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ARTICLE

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ABSTRACT

It was hypothesized that human sleep might respond to the fields emitted by such natural sources as magnetic activity of the sun and the earth's magnetic fields. However, the experiments aimed on testing this hypothesis remain scarce. Previously, we found an increase in the amounts of stages N2 or N3 during napping of good sleepers under exposure to low-level (0.004 µT) electromagnetic fields of frequencies 1 Hz or 2 Hz. It remains unexplored whether these fields might additionally decrease latency to stage N1. In this study, we selected 13 people with falling asleep problems to examine the effects of low-level electromagnetic fields on sleep latency. Sleep of these study participants was polysomnographically recorded during three 50-min afternoon napping attempts, either with exposure to either 2 Hz/0.004 µT or 8 Hz/0.004 µT electromagnetic fields or without exposure. We did not find that the sham exposure differed from the 2 Hz and 8 Hz exposures in latency to N1, while latency to N2 after the sham exposure was even shorter than after either the 2 Hz or 8 Hz exposure. We concluded that, although the effects of tested fields might be beneficial for sleep intensity (e.g., due to prolongation of N3), they might not be additionally effective against the falling asleep problems.

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KEYWORDS
Extremely low-frequency electromagnetic fields; EEG spectrum; sleep latency; sleep stages

Introduction

When people sleep under natural environment (e.g., under a tent or a wooden hut), they are exposed to electromagnetic fields (ELF EMF) of low-level intensity and extremely low-frequencies including the frequency of their brain activity. Some of them tend to experience a favorable effect of this natural environment on their sleep, and they tend to attribute this effect not only to the influence of healthy atmosphere but also to a beneficial effect of natural Earth's magnetic fields on their sleep. These fields are emitted by such natural sources as magnetic activity of the sun and the earth's fields. Carrubba and Marino (2008) concluded that the human brain is able to detect, absorb, and respond

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to low-level ELF EMF. In the environment of post-industrial societies, the strengths of fields from man-made sources can drastically exceed the strength of fields from natural sources. Long-term exposure of people to EMF can reach several tenths of μT (Ilonen et al. 2008). Usually, inconclusive and/or contradictory results were reported in the studies of the effects of EMF on sleep. The findings of epidemiological studies raise questions regarding a causal link between ELF and self-reported effects on sleep. Such effects of ELF might be mediated by either electro-magnetic radiation at discrete frequencies or by broad-band white noise across the ELF spectrum (reviewed and discussed by Ohayon et al. 2019). The experimental studies of these effects are scares. The controlled laboratory studies of sleep under ELF EMF were usually inspired by the concerns about the 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, respectively). For instance, in a double-blind placebo-controlled study of 18 healthy volunteers, night sleep was found to be impaired by exposure to a 50 Hz /1μT EMF, but all changes in sleep characteristics were still within a normal range (Åkerstedt et al. 1999).

In two previous studies, we tested the influence of EMF of even lower frequencies (from 1 Hz to 8 Hz) on sleep of healthy young people during afternoon napping attempts. We found that sleep might be intensified under the exposure to the fields with frequencies 1 Hz or 2 Hz, as indicated by an increase in the amounts of stages N2 (Dorokhov et al. 2019) or N3 (Dorokhov et al. 2021). For instance, in the latter study 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 nap, while, for the remaining 20 min, amount of N3 and EEG powers in delta and theta ranges (1 Hz–8 Hz) continued to build up under the 8 Hz/ 0.004μT exposure and, especially, under the 2 Hz/0.004μT exposure. Such further buildup was not observed in the sham condition (Dorokhov et al. 2021).

The participants of this previous study (Dorokhov et al. 2021) were good nappers. Each of them demonstrated sleep latency shorter than 8 min. Since the exposure to ELF started at the 6^{th} minute of each napping attempt, the effect of this exposure on sleep latency was documented. Therefore, it remains to be explored whether such intervention can be beneficent not only for sleep intensity of good sleepers but also for people with long latency to sleep. For instance, it would be of both theoretical and practical importance to answer such a question as: Can the exposure to ELF help a bad napper to enter to sleep in the afternoon? To address this question, we repeated the previous experimental study with bad rather than good nappers as the study participants (i.e., with those who, unlike the participants of the previous study, complained about the inability to fall asleep during the first 15 minutes of afternoon napping attempt).

Methods

Study volunteers (13, 6 females) were recruited among university students. The report of inability to fall asleep on demand in the afternoon within the first 15 min of napping attempt was the inclusion criterion. Such an inability was later confirmed for each of 13 volunteers by the results of polysomnographic sleep examination in sham condition. The exclusion criteria included pregnancy or breastfeeding, age younger than 18 years, history of mental disorder, complaints about poor physical condition and functioning, colds and missing classes during the previous two 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 two weeks).

The participants visited the sleep laboratory three times with the intervals between these visits varying from 5 to 25 days. The recordings were usually completed within 1 h somewhere between 1 a.m. and 4 a.m. They were uninformed about an exposure condition and were randomly assigned to either sham exposure or EMF exposure (7 vs. 6). From those 6 who were first exposed to EMF, 3 were exposed to 2 Hz frequency and 3 were exposed to 8 Hz frequency. From those 7 who started with sham exposure, 3 were exposed to 2 Hz during their 2nd nap while 4 were exposed to 8 Hz. The conditions did not differ on the number of female participants in either follicular or luteal phase of their menstrual cycle.

During the electrodes' application procedure in the sleep laboratory, the participant was lying in bed under dim light (app. 10 lux). When ready to the polysomnographic recording, he/she was instructed to try to relax after light off and to fall asleep, the earlier the better.

To switch off the light, a researcher used a remote light controller. The first 5-min interval of recording was always performed without any interventions. A device for EMF emitting (the ELF EMF generator "ECOSleep") was certified by the State standard GOST R 0159555 from 15.12.2017. It was unseen from the bed and it was set by a researcher either on or off for the next 45 min. Consequently, the participant cannot recognize whether it was switched on or off during any of three napping attempts. The distance from the device to the head of participant was 700 mm long. This allowed the generation of the 0.004 μT EMF at the head level. The bifilar planar spiral coils (with diameter of 50 mm) generated an alternating magnetic field (inductance L = 0.5 μH with the resistance R = 15 Ω). The highest possible voltage of the field inductor was around 3 V. In order to calculate intensity of EMF (the square-form current of 2 Hz or 8 Hz pulses with the duty factor equal to 0.5), the field parameters were measured with the indicator of parameters of electric and magnetic fields BE-METP-AT-002 (the verification certificate №AA 3,442,920/07356, OOO NTM-Zaschita, Russia). The intensity of EMF in the center of inductor B_0 was 22 μT. The induced field B 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 EMF intensity reached 0.004 μT at the distance of 700 mm between the device and head.

For polysomnographic recordings, a 16-channel wireless system ("Neuropolygraph 24", Neurotech, Taganrog, Russia) was used. A monitoring montage for these recordings was standard (one chin electromyogram channel, two electro-oculogram channels, and 13 EEG channels). 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. The conventional visual scoring procedure (Iber et al. 2007) was performed on 30-sec epochs of each 50-min records by two experienced scorers uninformed about an exposure condition. During the preliminary analysis, each record was scored by the scorers independently. For any of

Table 1. One- and two-way rANOVAs of sleep latencies, sleep stages and EEG spectra in 50-min nap.

Repeated measure	"Treatment"			Its interaction with "Time"		
Compared conditions	Sham-2 Hz	Sham-8 Hz	All	Sham-2 Hz	Sham-8 Hz	All
Sleep index	$F_{1/12}$	$F_{1/12}$	$F_{2/24}$			
Sleep length prior to nap	0.064	0.751	0.531			
Latency to N1	3.453	2.028	1.958			
Latency to N2	5.901*	5.490*	2.872			
	$F_{1/12}$	$F_{1/12}$	$F_{2/24}$	$F_{4/48}$	$F_{4/48}$	$F_{8/96}$
Amount of wake and three stages of NREM sleep, min:						
Amount of W	3.503	3.101	2.228	2.662*	1.186	1.459
Amount of N1	0.023	0.246	0.057	0.454	0.825	0.383
Amount of N2	6.484*	2.827	3.034	0.805	0.393	0.600
Amount of N3	1.050	2.065	0.837	1.245	0.763	0.841
Spectral power densities, ln(μV^2):						
Averaged, 1 Hz-15 Hz	3.114	0.012	0.280	2.751*	0.985	1.358
Delta, 1 Hz-4 Hz	7.922*	0.608	1.330	3.363*	2.536	2.246
Theta, 5 Hz-8 Hz	4.426	0.192	0.660	1.933	1.150	1.272
Alpha, 9 Hz-12 Hz	3.819	3.026	2.943	2.999*	1.135	1.409
Sigma, 13 Hz-16 Hz	3.746	0.202	0.956	2.991*	0.285	0.994

In one-way rANOVA (sleep latencies), repeated measure was "Treatment" (Sham vs. 2 Hz, Sham vs. 8 Hz, and All three: Sham vs. 2 Hz vs. 8 Hz). In two-way rANOVA (other sleep indexes), repeated measures were "Time" (5th 10-Min intervals of napping attempt) and "Treatment". Level of significance for F-ratio: *$p < 0.05$. The results of two-way rANOVAs are illustrated in Figure 1.

stages, the initial agreement was not lower than 85%. To produce consensus scores, the scorers reexamined together all intervals with discrepant scores. The epochs were classified into 5 stages, wake (W), REM (Rapid Eye Movement) sleep, and Non-Rapid Eye Movement (NREM) sleep stages N1, N2, and N3. The amounts of sleep stages W, N1, N2, and N3 were analyzed on 5 10-min intervals of each 50-min record (Table 1 and Figure 1 (a)). Latencies to the first occurrence of stages N1 and N2 were calculated for each nap (Table 1).

In order to remove all epochs containing artifacts from further analysis, visual inspection on 1-s epochs was performed for the EEG signals from 5 derivations (Fz, F4, Cz, Pz and O_2 referenced to the ear mastoid sites, M1/M2). These 5 EEG signals were used for calculating the EEG power density spectra (Figure 1(b,c)). Power spectra densities for the artifact-free epochs were computed using the FFTW (Fastest Fourier Transform in the West) package (Frigo and Johnson 2005; see www.fftw.org for more detail). In the calculations of absolute spectral power densities (μV^2) for each of 1-s epochs, Hamming window was used. Further analysis was limited to 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 each of 30-s scoring intervals, these 16 single-Hz power densities were averaged and ln-transformed. The number of 1-s epochs averaged on 30-s intervals was always larger than 5. The individual ln-transformed powers were further averaged for statistical analyses (Figure 1(b,c)) over 5 derivations and within 5 10-min intervals. Additional averaging was performed 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$_{23.0}$ statistical software package (IBM, Armonk, NY, USA) was utilized for one- or two-way repeated measure ANOVAs (rANOVAs), either on the whole 50-min napping

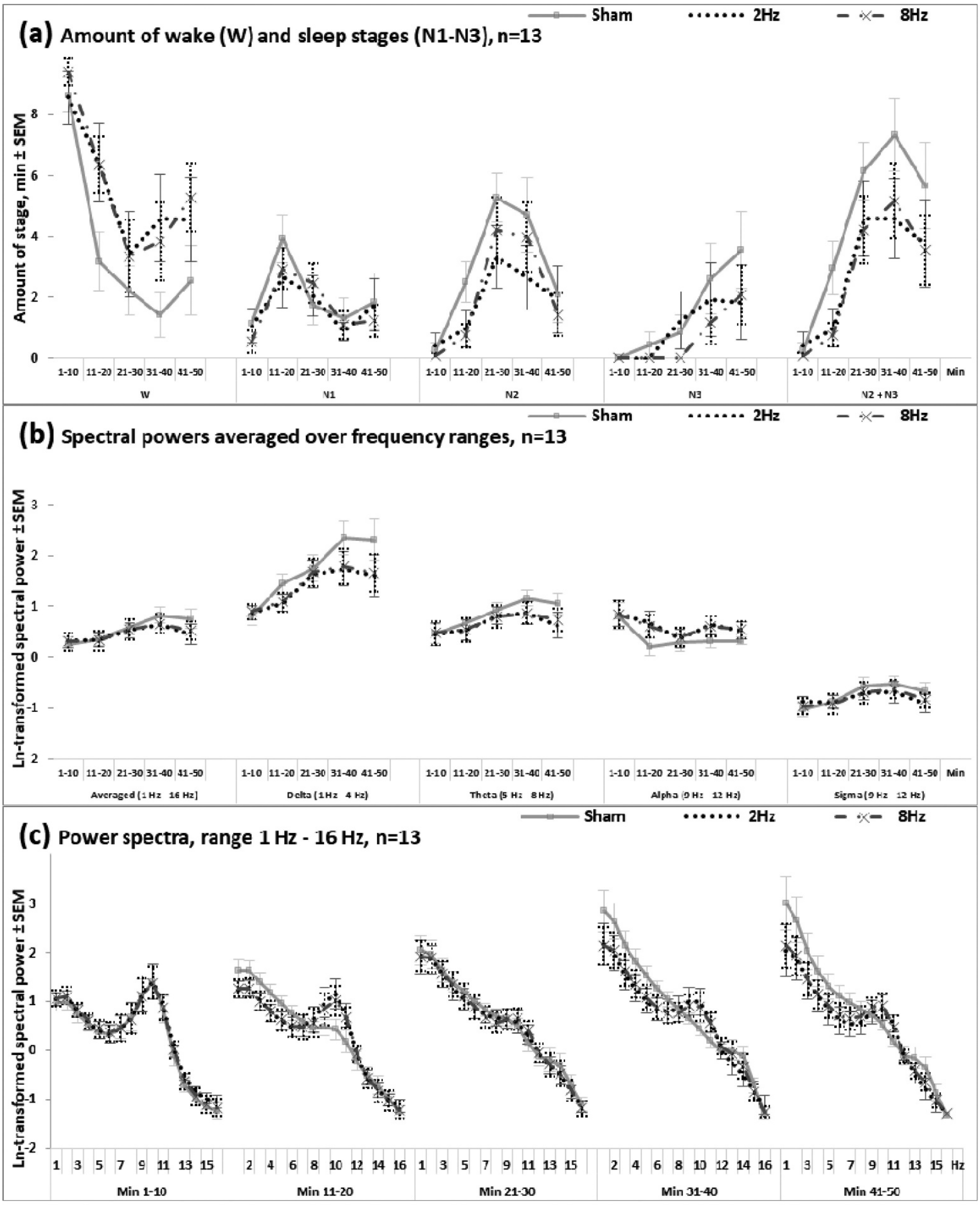

Figure 1. Sleep stages and spectral powers throughout 50-min nap. A sequence of 5 10-min intervals of three afternoon napping attempts (sham, 2-Hz and 8-Hz treatment at min 5–50); (a) sleep stages; (b) spectral powers for frequency ranges, and (c) power spectra. See significance of differences between conditions in Table 1.

interval or on 5 to 10-min intervals, respectively (Table 1). 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 Table 1).

Results

Mean age ± standard deviation for 14 study participants was 19.23 ± 1.48 (ranged between 18 and 22 years). Mean self-reported durations of night sleep prior to the napping attempt were 5.57 ± 2.19, 6.50 ± 2.01, and 6.44 ± 2.34 hours for sham, 2 Hz, and 8 Hz exposures, respectively. Mean sleep onset (N1) latencies were 11.79 ± 5.47, 23.68 ± 18.26, and 19.53 ± 14.37 min, respectively, and mean latencies to N2 were 18.45 ± 5.63, 29.72 ± 14.65, and 30.39 ± 14.79 min, respectively. As reported in Table 1, none of the differences between conditions was significant for self-reported durations of night sleep prior to napping attempt and for latency to N1. Pairwise comparisons indicated that latency to N2 was longer under exposure to the fields, either 2 Hz or 8 Hz, than in sham condition (Table 1).

Other results reported in Table 1 suggested that sleep under exposure to either 2 Hz or 8 Hz was not better than sleep without exposure. In pairwise comparisons with sham condition, sleep was worse under 2 Hz exposure as indicated by significantly smaller amount of N2 and significantly lower spectral powers, especially in low frequency ranges (Table 1 and Figure 1).

As indicated by the comparison of the sleep measures obtained in the 1st, 2nd, and 3rd naps, any influence of order of exposure on the sleep variables was non-significant (e.g., $p > 0.05$ for any interaction with order of exposure as the independent factor in three-way rANOVAs).

Discussion

The experimental studies of the effects of low-level ELF EMF of different frequencies might or might not provide support for the believes in beneficial influence of ELF EMF on human sleep. We tried to find evidence for improvement of objective sleep indexes under exposure to these EMF during afternoon nap that is regarded as a potent behavioral strategy minimizing sleepiness, fatigue and impairments of cognitive and physical functioning (Takahashi et al. 2004; Milner and Cote 2009; Caldwell et al. 2009). The exposure to magnetic fields with the characteristics resembling the natural earth's fields during such short naps might be utilized for enhancing their restorative function. We previously showed that, in the last 20 min of 50-min afternoon napping attempt, amount of N3 and powers in delta and theta ranges (1 Hz-8 Hz) continued to build up under the 2 Hz/0.004 μT exposure in contrast to a failure of such further buildup in the sham condition. Therefore, we suggested a deep-sleep-promoting action of the low-level 2 Hz electromagnetic fields (Dorokhov et al. 2021). However, due to short sleep latency in good sleepers selected for the previous study, we cannot examine the effect of these fields on sleep latency. Therefore, in the present study we further clarified the fact that such a beneficial action of 2 Hz/0.004μT might not be universal for various sleep stages. The study of poor nappers suggested that it might be limited to deeper sleep stages, especially N3, whereas these fields cannot accelerate the process of transition from wakefulness to N1 and N2 (i.e., the falling asleep process).

Such results – positive and negative – of two studies with the identical design require explanation. In the brain, the low frequency activity (<10 Hz) is the salient features of NREM sleep. It serves not only for distinguishing N3 from other stages (Iber et al. 2007) but also as the marker of the underlying sleep-wake regulating processes (Borbély 1982; Borbély et al. 2016). In particular, N3 is characterized by slow waves in 1 Hz–4 Hz frequency range and amplitude of these waves might reflect intensity of the process of "payment" of sleep debt accumulated during preceding wakefulness (Borbély 1982; Borbély et al. 2016). A stimulating influence of ELF EMF of 1 Hz or 2 Hz frequencies on slow waves might be an explanation of beneficial action of these fields detected in our previous studies (Dorokhov et al. 2019, 2021). Slow waves mostly reflect the influence of sleep drive on sleep and they are the major contributors to the score of the 1st principal component of the EEG spectrum, the marker of this drive's strength. However, the strength of opposing wake drive is associated with a score on the 2nd principal component of the EEG spectrum (Putilov et al. 2013). In one of our previous nap studies, we found that sleep latency depends exclusively from a score on this component, and does not correlate with a score of the 1st principal component of the EEG spectrum (Dorokhov et al. in press). Therefore, we might speculate that ELF EMF of 1 Hz or 2 Hz frequencies might stimulate the sleep drive associated with slow waves and with a score of the 1st principal component of the EEG spectrum, but not influence the wake drive associated with other ranges of the EEG spectrum and with a score of the 2nd principal component of the EEG spectrum.

Definitely, the findings of this and previous studies should be considered exploratory. The demonstration of their replicability in a larger sample is required. Moreover, it remains to be further explored whether ELF EMF of 1 Hz or 2 Hz frequencies might be beneficial not only for good sleepers but also for poor nappers (i.e., a relatively short, 50-min, interval of napping attempt did not allow the testing this suggestion in the present study). If such further experimental studies will lend support for the assumption of deep-sleep-promoting action of exposure to low-level ELF EMF, such a non-invasive intervention might be recommended for improving sleep.

Conclusion

We selected 13 poor nappers to test in three 50-min afternoon napping attempts whether the exposure to low-level electromagnetic fields of frequencies 2 Hz/8 Hz can accelerate the transition from wakefulness to sleep. We did not find the beneficial action of these fields on latency to sleep onset, and, therefore, we concluded that, although such fields might increase sleep intensity, they seem not to be effective for treatment of falling asleep problems.

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Disclosure statement

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

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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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