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ARTICLE

Effects of exposures to weak 2-Hz vs. 8-Hz electromagnetic fields on spectral characteristics of the electroencephalogram in afternoon nap

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ABSTRACT
The human brain seems to be able to respond to low-level extremely low-frequency electromagnetic fields. Controlled laboratory studies of human sleep under exposure to such fields are scarce, especially on the effects of 1 Hz – 16 Hz fields overlapping with the frequencies of the electroencephalographic (EEG) signal (e.g., delta, theta, alpha, and sigma activities). In a double-blind placebo-controlled study, we examined the effects of exposure to low-level electromagnetic fields of frequencies 2 Hz and 8 Hz on the EEG power density spectra in the range from 1 Hz to 16 Hz and sleep structure. Sleep of 14 young healthy volunteers was polysomnographically recorded during three 50-min afternoon naps (either without exposure or with 2 Hz/0.004 μT or 8 Hz/0.004 μT electromagnetic field). During the first 30 min of a nap the sham, 2 Hz or 8 Hz/0.004 μT exposures had the same effect. For the remaining 20 min, amount of stage 3 sleep and powers in 1 Hz-8 Hz range continued to build up under the 8 Hz/0.004μT and, especially, under the 2 Hz/0.004 μT exposure, whereas they did not change in the sham condition. Therefore, the low-level 2 Hz electromagnetic fields might stimulate deep sleep in the afternoon nap.

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Extremely low-frequency electromagnetic fields; EEG spectrum; delta sleep; slow-wave activity; sleep stages

Introduction

Life has evolved under exposure to extremely low-frequency electromagnetic fields (ELF-EMF) of low-level intensity from natural sources, such as the magnetic activity of the sun and the earth's fields. The human brain appears to be able to detect, absorb, and respond to low-level ELF-EMF (see Carrubba and Marino 2008, for review). In the post-industrial societies, the strengths of fields from all man-made sources can exceed those from natural sources by several orders of magnitude. It was estimated that a modern time long-term exposure to EMF can reach several tenths of μT (Ilonen et al. 2008). The studies of the effects of EMF on sleep provided results that are often inconclusive and/or contradictory.

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Since the effects might be mediated by either electromagnetic radiation at discrete frequencies or by broad-band white noise across the ELF spectrum, such epidemiological findings raise questions regarding whether there is a causal link between ELF and reported effects on human sleep (see the review by Ohayon et al. 2019, for more details on these discussions).

To date, there have been few-controlled laboratory studies on sleep under ELF-EMF produced in a narrow frequency range. They were inspired by the concerns about exposure to EMF generated by the electrical power grid and electrical devices with a frequency of either 50 Hz or 60 Hz (i.e., either in Europe or in North America). In a double-blind placebo-controlled study of 18 healthy volunteers, Åkerstedt et al. (1999) reported that night sleep was impaired by exposure to a 50 Hz/1μT EMF, but all changes in sleep characteristics were still within a normal range. In the study with between-subjects design reported by Graham and Cook (1999), continuous, intermittent (1-h off/1-h on), and sham exposure of 7–9 healthy men to a 60 Hz/28.3μT magnetic field was associated with an altered sleep architecture in one of the three (intermittent) exposure group.

A rather big proportion of daytime working people can benefit from afternoon nap that is regarded as a potent behavioural strategy minimizing sleepiness, fatigue, and impairments of cognitive and physical functioning (Takahashi et al. 2004; Milner and Cote 2009; Caldwell et al. 2009). Therefore, it is both of practical and theoretical importance to determine whether nap's efficacy can be increased by exposure to low-level EMF falling in the frequency range of slow waves (1 Hz-4 Hz) because these waves are generated by the brain during the deepest sleep stage. It remains unknown whether the low-level intensity ELF-EMF characterized by the profoundly lower than 50 Hz-60 Hz frequencies (e.g., between 1 Hz and 16 Hz) may interfere with human sleep characteristics. Since these frequencies are typical for natural ELF-EMF, they are of special interest in experimental elaboration. Besides, they overlap with the frequency range of the electroencephalographic (EEG) signal recorded from the surface of the human scalp. The specific frequency patterns emitted by the brain in the range between 1 Hz and 16 Hz were utilized by sleep researchers for subdivision of the sleep-wake state continuum into the wake and sleep stages. Namely, the low-frequency activity (<10 Hz) and the sleep spindle frequency activity (app. 12 Hz–15 Hz) are two silent features of Non-Rapid Eye Movement (NREM) sleep. They serve not only for distinguishing between sleep stages (Iber et al. 2007) but also as the markers of the underlying sleep-wake regulating processes (Borbély 1982; Borbély et al. 2016). In particular, the deepest stage of sleep stage 3 or slow-wave sleep, is characterized by slow waves in 1 Hz-4 Hz frequency range. It is believed that the amplitude of these waves reflects the intensity of the process of "payment" of sleep debt accumulated during preceding wakefulness (Borbély 1982; Borbély et al. 2016).

Previously, we examined whether an exposure to a low-level intensity 1 Hz EMF can increase the amount of this and other stages of NREM sleep (Dorokhov et al. 2019). We found that, under the exposure to 1 Hz/0.004 μT electromagnetic field, the total duration of sleep was significantly increased due to a significant increase of the amount of stage 2 sleep. The effect of on the amount of stage 3 sleep was non-significant despite the overlap of this intervention frequency with the frequency of slow waves. We concluded that the exposure to an extremely slow (1 Hz) electromagnetic field did not reveal any sleep-disturbing effects. Rather, the effects were beneficial for sleep. In the present study, we compared the effects of exposure to EMF of two different frequencies, 2 Hz and 8 Hz, for testing whether such exposure can modify spectral EEG power densities in delta and theta ranges during stages 2 and 3 of NREM sleep.

Consequently, we hypothesized that, due to the overlap of the frequencies of such fields with the frequencies of brain waves, they might promote stages 2 and 3 of NREM sleep stages in a 50-min afternoon napping attempt.

Methods

Study volunteers (14, 6 females) were recruited among university students. The exclusion criteria included the reporting inability to fall asleep on demand in the afternoon within less than 10 min, pregnancy or breastfeeding, age younger than 18 years, colds and missing classes during the previous 2 weeks, involvement in shift or night work, crossing several meridians during the previous month, irregular sleep-wake schedule (i.e., more than 1-h difference in bedtimes in 10 preceding weekdays), or frequent sleep deprivation (i.e., at least, two cases per week in the previous 2 weeks). The recruited volunteers also were required to deny the history of mental or sleep disorder and complaints about poor physical condition and functioning.

The participants visited the sleep laboratory three times with the intervals between these visits varying from 3 days to 1 month. Each visit lasted for less than 2 h. The napping attempts were not started earlier than midday and did not finish later than 5 p.m. The participants were uninformed about an exposure condition and order. They were randomly assigned to either sham or EMF exposure condition (7 vs. 7). From those 7 who were first exposed to EMF, 4 were exposed to 2 Hz and 3 were exposed to 8 Hz, and their sham exposure always occurred in the 3rd nap. From those 7 who were the first sham-exposed, 4 were exposed to 2 Hz and 3 were exposed to 8 Hz during their 2nd nap. The conditions did not differ on the number of female participants in either follicular or luteal phase of their menstrual cycle. The same was true for the nap order.

During the electrodes' application procedure, the participant was lying in bed in the sleep laboratory under dim light (app. 10 lux). He/she was instructed to try to nap after light off for the following 50 min.

A researcher switched off the light using a remote light controller, and the recording started with the first 5-min interval without any interventions. For the next 45 min, an EMF emitting device (the ELF-EMF generator "ECOSleep" certified by the State standard GOST R 0159555 from 15.12.2017) was set by a researcher either on or off. This device was placed at the distance of 700 mm from the participant's head to allow the generation of the 0.004 µT EMF around the head. It was unseen from the bed, and, during any of three naps, the participant cannot recognize whether it was switched on or off. An alternating magnetic field (inductance L = 0.5 µH with the resistance R = 15 Ω) was generated by the bifilar planar spiral coils (a coil diameter is 50 mm). The highest possible voltage of the field inductor was approximately 3 V. The current had the form of square 2 Hz or 8 Hz pulses with the duty factor equal to 0.5. To calculate the intensity of EMF at the distance of 700 mm from the device, the field parameters were measured with the BE-METP-AT-002 ("Indicator of parameters of electric and magnetic fields", verification certificate №AA 3,442,920/07356, OOO NTM-Zaschita, Russia). The intensity of EMF in the centre of inductor B_0 was 22 µT. The field B induced at the distance r was calculated as

$$B = B_0 * (r_0/r)^2$$

where r_0 was equal to 10 mm. The results of calculations suggested that, on the distance of 700 mm, EMF intensity reached 0.004 μT.

A 16-channel wireless system ("Neuropolygraph 24", Neurotech, Taganrog, Russia) was used for polysomnographic recordings. A monitoring montage for polysomnographic recordings were standard (one chin electromyogram channel, two electro-oculogram channels, and 13 EEG channels), and all electrodes were placed in accord with the International 10–20 system of electrode placement. The recorded signals were conditioned by the high-pass, low-pass and notch filters with the frequencies of 0.5 Hz, 35 Hz, and 50 Hz, respectively. The signals were sampled and stored on a hard disc with a frequency of 500 Hz. Two experienced scorers performed conventional visual scoring procedure (Iber et al. 2007) on 30-sec epochs of each 50-min record. They were uninformed about an exposure condition. During the preliminary scoring, each record was scored by the scorers independently, the initial agreement was found to vary depending upon a stage, but it was not lower than 85% for any stage. During the final scoring, they reexamined together all intervals with discrepant scores for producing consensus scores. The epochs was classified into stages including wake stage (W), REM sleep, and three stages of NREM sleep, stage 1 sleep or N1, stage 2 sleep or N2, and stage 3 sleep or slow-wave sleep or N3. In the present report, the amounts of sleep stages were analyzed on 5 10-min intervals of each 50-min record (Tables 1 and 2, and Figure 1(a)).

The EEG signals from 5 derivations (Fz, F4, Cz, Pz, and O2 referenced to the ear mastoid sites, M1/M2) were visually inspected on 1-s epochs for removing all epochs containing artifacts from further analysis. These EEG signals were used for calculating the EEG power density spectra (Figure 1(c)). The FFTW (Fastest Fourier Transform in the West) package (Frigo and Johnson 2005) was applied to compute power spectra densities for the artifact-free epochs (see www.fftw.org for more detail). In order to calculate absolute spectral power densities (μV2) for each of the first 16 single-Hz frequency bandwidth (i.e., 0.50–1.49 Hz, 1.50–2.49 Hz, 2.50–3.49 Hz, … , etc.) on 1-s epochs, hamming window was used. These 16 single-Hz power densities were averaged on each of 30-s intervals of EEG records (i.e., the interval of stage scoring) and in-transformed. The number of averaged 1-s epochs varied between 5 and 30. For statistical analyses, the individual in-transformed powers were further averaged (Figure 1(b,c)), e.g., over 5 derivations and within 10-min intervals, over the whole 16-Hz range (Figure 1(b)), and over 4 4-Hz frequency ranges, delta, theta, alpha, and sigma (Figure 1(b)).

The $SPSS_{22.0}$ statistical software package (IBM, Armonk, NY, USA) was used for running two-way repeated measure ANOVAs (rANOVAs), either on 5 10-min intervals or on the last two10-min intervals (Tables 1 and 2, respectively). The significance level was set at 0.05.

Results

Mean age ± standard deviation for 14 study participants was 19.43 ± 1.22 (ranged between 18 and 22 years). Mean self-reported durations of night sleep prior to the sham, 2 Hz, and 8 Hz exposures were 4.88 ± 3.05, 6.00 ± 2.61, and 5.69 ± 2.31 hours, respectively. Mean sleep onset (N1) latencies were 3.75 ± 2.86, 4.36 ± 2.06, and 5.50 ± 2.57 min, respectively. Mean latencies to N2 were 12.83 ± 8.26, 10.64 ± 5.76, and 15.00 ± 11.81 min, respectively. None of the differences between conditions was significant.

Table 1. Two-way rANOVAs of sleep stages and power density spectra in a 50-min nap.

Repeated measure	"Treatment"			Its interaction with "Time"		
Compared conditions	Sham-2 Hz	Sham-8 Hz	All three	Sham-2 Hz	Sham-8 Hz	All three
Sleep index	$F_{1/13}$	$F_{1/13}$	$F_{2/26}$	$F_{4/52}$	$F_{4/52}$	$F_{8/104}$
Amount of wake and three stages of NREM sleep, min:						
Amount of W	0.447	2.407	2.615	2.095	2.557	1.376
Amount of N1	1.960	2.981	2.429	1.169	0.705	0.902
Amount of N2	0.364	0.805	0.806	0.444	0.972	0.750
Amount of N3	0.826	1.720	0.864	4.197*	1.834	1.830
Amount of N2 + N3	2.901	0.185	1.132	2.794*	0.949	1.337
Spectral power densities, ln(μV^2):						
Averaged, 1 Hz-15 Hz	0.692	1.355	1.065	4.272*	1.430	2.113
Delta, 1 Hz-4 Hz	0.534	1.454	0.878	8.527***	3.507*	4.205***
Theta, 5 Hz-8 Hz	1.063	1.585	1.242	4.397*	2.275	2.586*
Alpha, 9 Hz-12 Hz	0.257	1.694	1.504	0.528	0.750	0.682
Sigma, 13 Hz-16 Hz	0.207	0.367	0.300	1.228	1.066	0.992

In two-way rANOVA, repeated measures were "Time" (5th 10-Min intervals of napping attempt) and "Treatment" (Sham vs. 2 Hz, Sham vs. 8 Hz, and All three: Sham vs. 2 Hz vs. 8 Hz). F_{df}: Mauchly's test was conducted to assess the sphericity and, if necessary, the Huynh-Feldt correction was used to adjust the degrees of freedom, but the original degrees of freedom are given in the 3rd line. Level of significance for F-ratio: $*p< 0.05$, $**p< 0.01$, $***p< 0.001$. The results are illustrated in Figure 1.

The results reported in Table 1 suggested that only slow-wave sleep (N3) and spectral power densities in delta and theta ranges (1 Hz-8 Hz) demonstrated significantly different time courses in three conditions. As can be seen in Figure 1, the action of the sham exposure did not differ from the action of the 2 Hz and 8 Hz/0.004 μT exposures only during the first 30 min of a nap. For the remaining 20 min, amount of stage 3 sleep, amount of the sum of stages 2 and 3, and powers in delta and theta ranges (1 Hz-8 Hz) did not show any increase in the sham condition. In contrast, they continued to build up under the 8 Hz/0.004 μT exposure and, especially, under the 2 Hz/0.004 μT exposure (Figure 1). When the analysis was limited to these 20 minutes (Table 2), the differences indicating a higher amount of deep sleep and higher power densities in delta and theta ranges were confirmed for the 2 Hz/0.004 μT exposure.

In a comparison of the sleep measures obtained in the 1st, 2nd, and 3rd naps, a significant influence of the order of exposure on the effect of 2 Hz EMF was not found ($p > 0.05$ for any interaction with an order of exposure as the independent factor in three-way rANOVAs).

Discussion

Controlled laboratory studies on human sleep under low-level intensity ELF EMF are scarce, and sleep-disturbing rather than sleep-promoting effects were reported in the experiments examining frequencies generated by the electrical power grid and electrical devices (50 Hz and 60 Hz). Since lower frequency range (1 Hz-16 Hz) overlaps with the frequency range of the most powerful spectral components of EEG signal emitted by the brain during N2 and N3 stages of NREM sleep, it is of special interest to test whether 2 Hz or 8 Hz EMF of close to natural intensity interferes with human sleep in the afternoon. The EMF of the particular ranges of delta and theta activity of the human brain might increase the amount of deeper sleep stages (N2 and N3) characterized by high amplitude activity in these two ranges and regarded an indicator of the restorative

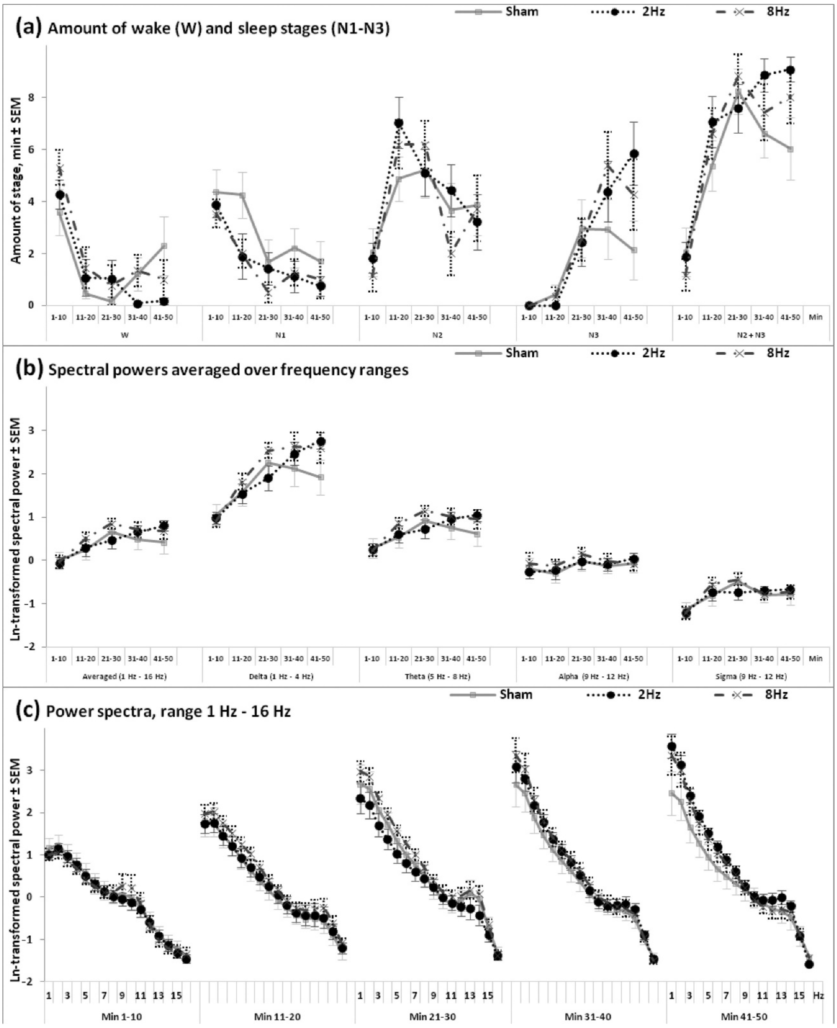

Figure 1. Sleep stages and spectral power densities throughout 50-min nap. A sequence of 5 10-min intervals of three-afternoon napping attempts (sham, 2-Hz and 8-Hz treatment at min 5–50); (a) sleep stages; (b) spectral powers in different frequency ranges, and (c) power spectra. See statistical results (two-way rANOVAs) in Tables 1 and 2.

function of sleep. In the previous pilot study, we tested the possibility to increase an amount of N3 and other NREM sleep stages by exposing healthy volunteers during minutes 10th–50th of an afternoon napping attempt to a low-level (0.004 μT) 1-Hz EMF. Although the amount of N3 remained unchanged in this exposure condition relative to the sham condition, the total duration of sleep become longer due to the increase of N2 amount. In the present blind placebo-controlled study, young healthy volunteers were exposed during minutes 5th–50th to a low-level (0.004 μT) 2-Hz and 8-Hz EMF. In addition to sleep stages, spectral power densities in the range between 1 Hz and 16 Hz were compared. For the last 20 min of an afternoon nap, amount of stages 2 and 3 and powers in delta and theta ranges (1 Hz-8 Hz) continued to build up only

Table 2. Two-way rANOVAs of sleep stages and power density spectra in the last 20 min of a nap.

Repeated measure	"Treatment"			Its interaction with "Time"		
Compared conditions	Sham-2 Hz	Sham-8 Hz	All three	Sham-2 Hz	Sham-8 Hz	All three
Sleep index	$F_{1/13}$	$F_{1/13}$	$F_{2/26}$	$F_{1/13}$	$F_{1/13}$	$F_{2/26}$
Amount of wake and three stages of NREM sleep, min:						
Amount of W	3.690	0.230	1.808	1.280	1.183	0.669
Amount of N1	1.599	0.678	1.028	0.006	0.003	0.163
Amount of N2	0.025	1.811	0.894	0.246	0.286	0.678
Amount of N3	3.084	2.854	1.953	5.435*	0.010	1.689
Amount of N2 + N3	8.852**	0.620	2.715	0.508	1.047	0.303
Spectral power densities, ln(μV^2):						
Averaged, 1 Hz-15 Hz	4.200	1.881	1.859	1.855	1.084	1.205
Delta, 1 Hz-4 Hz	4.961*	3.210	2.489	5.895*	2.644	3.103
Theta, 5 Hz-8 Hz	5.055*	2.004	2.156	3.418	2.061	2.184
Alpha, 9 Hz-12 Hz	0.347	0.197	0.112	0.469	1.030	0.383
Sigma, 13 Hz-16 Hz	0.897	0.064	0.072	0.022	0.008	0.016

In two-way rANOVA, repeated measures were "Time" (the last two 10-Min intervals of napping attempt) and "Treatment" (Sham vs. 2 Hz, Sham vs. 8 Hz, and All three: Sham vs. 2 Hz vs. 8 Hz). F_{df}: Mauchly's test was conducted to assess the sphericity and, if necessary, the Huynh-Feldt correction was used to adjust the degrees of freedom, but the original degrees of freedom are given in the 3rd line. Level of significance for F-ratio: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. The results are illustrated in Figure 1Table 3.

Table 3. Difference between sham and 2-Hz exposure in amounts of some of sleep stages and power densities in some of frequency ranges in the last 20 min of a nap.

Time interval	Min 31–40			Min 41–50			Averaged		
	Difference		Corre-	Difference		Corre-	Difference		Corre-
Sleep index	Mean	SEM	lation	Mean	SEM	lation	Mean	SEM	lation
Difference in amount of N3 or N2+ N3, min:									
Amount of N3	−0.75	0.67	0.407	−1.52*	0.67	0.419	−1.14	0.65	0.393
Amount of N2 + N3	−1.03**	0.28	0.795**	−1.45	0.67	−0.007	−1.24*	0.42	0.577*
Difference in spectral power densities, ln(μV^2):									
Delta, 1 Hz-4 Hz	−0.35	0.23	0.822**	−0.83*	0.32	0.621*	−0.59*	0.26	0.768**
Theta, 5 Hz-8 Hz	−0.23	0.12	0.896***	−0.47*	0.21	0.685*	0.35*	0.16	0.831***

Paired t-test for the values obtained for the last two 10-Min intervals of napping attempt in sham vs. 2 Hz exposure. SEM: Standard Error of Mean; Correlation: Paired exposures correlations. Level of significance for the difference or correlation coefficient: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. The results are illustrated in Figure 1.

under the 8 Hz/0.004 μT exposure and, especially, under the 2 Hz/0.004 μT exposure. In contrast, they did not show any increase in the sham condition. Therefore, a sleep-promoting action of the low-level 2 Hz electromagnetic fields might be manifesting in an increase of the amount of slow-wave sleep and slow-wave activity in the first 90-min cycle of sleep.

The major limitation of this study is the small size of our sample. Therefore, a demonstration of replicability of the revealed effects suggesting recovery function of a nap under the low-level 2 Hz electromagnetic fields in a larger sample is necessary. Moreover, further examination of such action of exposure to a low-level 2 Hz EMF might include the experimental comparison of different (lower vs. higher) frequencies (e.g., in the ranges of 1 Hz-8 Hz, 9 Hz-16 Hz, 17 Hz-32 Hz, and 33 Hz-64 Hz). Finally, further examination might be also aimed at testing a possibility of reducing latency to N2 by switching an EMF emitting device prior to napping attempt rather than on its 5th minute.

If such further experimental studies will lend support for the assumption of sleep-promoting rather than sleep-disturbing action of exposure to low-level ELF-EMF, such a non-invasive intervention might be recommended for improving the condition of afternoon naps taken for the reducing daytime sleepiness and fatigue. There are people believing that, in natural surroundings (e.g., under a tent or a wooden hut), they experienced improvement of their sleep not only due to the healthy atmosphere but also due to perceiving natural earth's magnetic fields. Therefore, the experimental studies of the effects of low-level ELF-EMF of different frequencies in the frequency range of the human EEG might be also aimed at testing such beliefs, and, if supported, the interventions with magnetic fields with the characteristics resembling the natural earth's fields might be used for enhancing the restorative function of sleep.

To conclude, in a double-blind placebo-controlled study, we examined whether an exposure to low-level electromagnetic fields (0.004 μT) of specific frequencies (placebo vs. 2 Hz vs. 8 Hz) affect sleep architecture and the EEG power density spectra in the delta, theta, alpha, and sigma frequency ranges during the napping attempts of 14 young healthy adults. We found that, as compared to the sham exposure, the 2 Hz/0.004 μT exposure is associated with a higher amount of deep sleep and higher power densities in delta and theta range during the last 20 min of napping attempt. The possibility of such a sleep-promoting rather than a sleep-disturbing action of this exposure requires replication.

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Disclosure statement

The authors have no conflicts of interest to declare.

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Ethical approval

All procedures performed in the studies were in accordance with the ethical standards of the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The protocols of the studies were approved by the Ethics Committee of the Institutes (#2 from 03.06.2019). Each participant of the experimental study was informed in detail about all procedures and gave his/her written consent.

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