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Age- and gender-associated differences in the sleepy brain's electroencephalogram

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Abstract

Background. With the eyes closed, an increase in sleepiness is associated with a decrease of spectral electroencephalographic (EEG) power in the high-frequency rage (i.e. alpha activity) and an increase of the power in the low-frequency range (i.e. theta activity). It has been suggested that the changes in the high- and low-frequency ranges might determine the two (earlier and later) drowsiness stages that precede sleep onset, respectively. *Objective*. We tested whether such spectral EEG signatures of sleepiness vary with age or gender. *Approach*. The EEG signal was recorded at 2 h intervals in 48 volunteers (15–67 years, 27 females) deprived of sleep between Friday evening and Sunday evening. The EEG signatures of sleepiness were calculated by expressing each EEG spectrum as a deviation from the initial (Friday evening) EEG spectrum. *Main results*. An age- and gender-specific variation was found in the signatures. Only the pattern of age-associated variation changed with an increase in the sleepiness level. A two-stage response to the increase of sleepiness was confirmed, but only in younger study participants. Subjective sleepiness was associated with neither age nor gender. *Significance*. In sleep-deprivation research, accounting for age- and gender-specific variations in the spectral EEG measures of drowsiness might be recommended. The results did not reveal any disturbance of the motivational function of subjective sleepiness in older study participants.

1. Introduction

With the eyes closed, sleepiness is associated with a decrease of spectral electroencephalographic (EEG) power density in the high-frequency rage and a change in the opposite direction in the low-frequency range, i.e. the alpha rhythm is attenuated, while the amplitudes of the theta and delta waves become larger (e.g. Lorenzo *et al* 1995, Leproult *et al* 2003, Strijkstra *et al* 2003, Marzano *et al* 2007, Putilov and Donskaya 2014). In practical terms, we proposed to determine two stages of drowsiness: the marker of the first stage is a change from predominantly frontal alpha activity to a low-voltage EEG without this activity, whereas the marker of the next drowsiness stage preceding sleep onset is an increase in the delta and theta powers (Olbrich *et al* 2009). However, whether such spectral EEG responses of the sleepy brain vary with age or gender remains to be explored. Sleep aging literature discusses such hypothetical age-associated pathologies as a reduction in the neural mechanisms that regulate the need for sleep and a desensitization to the homeostatic sleep drive (see Mander *et al* 2017, for a review of the evidence for and against this view). Consequently, we explored the possibility of the influence of the age and gender of the participants of sleep-deprivation experiments on the spectral EEG responses to prolongation of wakefulness. Our hypotheses were as follows:

- that age- and gender-specific variation would be found in the response of the EEG spectrum to an increase in the sleepiness level;
- that the pattern of such age- and gender-specific variation would vary, depending upon sleepiness level.

2. Methods

The paid volunteers were recruited for the two-day sleep-deprivation experiments from the staff of the combined medical research institutes and from the surrounding community. During a pre-experimental interview, 48 participants (27 females) confirmed that they had no current health problems, no history of psychiatric or sleep disorders, and no involvement in shift work or trans-meridian flights in the preceding month. Their ages ranged between 15 and 67 years with a mean age $\pm$ standard deviation of 36.6 $\pm$ 13.1 years. The participants represented three age categories, which we will call the younger, intermediate, and older ages in this paper (15–26 years, $n = 15$, 30–40 years, $n = 18$, and 46–67 years, $n = 15$). For a week prior to the experiment, they were asked to keep to a regular sleeping and waking schedule (i.e. not more than a 1 h difference for bedtimes and for waking times) and to report the history of their sleep for each of these seven days (i.e. bedtime, waking time, sleep onset latency, night sleep satisfaction, and nap frequency and duration).

On Friday evening, the participants were asked to arrive at the research unit of the Institute before 18:30 to stay there until Sunday evening (19:30). Twenty-five resting EEG recordings (2 min with the eyes open and then 5 min with the eyes closed) separated by 2 h intervals were scheduled between 19:00 on Friday and 19:00 on Sunday. The participants were informed about a bonus that depended upon the total duration of wakefulness maintained throughout the experiment. During the time interval between the 16th and 25th recording sessions, their payment gradually increased to up to 100% of the baseline payment. Despite this, 23 out of the 48 participants completed less than 25 recording sessions (12–23) and their dropping out was mostly explained by an irresistible desire to sleep.

Subjective sleepiness was self-scored before and after each EEG recording session using the nine-step Karolinska Sleepiness Scale (KSS, Åkerstedt and Gillberg 1990). To relate the KSS score to the objective (spectral EEG) sleepiness measures, the KSS scores reported by each participant in up to 25 EEG recording sessions were expressed as deviations from the initial score reported at 19:00 (Friday evening).

Participants were also engaged in questionnaire assessments and performance measurements. During their free time they were able to surf the Internet, watch TV, read, write, listen to music, and play board and computer games. Participants were able to freely move between several rooms of the research unit. Throughout the experiment, they consumed light snacks and drinks at self-chosen times (with the exception of alcohol and caffeinated beverages). The taking of any medication or heavy meals, smoking, vigorous physical activity, and exposure to light $>$500 lux were not allowed.

Frontal (Fz–A2) and occipital (Oz-A2) electrodes were used for all EEG recordings in accordance with the International 10–20 system of electrode placement. To fix the electrodes, Ten20 conductive paste (Nicolet Biomedical, Madison, WI, USA) was applied. The electrodes were removed after each EEG measurement. Their exact positions were preliminarily inked by permanent marker. The EEG signals were recorded by a 16-channel electroencephalograph (Neuron-Spectrum-2, Neurosoft, Ivanovo, Russia), and conditioned by high-pass, low-pass, and notch filters (0.5 Hz, 35 Hz and 50 Hz, respectively), sampled, and stored on a hard disc at a frequency of 200 Hz.

The EEG signals collected were visually inspected in 2 s epochs to remove all epochs containing artifacts from further analysis. The fastest Fourier transform in the West (FFTW) package (Frigo and Johnson 2005) was applied to compute spectral power densities for the artifact-free epochs (see www.fftw.org for more detail). Rectangular window taper was used on non-overlapping 1 s epochs to calculate the absolute spectral power densities (μV^2) for each of the first 16 single-Hz frequency bandwidths (i.e. 0.50–1.49 Hz, 1.50–2.49 Hz, 2.50–3.49 Hz, etc). Previously, this EEG dataset was used together with another dataset to develop a single spectral EEG measure of sleepiness calculated by summing 16 weighted single-Hz power densities of the EEG spectrum (Putilov *et al* 2019).

The single-Hz power densities were averaged over each one-minute interval of the EEG record and ln-transformed. These ln-transformed powers were further averaged over two derivations. Moreover, additional averaging was performed over two minutes with the eyes open, over the first two minutes with the eyes closed, and over the 5 min eyes-closed section (figure 1). Similarly to the subjective (KSS) sleepiness assessments, the values obtained from the 25 EEG recording sessions were subtracted from the values obtained in the first session (at 19:00 of Friday evening).

The $SPSS_{23.0}$ statistical software package (IBM, Armonk, NY, USA) was used to test the significance of the effects of the age and gender of study participant on sleepiness measures. Spearman's coefficient of correlation (ρ) was calculated to examine the associations of the time course of subjective (KSS) sleepiness with the time

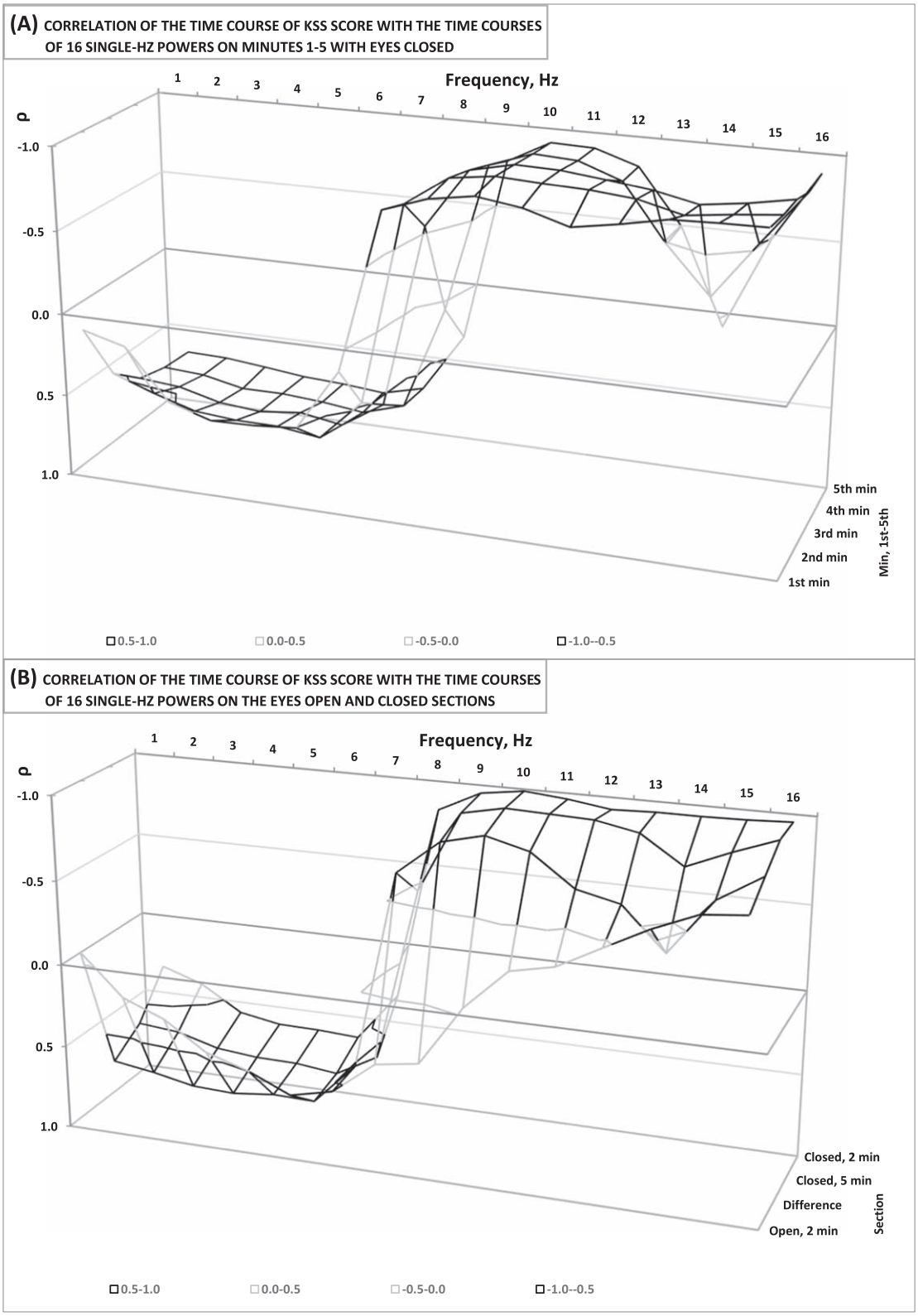

Figure 1. Correlations of the KSS time course with the time courses of 16 single-Hz powers. Each KSS score was expressed as a deviation from the initial KSS score at 19:00 and each of 16 spectral powers from 1 Hz to 16 Hz was expressed as a deviation from the initial power at 19:00. The time course of such KSS scores was correlated with the time course of each of the 16 spectral powers. The powers were either calculated separately for each of the five one-minute intervals of the eyes-closed section of the EEG record (A) or by averaging over several (two or five) minutes of the EGG record (B). Open, 2 min, closed, 5 min, and closed, 2 min: averaging over 2 min with the eyes open, the following 5 min with the eyes closed, and the first 2 min with the eyes closed; Difference: the difference between the eyes-open and -closed sections. Spearman's coefficient of correlation (ρ) below −0.50 and above +0.50 were significant with $p < 0.001$ ($n = 48$).

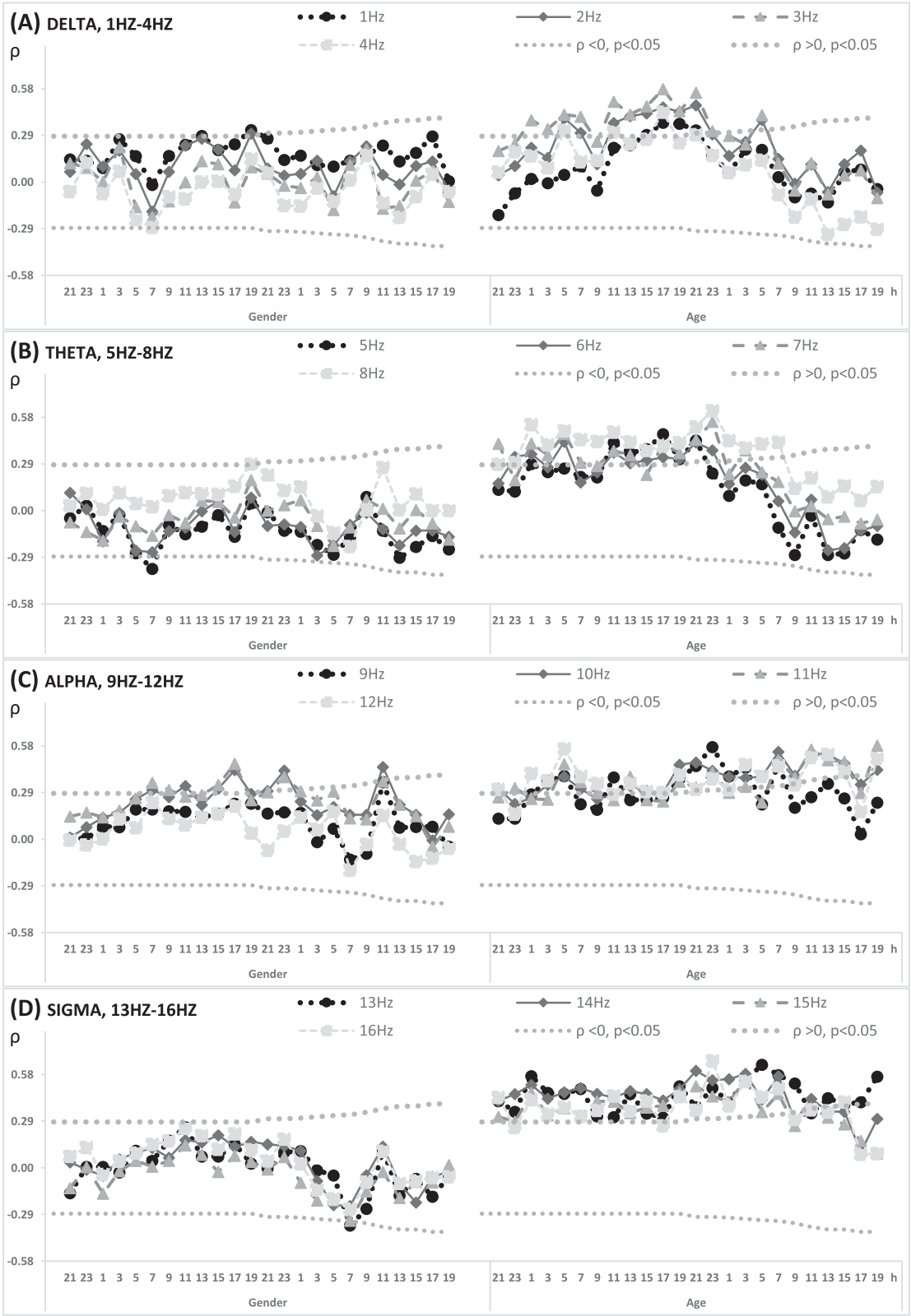

Figure 2. Correlations of single-Hz powers with age and gender. Data from the first 2 min with the eyes closed. Single-Hz spectral powers were correlated with age (years) and gender (1—male, 2—female), respectively. Spearman's coefficient of correlation (ρ) below −0.29 and above +0.29 were significant with $p < 0.05$ ($n = 48$).

courses of objective (EEG) sleepiness using the intervals of 25 EEG recording sessions (figure 1) and to relate sleepiness measures collected during the 25 EEG recording sessions to either age or gender (figure 2, left and right, respectively). The significance of the effects of the two independent factors 'Age' and 'Gender' on four intervals of twelve consecutive measurements of objective sleepiness were tested with four-way repeated

Table 1. Results of four rANOVAs with 'Age' and 'Gender' as independent factors.

Inter-subject effects			'Gender'		'Age'		Interaction	
Day	Time interval	*n*	*df*	*F*	*df*	*F*	*df*	*F*
1	21:00–19:00	48	1/42	1.50	2/42	8.14***	2/42	1.09
1–2	05:00–03:00	39	1/33	0.45	2/33	6.16**	2/33	0.57
1–2	13:00–11:00	29	1/23	0.31	2/23	2.26	2/23	0.60
2	21:00–19:00	25	1/19	0.46	2/19	1.97	2/19	1.82
Within-subject effects			Interactions of 'Gender' or 'Age' with 'Frequency'					
1	21:00–19:00	48	15/630	2.55**	30/630	1.98**	30/630	0.93
1–2	05:00–03:00	39	15/495	2.18**	30/495	1.93**	30/495	1.26
1–2	13:00–11:00	29	15/345	1.75*	30/345	3.17***	30/345	1.89**
2	21:00–19:00	25	15/285	0.60	30/285	3.53***	30/285	1.94**
Within-subject effects			Interactions of 'Gender' or 'Age' with 'Time'					
1	21:00–19:00	48	11/462	1.06	22/462	2.24*	22/462	1.17
1–2	05:00–03:00	39	11/363	0.57	22/363	1.15	22/363	0.95
1–2	13:00–11:00	29	11/253	0.48	22/253	0.64	22/253	0.54
2	21:00–19:00	25	11/209	0.99	22/209	1.00	22/209	0.87
Triple interaction of			'Gender' or 'Age' with 'Frequency' * 'Time'					
1	21:00–19:00	48	165/6930	2.04*	330/6930	1.51*	330/6930	0.95
1–2	05:00–03:00	39	165/5445	0.97	330/5445	2.08**	330/5445	1.08
1–2	13:00–11:00	29	165/3795	1.00	330/3795	2.21**	330/3795	0.78
2	21:00–19:00	25	165/3135	1.19	330/3135	1.10	330/3135	0.89

Note: Data from the EEG recorded during the first two minutes with the eyes closed. Differential spectra at intervals from 1 Hz to 16 Hz were obtained by relating all power spectra to the initial EEG spectrum (at 19:00). In four-way rANOVAs of spectra obtained for four overlapping 24 h intervals (from 21:00–19:00 of day 1 to 21:00–19:00 of day 2), the independent factors were 'Gender' (male or female) and 'Age' (younger, intermediate, or older), and the repeated measures were 'Frequency' (single-Hz frequencies from 1 Hz to 16 Hz) and 'Time' (12 time points divided by two-h intervals). Interaction: 'Age' by 'Gender' interaction; *df*: degree of freedom; *F*: F-ratio. Levels of significance for the *F*-ratio: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. Interactions of 'Gender' or 'Age' with 'Frequency' are illustrated by the correlations in figure 2. Triple interactions of 'Age' with 'Frequency' and 'Time' are illustrated by the correlations in figure 2, left. See also the results for the interactions of 'Gender' or 'Age' with 'Frequency' in figures 3(A) and (B) and the results for the time courses of powers for two of the 16 frequencies (6 Hz and 10 Hz) in figures 4(A) and (B).

measure ANOVAs (rANOVAs). The first of the two repeated measures was 'Frequency' (16 single-Hz spectral powers in intervals from 1 Hz to 16 Hz or four single-Hz spectral powers in four intervals, delta, theta, alpha, and sigma). The second measure was 'Time' (four overlapping time intervals, the first from 21:00 of Friday to 19:00 of Saturday and the fourth from 21:00 of Saturday to 19:00 Sunday). Mauchly's test was conducted to assess the sphericity. If necessary, the Greenhouse–Geiser correction was then used to adjust the degrees of freedom, but the original degrees of freedom are reported in table 1. A three-way rANOVA with the same independent factors ('Age' and 'Gender') and the same repeated measure 'Time' was run using the KSS scores to test the significance of the main effects of these independent factors on subjective sleepiness. Moreover, a two-way MANOVA with the independent factors 'Age' or 'Gender' was performed to examine age- and gender-associated differences in the baseline KSS score (19:00 of Friday evening) and at pre-experimental sleep times.

3. Results

The two-way MANOVA yielded significant age- and gender-related variation in sleep times during a week preceding the experimental sleep deprivation. The older study participants reported shorter sleep duration and earlier bedtimes and waking times compared to, at least, the younger participants (main effects of 'Age': $F_{2,42} = 4.307$, $p = 0.020$, $F_{2,42} = 3.276$, $p = 0.048$, and $F_{2,42} = 6.094$, $p = 0.005$, respectively). Moreover, a significantly earlier waking time was reported by the male participants (main effect of 'Gender': $F_{1,42} = 4.415$, $p = 0.042$). Neither age- nor gender-associated differences were found for other self-reports included in the sleep history (i.e. night sleep onset latency, night sleep satisfaction, and nap frequency and duration). Moreover, neither age nor gender was related to the subjective sleepiness (KSS) score obtained for the first EEG recording session (19:00 Friday evening).

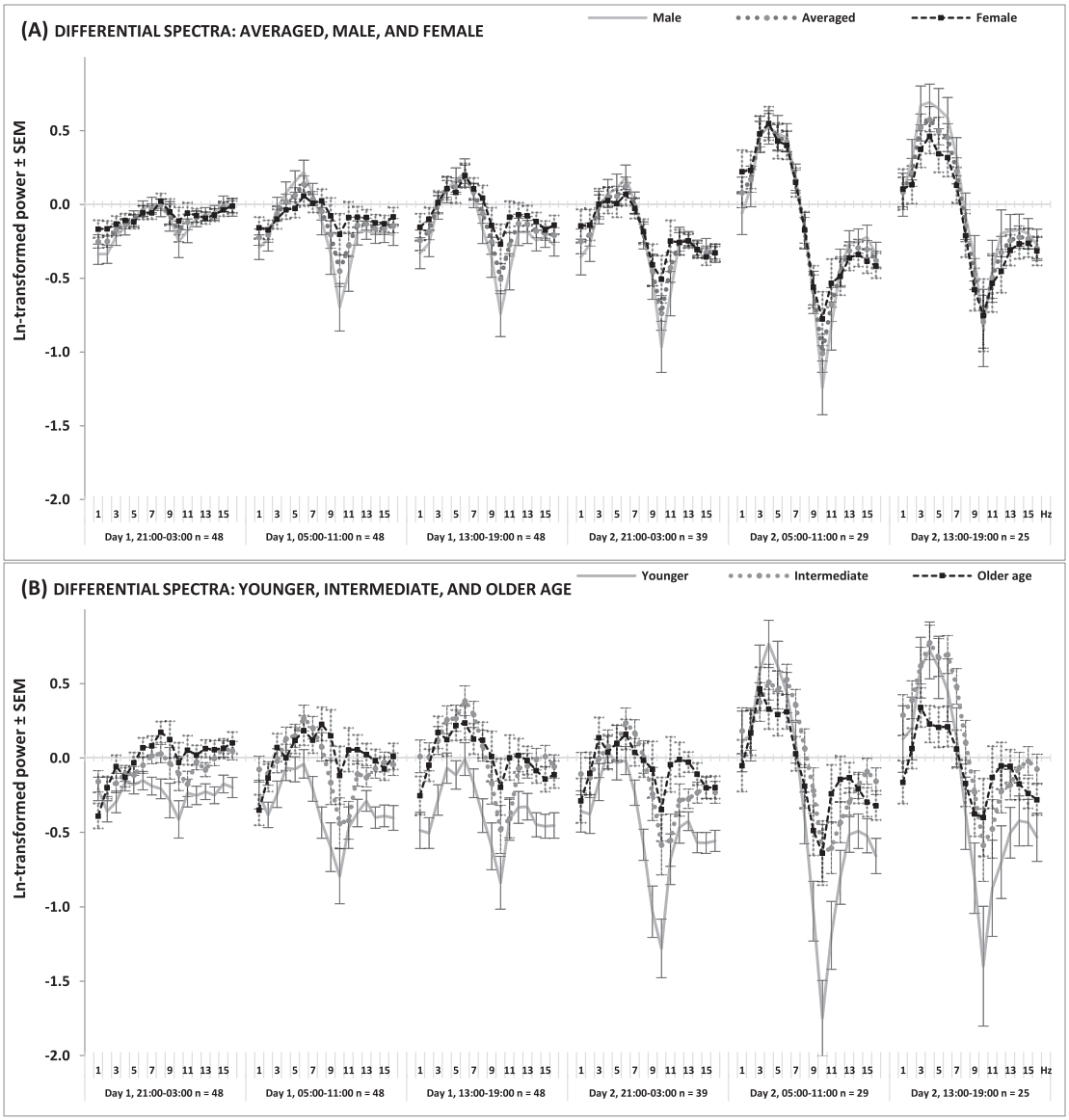

Figure 3. Differential spectra. Data from the first two minutes with closed eyes. Each EEG power spectrum for the intervals of frequencies from 1 Hz to 16 Hz was expressed as a deviation from the initial EEG power spectrum at 19:00. The frequencies from 1 Hz to 16 Hz were analyzed on six consecutive 8 h intervals using the data of the whole sample, two gender subsamples (A), and three age subsamples (B).

Figure 1 illustrates that, over the two-day period of the sleep-deprivation study, the time courses of the KSS scores correlated strongly with the majority of the 16 time courses of the single-Hz spectral powers. For instance, the correlations ($p < 0.001$) were reliably detected in the theta range, and especially in the alpha range. The strongest (less than −0.98) coefficient was shown by the time course of the 10 Hz power in the second minute with the eyes closed (figure 1(A)). Identically strong correlation coefficients were also obtained after averaging over the first two, or over all five minutes, with the eyes closed (figure 1(B)). Therefore, the single-Hz powers averaged over the first two minutes of the eyes-closed section of the EEG record were chosen to quantify the strength of the association of objective sleepiness with the age or gender of the study participants (figures 2–4).

Figure 2 illustrates that age and gender were significant correlates of some of the single-Hz powers (figure 2, left and right, respectively). The responses of the powers in the delta and alpha frequency ranges were more prominent in male than in female study participants (table 1 and figures 2(A), (C), 3(A), and 4(A)). This pattern of gender-specific variation remained unchanged throughout the sleep-deprivation study (figure 2, right, and 3A). In contrast, the pattern of age-specific variation changed profoundly (figure 2, left, and 3B). For example, the differential spectra of the younger participants were mostly lower than the spectra of the older participants for the majority of the frequency ranges. However, during the second day of the experiments, the differential spectral powers in the theta range became higher than those of the older participants, while the differential spectral powers in the alpha range remained lower (figures 3(B) and 4(B)). Therefore, during this day, younger

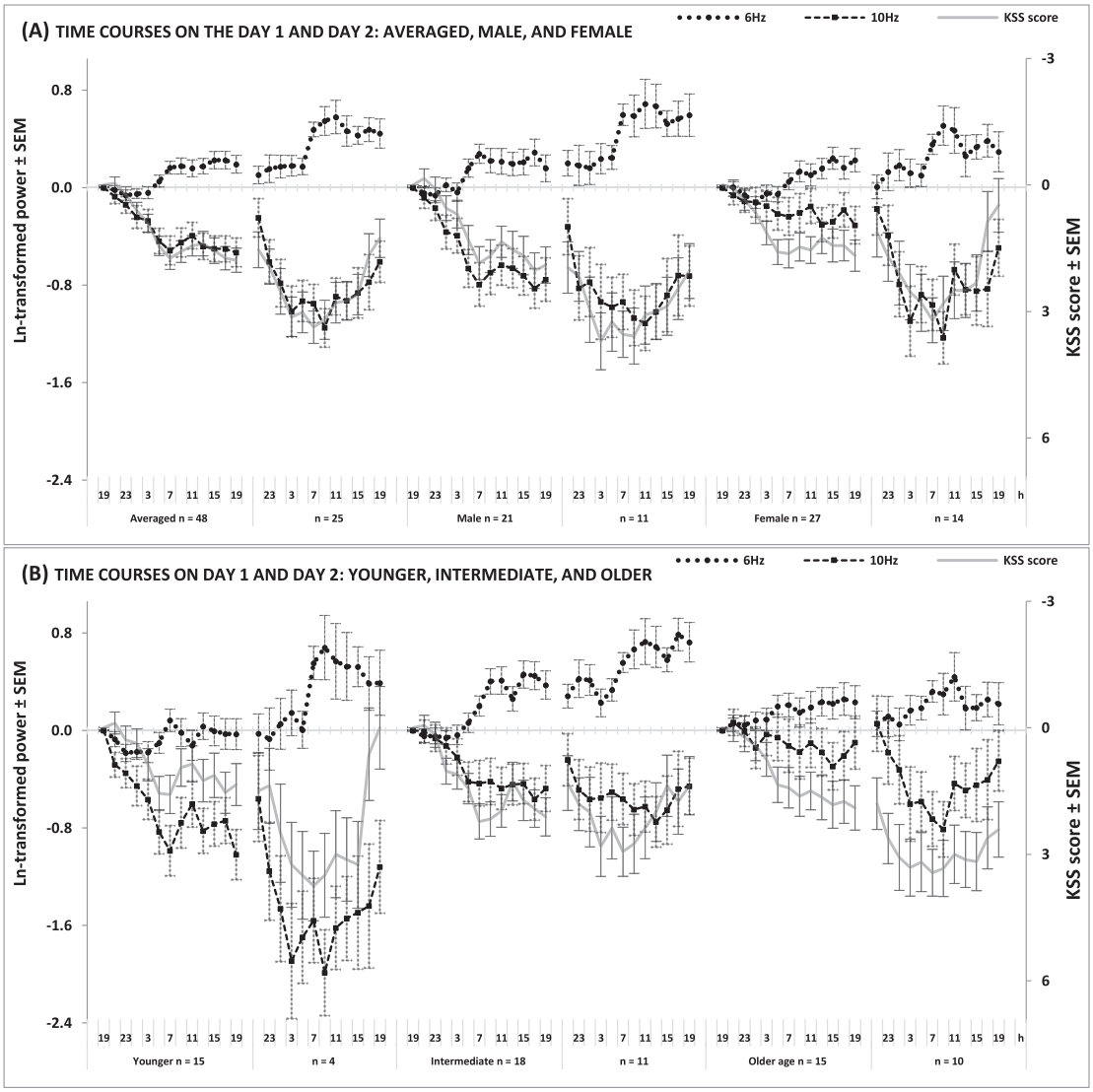

Figure 4. Time courses of sleepiness measures. The time courses of the KSS score and the time courses of the single-Hz powers are shown on the examples of the time courses for 6 Hz and 10 Hz. The time courses were calculated separately for the first and second day of the study, $n = 48$ and $n = 25$–42, respectively, for the whole sample, two gender subsamples (A), and three age subsamples (B).

participants demonstrated the highest amplitude of deviation from the initial spectrum in both the slow and fast frequency ranges, i.e. positive deviation in the theta range and negative deviation in the alpha range (figures 3(B) and 4(B)).

Such gender- and age-specific differences were significant, as indicated by four-way rANOVAs (table 1). The significant relationships of age or gender with some of the single-Hz powers (figure 2, left or right, and 3A or 3B) were statistically proved by the significant interactions of 'Age' or 'Gender' with 'Frequency' (table 1). The significant change in the relationship of age with some of the single-Hz powers (figure 2, left, and 3B) was statistically proved by the significant triple interactions, 'Age' by 'Frequency' by 'Time' (table 1).

Finally, table 2 contains results confirming the significance of the differences between younger and older ages in each of four frequency ranges: delta, theta, alpha, and sigma. It additionally confirms that, at least for slow frequency ranges, the differences between the younger and older ages became smaller during the second day of the experiment. Older participants already responded with an increase in theta power during the first day of the experiment, while in younger participants, this power did not deviate much from that of the alert state on this day. Only on the second day did their theta power respond in a similar way to the power of older participants (i.e. by an increase relative to the alert state). In contrast, younger participants already responded with a decrease of alpha power on the first day of the experiment, while, on this day, this power in older participants did not deviate much from that of the alert state. Only on the second day did their alpha power respond in a similar way to the power of younger participants (i.e. by a decrease, relative to the alert state). However, even on this day, the

Table 2. Results of 16 rANOVAs with 'Age' and 'Gender' as independent factors.

Inter-subject effects			'Age'		*p*: Younger versus		Intermediate
Day	Time interval	*n*	*df*	*F*	Older	Intermediate	versus older
Delta, 1 Hz–4 Hz							
1	21:00–19:00	48	2/42	3.54*	0.281	0.036	1.000
1–2	05:00–03:00	39	2/33	2.38	0.440	0.128	1.000
1–2	13:00–11:00	29	2/23	0.23	1.000	1.000	1.000
2	21:00–19:00	25	2/19	0.77	1.000	1.000	0.728
Theta, 5 Hz–8 Hz							
1	21:00–19:00	48	2/42	7.00**	0.009	0.036	1.000
1–2	05:00–03:00	39	2/33	4.70*	0.130	0.128	1.000
1–2	13:00–11:00	29	2/23	1.94	1.000	1.000	0.363
2	21:00–19:00	25	2/19	2.53	1.000	1.000	0.159
Alpha, 9 Hz–12 Hz							
1	21:00–19:00	48	2/42	4.69*	0.012	0.278	0.410
1–2	05:00–03:00	39	2/33	4.53*	0.015	0.739	0.231
1–2	13:00–11:00	29	2/23	4.56*	0.019	0.154	0.725
2	21:00–19:00	25	2/19	4.41*	0.025	0.079	1.000
Sigma, 13 Hz–16 Hz							
1	21:00–19:00	48	2/42	9.04**	0.002	0.002	1.000
1–2	05:00–03:00	39	2/33	8.29**	0.002	0.010	1.000
1–2	13:00–11:00	29	2/23	4.28*	0.064	0.034	1.000
2	21:00–19:00	25	2/19	3.66*	0.099	0.048	1.000

Note: Data from the EEG recorded during the first two minutes with the eyes closed. Differential spectra for the intervals from 1 Hz to 16 Hz were obtained by relating all power spectra to the initial EEG spectrum (at 19:00). In the four-way rANOVAs of four single-Hz powers (delta, theta, alpha, and sigma) obtained for four overlapping 24 h intervals (from 21:00–19:00 of day 1 to 21:00–19:00 of day 2), the independent factors were 'Gender' (male or female) and 'Age' (younger, intermediate, or older), and the repeated measures were 'Frequency' (single-Hz frequencies from 1 Hz to 4 Hz or from 5 Hz to 8 Hz or 9 Hz to 12 Hz or from 13 Hz to 16 Hz) and 'Time' (12 time points divided by two-h intervals). *df*: degree of freedom; *F*: F-ratio for main effect of factor 'Age'; *p*: younger versus intermediate or versus older, or intermediate versus older: *p* for *post hoc* pairwise comparison with the Bonferroni adjustment for multiple comparisons. Levels of significance for the *F*-ratio: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. See the results for the time courses of powers for two of the 16 frequencies (6 Hz and 10 Hz) in figures 4(A) and (B).

decrease in alpha power was significantly smaller in older participants, as compared to that of the younger participants (table 2 and figure 3(B)).

Therefore, irrespective of age, both theta and alpha ranges were involved in the response to sleep loss, with an increase in theta power and a decrease in alpha power relative to the spectrum of the alert state. However, participants of different ages differed in the development of their response to the increasing need for sleep throughout the deprivation experiment (figure 2, left, 3B and 4B, and tables 1 and 2). Similarly, both genders responded to sleep loss by an increase of the powers in the low-frequency ranges and a decrease of the powers in the high-frequency ranges. However, the male study participants demonstrated more pronounced responses in the delta, and especially in the alpha frequency ranges (table 1 and figures 2(A), (C), 3(A) and 4(A)).

The results suggested that, compared to other spectral powers, the alpha power is the most reliable and persistent marker of sleepiness, i.e. it was significant over the whole interval of the two-day sleep-deprivation experiment (figures 1–4). Similarly to the association with the subjective sleepiness assessment (figure 1), the association of alpha power with age or gender always followed the same trend (figures 2–4). Although the theta and delta powers were among other reliable correlates of sleepiness, their associations were not as strong, because these powers did not increase in the younger study participants during the first day of the sleep-deprivation experiments (figure 4(B)). However, the powers of these ranges already increased in older participants on this day (figures 3(B) and 4(B)). Therefore, during the first sleep-deprivation day, changes in the theta range might not serve as a good objective marker of sleep loss in younger participants, while changes in the alpha range might not serve as a good objective marker of sleep loss in older participants. Either of the two frequency ranges could serve as good markers for sleep loss in volunteers of intermediate age (figures 3(B) and

4(B)). During the second sleep-deprivation day, this age-associated variation in the differential spectra became less evident (tables 1 and 2).

In contrast to objective (spectral EEG) sleepiness, the subjective sleepiness (KSS) score showed no significant relationship with either age or gender (figures 4(B) and (A), respectively). Three-way rANOVAs yielded a result of 'no significance' for both the significance of the main effects of the independent factors ('Age' and 'Gender') and the significance of their interactions with 'Time'.

4. Discussion

We explored links between the age and gender of the participants of the sleep-deprivation experiment and the pattern of spectral EEG response to the increase of wakefulness duration. We found an age- and gender-specific variation in the spectral EEG signature of sleepiness, and a dependence of age- but not gender-specific variation for the sleepiness level. In general, our results for the spectral EEG response to sleep loss are in line with the previous reports indicating that, with closed eyes, sleepiness is associated with a decrease of the spectral power density in the high-frequency rage and an increase of the power in the low-frequency range (Lorenzo *et al* 1995, Leproult *et al* 2003, Strijkstra *et al* 2003, Marzano *et al* 2007, Putilov and Donskaya 2014). In a study of 15 people aged 19–35 years, Olbrich *et al* (2009) recommended that the first of the two stages of drowsiness should be identified using a change from predominantly frontal alpha activity to a low-voltage EEG without this activity, and that the next drowsiness stage preceding sleep onset should be identified by an increase of delta and theta power. These two stages were supported by the the results of this study, but only for younger participants. We additionally found that such staging cannot be extended to the spectral EEG of older people. The application of such a recommendation to these people might lead to an overestimation of the level of their sleepiness, due to the relatively early response of the low-frequency range to sleep loss. Such findings support the necessity to develop somewhat different spectral EEG criteria for levels of sleepiness in young versus old volunteers.

As we previously proposed (Putilov and Donskaya 2016, Putilov *et al* 2019), the brain's response to sleep loss might affect a wide range of frequencies of the EEG signal rather than only one of the traditionally recognized frequency ranges. The EEG changes in several ranges might reflect the underlying influence of at least two antagonistic sleep–wake regulation processes, i.e. the drivers for waking and sleeping. The change in each of the single-Hz powers might reflect the opposing influence of these drives and the strength of each drive might depend upon age, gender, duration of permanent wakefulness, and so on (Putilov and Donskaya 2016). Since the response that manifests as alpha-rhythm attenuation seemed to be very strong in younger participants, this power-decreasing response might already influence the neighboring theta range after moderate sleep loss by reducing the powers in this range. In contrast, due to the relatively higher strength of the opposing (power-increasing) response centered on the theta range in older participants, its influence on the neighboring (alpha) range might delay the reduction of the alpha rhythm. As a result, older study participants showed a relatively weak response in the alpha frequency range, by contrast with a relatively strong response in the theta range, whereas younger participants demonstrated a profound response in the alpha range, contrasted with a decay rather than a buildup of the powers in the delta and theta ranges.

Human sleep–wake behaviors change drastically with advancing age. Older adults often rise early, feel sleepy during the day, take a nap, go to bed early, have difficulty falling asleep and suffer from frequent night sleep interruptions and early morning awakenings. However, experimental studies of the age-associated differences in the adverse effects of night sleep deprivation have consistently revealed that acute sleep loss seems to be more disruptive for the young than for the old. In particular, older study participants are more resistant than younger participants to alertness impairment (e.g. Brendel *et al* 1990, Smulders *et al* 1997, Cajochen *et al* 2006, Duffy *et al* 2009, Dijk *et al* 2010, Landolt *et al* 2012, Putilov and Donskaya 2016, Zitting *et al* 2018). One could expect that younger adults become sleepier than older adults during experiments on the prolongation of wakefulness beyond its normal interval. However, such an expectation does not explain why younger adults do not go to sleep earlier, become sleepier during the day and nap more frequently under pre-experimental conditions. Our analysis of the subjective measure of sleepiness (KSS) score revealed the age independence of feeling sleepy in participants with significantly different sleep times that was, as expected, earlier in older participants compared to younger participants. It was proposed that the subjective sensation of sleepiness prior to habitual bedtime might have evolved to motivate humans to switch to sleep-preparatory behaviors from any other current daytime activities (Axelsson *et al* 2020). Therefore, the results for subjective sleepiness can be regarded as indicating the preservation of adaptive motivational function of subjective sleepiness in the old.

Moreover, the results suggesting the age-independent response of subjective sleepiness to sleep loss and the significant early changes in some of the objective measures of sleepiness in sleep-deprived older participants (e.g. the increase of theta activity during the first sleep-deprivation night) can be interpreted as providing evidence

against such hypothetical age-associated pathologies as a desensitization to the homeostatic sleep drive and a reduction in the neural mechanisms for regulating sleep need (see Mander *et al* 2017).

5. Conclusions

We revealed reliable associations of gender and age with objective, but not subjective, measures of sleepiness over the course of two-day sleep deprivation experiments. We also found that the pattern of age-specific variation in the EEG signature of sleepiness changed with an increase in sleepiness level. Therefore, the development of age- and gender-specific EEG criteria for sleepiness might be recommended for further sleep deprivation studies. The results also can be interpreted as suggesting that the motivational function of subjective sleepiness was not disturbed in older study participants.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical approval and informed consent

All procedures performed in these studies were conducted in accordance with the principles embodied in the Declaration of Helsinki. The protocols for the experimental sleep deprivation studies were approved by the Ethics Committee of the Institute for Molecular Biology and Biophysics of the Federal Research Centre for Fundamental and Translational Medicine, Novosibirsk, Russia.

Informed written consent to participate in the study was obtained from all individual participants included in the experimental study.

Authors' contributions

AAP and OGD designed and performed the sleep deprivation studies; AAP, OGD, VBD, and MGP contributed equally to the analysis of experimental data, and AAP wrote the paper.

Availability of data and material

On reasonable request to the corresponding author.

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