2). Data from the survey were analyzed to test the significance of the association of being female with lower subjective sleep quality. The binary logistic regression

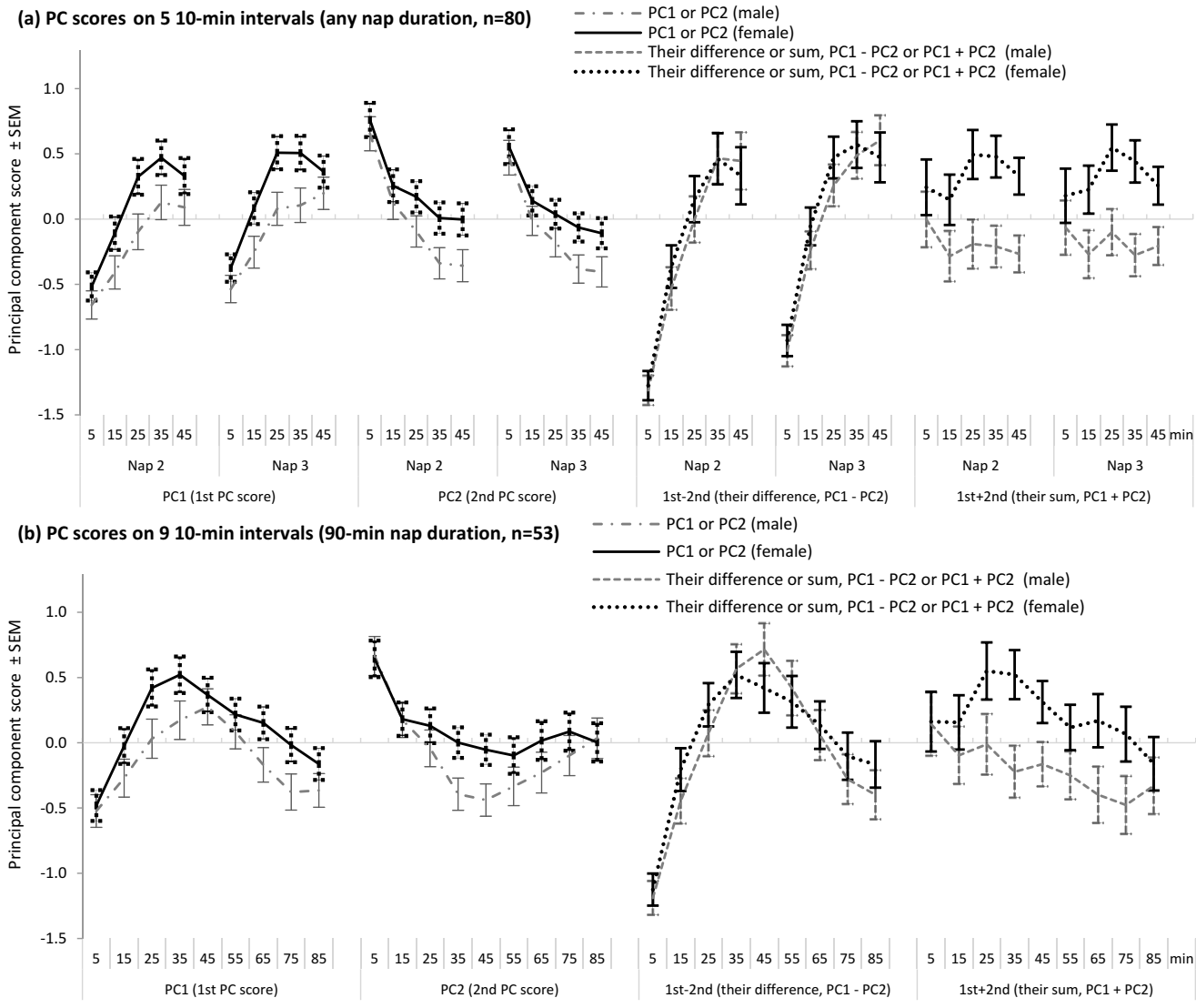

Figure 4. Time courses of the 1st and 2nd principal component scores across 10-min intervals. (a) Averaged within 5 10-min intervals of each of two naps. (b) Averaged over two naps and within 9 10-min intervals (only 90-min napping attempts).

Table 1. F-ratio for main effect of independent factor "Sex" in 10 rANOVAs.

	Spectra		PC score		Stage		Latency		ESS score	
	$F_{1/78}$	$F_{1/26}$	$F_{1/78}$	$F_{1/26}$	$F_{1/78}$	$F_{1/26}$	$F_{1/78}$	$F_{1/26}$	$F_{1/78}$	$F_{1/26}$
F-ratio for "Sex"	3.57	7.78**	6.15*	5.33*	7.92**	7.89**	0.05	0.33	1.37	3.16
	Repeated measures									
"2 Naps"	+	-	+	-	+	+	+	+	+	+
"5 Intervals"	+	-	+	-	+	-	-	-	-	-
"9 Intervals"	-	-	-	-	-	+	-	-	-	-
"16 Frequencies"	+	+	-	-	-	-	-	-	-	-
"2 PC scores"	-	-	+	+	-	-	-	-	-	-
"4 Stages"	-	-	-	-	+	-	-	-	-	-
"5 Stages"	-	+	-	+	-	+	-	-	-	-
"2 Latencies"	-	-	-	-	-	-	+	+	-	-

"Sex" was the only independent factor (male vs. female, $n = 40/15$ vs. 40/13, respectively) in two-, three-, four-way rANOVAs (i.e., with one-, two, and three repeated measures marked as "+"); "2 Naps": (Nap 2 and Nap 3); "5 Intervals:" 5 10-min intervals of napping attempt; "9 Intervals:" 9 such intervals; "16 Frequencies:" 16 single-Hz frequencies from 1 Hz to 16 Hz; "2 PC score:" Scores on the 1st and 2nd Principal Components of the EEG spectrum; "4 Stages:" Stages W, N1, N2, and N3; "5 Stages:" The same 4 stages plus stage R; "2 Latencies:" Latencies to N1 and N2. ESS score: The 8-item Epworth Sleepiness Scale was administered prior to each of the napping attempts for scoring subjective daytime sleepiness (Johns 1991). Level of significance for F-ratio: *$p < 0.05$, **$p < 0.01$.

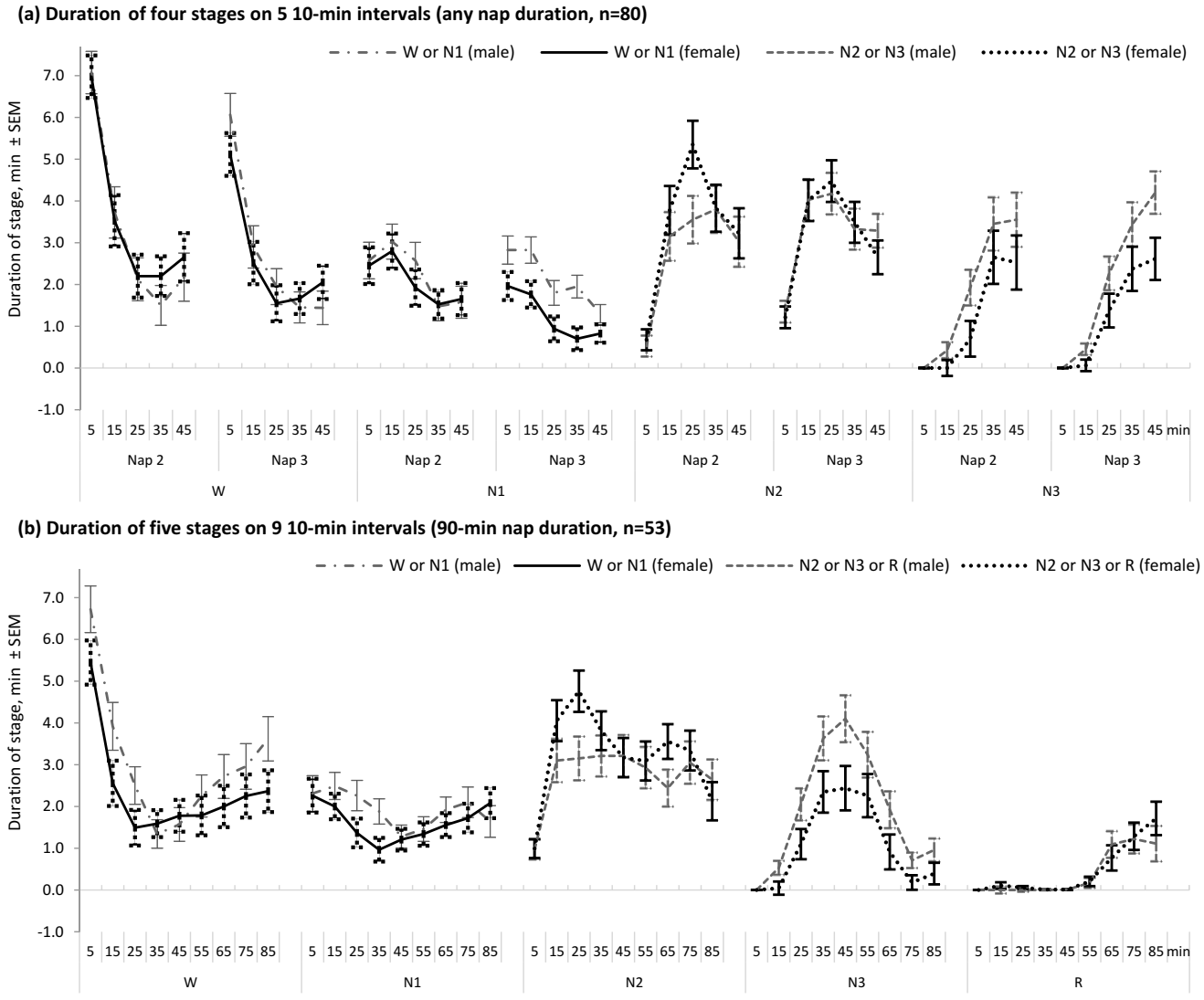

Figure 5. Time courses of durations of 4 or 5 stages across 10-min intervals. (a) Two principal component scores, their difference, and sum averaged within 5 10-min intervals of each of two naps. (b) Two principal component scores, their difference, and sum averaged over two naps and within 9 10-min intervals (only 90-min napping attempts).

Table 2. Pearson's correlation coefficients between delta power and principal component scores.

Index	Spectral power in the delta range (1 Hz-4 Hz) on 9 10-min intervals of nap								
Min	5	15	25	35	45	55	65	75	85
PC score	$n = 80$	$n = 80$	$n = 80$	$n = 80$	$n = 80$	$n = 53$	$n = 53$	$n = 53$	$n = 53$
1st	0.528***	0.743***	0.772***	0.814***	0.856***	0.876***	0.878***	0.882***	0.880***
2nd	0.079	−0.031	−0.138	−0.412***	−0.559***	−0.741***	−0.529***	−0.407***	−0.482***

Significant Pearson's correlation coefficients reflect the combined contribution of the two Principal Component (PC) scores, the spectral EEG markers of the drives for sleep and wake, respectively, to delta power, and the conventional index of sleep pressure. Level of significance of the coefficient: ***$p < 0.001$.

analysis was applied to predict the gender of participants of the sleep survey (Table 3).

Results

According to the results of two-, three- and four-way rANOVAs, Nap 2 and Nap 3 did not significantly differ in spectral EEG indexes. Two naps did not differ in the proportion of female students in the follicular and luteal phases of their cycle (7 and 10 vs. 11 and 10 in the follicular and luteal phases during the 2nd and 3rd nap, respectively, χ^2 (df = 1) = 0.921, p = 0.337).

Neither ESS scores nor latencies to stages 1 and 2 sleep (Figure 1a) showed a statistically significant sex-associated difference (Table 1).

Table 3. Results of regression analysis aimed on prediction of gender of university students.

Questionnaire	Self-assessment	B	Exp(B)	−95% CI	+95% CI
ESS	ESS score	0.038	1.039	0.996	1.084
PSQI	Sleep duration, last month	0.372	1.451	0.835	2.520
	SOL, last month	−0.009	0.991	0.980	1.001
	Hours slept, last month	−0.410	0.664	0.357	1.233
	Sleep efficiency, %, last month	0.045	1.046	0.996	1.099
	Subjective sleep quality score	−0.427***	0.652	0.517	0.823

Results of binary logistic regression analysis aimed on the prediction of gender (male vs. female, $n = 214$ vs. 419, respectively). Level of significance for B (beta coefficient) calculated for each of the predictors of gender: ***$p < 0.001$. Exp(B): The odds ratios for predictors (the exponentiation of regression coefficient); −95% CI, +95% CI: their 95% Confidence Intervals. ESS: Score on the 8-item Epworth Sleepiness Scale was used for the determination of the level of daytime sleepiness (Johns 1991); SOL: Latency to Sleep Onset. The Pittsburgh Sleep Quality Index (PSQI) was used for self-reporting monthly averaged SOL, sleep duration, hours slept, sleep efficiency, and subjective sleep quality score (Buysse et al. 1989).

Irrespective of the stage, female study participants had higher spectral power densities on the whole tested interval of frequencies from 1 Hz to 16 Hz (Table 1 and Figure 1b), and, as predicted, they had higher scores on two principal components of the EEG spectrum (Table 1 and Figure 1c).

The results suggesting higher spectral powers and higher scores in female students were confirmed by the rANOVAs. Such higher powers and scores were found in female students on each of 10-min intervals of 90- or 50-min napping attempts (Table 1 and Figures 2–4). The relations between spectral powers and principal component scores are documented in Table 2 on the example of correlations with powers in the delta frequency range. The significant correlations between these powers and scores suggest the combined contribution of the two scores, the spectral EEG markers of the drives for sleep and wake, respectively, to delta power, and the conventional index of sleep pressure.

There were also significant sex-associated differences in durations of stages (Table 1). While higher durations of W, N1, and N3 were found in male students, a higher duration of N2 was found in female students (Table 1 and Figure 5).

As predicted, the regression analysis of data from the survey yielded a significant association of being female with lower subjective sleep quality scores (Table 3). The associations with other self-assessments (ESS score, latency to sleep onset, sleep duration, hours slept, and sleep efficiency) were not significant predictors of gender.

Discussion

It is well-established that, compared to men, women are better than men on sleep quality measured by the polysomnographic method, but, in contrast, they more often than men report sleep-related complaints. Here, we tested the hypothesis that these paradoxical observations can be explained by the sex-associated differences in the opposing drives for sleep and wake. We hypothesized that both drives could be stronger in women than men. The women's stronger sleep drive might be a major contributor to the objective characteristics of sleep quality, while the women's stronger wake drive might influence on their subjective feeling of worse sleep quality. The hypothesis of women's stronger drives was supported by the present results of a comparison of principal component scores in male and female students. As predicted, we found significantly higher scores on both principal components of the EEG spectrum in female than in male students thus supporting the proposed explanation of the paradox of bidirectional sex-associated differences in objective vs. subjective indicators of sleep quality.

The present results also confirmed several previous reports (e.g., Carrier et al. 2001; Dijk et al. 1989; Fukuda et al. 1999; Svetnik et al. 2017) indicating that the amplitude of NREM slow-wave activity is higher in women than men. In more detail, a stronger sleep drive indicated by a higher level of this activity and a higher 1st score can explain why women compared to men demonstrate in polysomnographic studies higher sleep efficiency, higher sleep need, and deeper sleep. Thus, a strong sleep drive can underlie the sex-associated differences in objective measures of sleep quality as well as in some but not all subjective assessments, such as sleep desire, sleep satisfaction, and hypersomnolence. However, this difference in the strength of the sleep drive cannot explain the gaps between sexes in such subjective reports as the complaints about insufficient or non-restorative sleep and insomnia. Given that the 1st principal component, an indicator of the strength of the sleep drive, is the largest contributor to the EEG power, the contribution of the 2nd component, an indicator of the strength of the wake drive, can be entirely overlooked in the results on the conventional objective characteristics of sleep quality. It is likely that, in the presence of a stronger sleep drive, the traditional spectral EEG analyses fail to uncover the

influence of a stronger wake drive underlying the predisposition to report non-restorative sleep and insomnia symptoms. The present results confirmed the previous results suggesting that the conventional measure of sleep pressure, delta power, reflects the combined influence of two drives on the EEG spectrum, i.e., not only the influence of the drive for sleep but also the opposing influence of the drive for wake (Putilov 2011; Putilov et al. 2013). Principal component analysis of the EEG spectrum allows the separation of the influence of the wake drive from the opposing influence of the sleep drive.

Thus, a worse subjective perception of the quality of sleep demonstrated by women compared to men can be explained by such a stronger opposing drive for wake. It also can make women more vulnerable than men to perceiving the symptoms of insomnia which is the most common sleep disorder.

To our knowledge, this is the first report presenting results of a comparison of principal component scores in male and female study participants. However, there are limitations to our dataset. We studied the EEG markers of the drives for sleep and wake in this sample of male and female university students because it represents a group of young adults at the same life course stage and with a relatively small gender gap in social, cultural, and environmental determinants of their sleep and wakefulness. The results obtained for such a sample do not allow their generalization to other ages and subpopulations with more prominent psycho-social differences between genders. It cannot be excluded that the fundamental biological differences in the drives for wake and sleep might not be clearly evident in the presence of prominent differences in social, cultural, and environmental determinants of women's and men's sleep. Therefore, the present results, if confirmed in independent studies of other subpopulations, will require further research aimed on the direct measurements of associations of each of the principal component scores with various objective and subjective characteristics of men's and women's sleep.

Conclusions

Sleep in women differs from sleep in men in several respects. Objectively measured characteristics of sleep efficiency and quality were usually found to be better in healthy women than men, but, paradoxically, self-reports on sleep-related complaints indicated that, as a rule, women more frequently than men suffer from insufficient or non-restorative sleep. Moreover, they are more often diagnosed with insomnia which is the most common sleep disorder. In the present study, we predicted and found higher scores on the 1st and 2nd principal components of the EEG spectrum in female than in male participants. The fact that, as predicted, higher principal component scores yielded a significant association of being female, this association was interpreted as indicating stronger sleep and wake drives in women than men. Because the 1st principal component is the major contributor to objective indexes of sleep quality, a stronger women's sleep drive might explain women's better sleep quality in the results of polysomnographic studies. On the other hand, if a stronger women's wake drive can influence the perception of their sleep quality, this might be an explanation of their more frequent reports of sleep-related complaints.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Arcady A. Putilov http://orcid.org/0000-0003-2779-9046

Author contributions

Conceptualization AAP; Funding acquisition DSS and VBD; Data curation VBD, DSS, EBY, OVM, ANP, DES, EOG, AOT, NVL, and AAP, Resources AAP, DSS, and VBD; Project administration AAP, DSS, and VBD; Supervision AAP, DSS, and VBD; Software DES, ANP, DES, and AAP; Investigation VBD, ANP, and AAP; Methodology AAP, VBD, and DSS; Sleep scoring: ANP and EOG; Spectra calculation: DES; Validation AAP; Visualization AAP; Writing – review and editing VBD, ANP, DES, EOG, AOT, NVL, DSS, EBY, OVM, and AAP.

Data availability statement

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

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