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Spending the night next to a router – Results from the first human experimental study investigating the impact of Wi-Fi exposure on sleep

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ABSTRACT

Background: The use of wireless telecommunication systems such as wireless fidelity (Wi-Fi)-enabled devices has steadily increased in recent years. There are persistent concerns that radiofrequency electromagnetic field (RF-EMF) exposure might affect health. Possible effects of RF-EMF exposure on human sleep were examined with regard to mobile phones and base stations, but not with regard to Wi-Fi exposure.
Objectives: The present double-blind, sham-controlled, randomized, fully counterbalanced cross-over study addressed for the first time the question whether a whole night Wi-Fi exposure has an effect on sleep.
Methods: Thirty-four healthy young male subjects (mean ± SD: 24.1 ± 2.9 years) spent five nights in the sleep laboratory. A screening and adaptation night was followed by two experimental nights. Each of the experimental nights was preceded by a baseline night. Sleep was evaluated at the subjective level by a questionnaire and at the objective level (macro- and microstructure) by polysomnography. Either 2.45 GHz Wi-Fi (max psSAR10g of 6.4 mW/kg) or sham signals were delivered by a newly developed head exposure facility.
Results: Results showed no statistically significant acute effects of a whole-night Wi-Fi exposure on subjective sleep parameters as well as on parameters characterizing the macrostructure of sleep. Analyses of the microstructure of sleep revealed a reduction in global EEG power in the alpha frequency band (8.00–11.75 Hz) during NREM sleep under acute Wi-Fi exposure compared to sham.
Discussion: The results of the present human experimental study are well in line with several other neurophysiological studies showing that acute RF-EMF exposure has no effect on the macrostructure of sleep. The slight physiological changes in EEG power observed under Wi-Fi exposure are neither reflected in the subjective assessment of sleep nor at the level of objective measurements. The present results are not indicative of a sleep disturbing effect of Wi-Fi exposure.

1. Introduction

Wireless (communication) technologies are virtually indispensable in the everyday (working) life for the majority of the general population. Location-independent access to the Internet can be realized, for instance, by connecting wireless fidelity (Wi-Fi) enabled devices to Wireless Local Area Network (WLAN) access points, which are usually provided by a router. Like most other wireless communications systems, the two currently available Wi-Fi standards (2.45 GHz and 5 GHz) use electromagnetic fields (EMF) in the radio frequency (RF) range (according to ICNIRP (2020): 100 kHz–300 GHz) for information transmission. The basis for the WLAN technology, which was designed for close-range data communications, is the IEEE 802.11 standard series. While in the 2.45 GHz frequency range, the maximum permissible effective isotropic radiated power (EIRP) is set to 100 mW (ETSI, 2006), the 5 GHz Wi-Fi variant allows, dependent on the used sub-band and national regulations, a maximum EIRP of up to 1000 mW (ETSI, 2012). For example, in Germany up to 200 mW EIRP are allowed in the 5.15–5.25 GHz band and in the 5.47–5.73 GHz band up to 1 W EIRP are allowed, provided that transmit power control and mitigation techniques are implemented, thus typical transmitted EIRP power will remain substantially below 1 W EIRP even in the 5 GHz frequency range. To

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guarantee adequate Wi-Fi coverage, the number of public and private access points has risen steadily in recent years. An E-communications household survey conducted among 26,730 EU citizens in the 27 Member States of the European Union in 2007 showed that at this time more than every fifth respondent (22%) used a Wi-Fi router at home. Compared to the two previous years, this was an increase by 8% and 11%, respectively (TNS Opinion and Social, 2008). SCENIHR (2015) notes that the number of sources of indoor exposure (including Wi-Fi) has increased over the years. The installation of a large number of short-range base stations for mobile/wireless communication according to various standards has led to shorter distances to the transmitters in everyday life. However, due to the low standardized maximum EIRP of e.g. Wi-Fi components, the cumulative exposure of several of these devices remains marginal compared to the reference levels of the international guidelines (SCENIHR, 2015).

Nevertheless, in the home environment Wi-Fi router are often placed very close to the sleeping quarters, especially in apartments or small houses. Therefore, under certain circumstances, the resulting Wi-Fi exposure level in this particular microenvironment may be higher than that of other RF-EMF sources. Breckenkamp et al. (2012) measured exposure to RF-EMF sources in 1348 German bedrooms at four fixed positions between 8 a.m. and 9 p.m. They observed that neither mobile phones nor broadcast were the main sources of exposure in this particular living area, but cordless phones and Wi-Fi. Together, these two sources accounted for 82% of total RF-EMF exposure. In a study by Tomitsch and Dechant (2015) daytime RF-EMF spot measurements at bedside were repeatedly performed in 103 households in 2006, 2009 and 2012 under conditions simulating a typical night's situation. Amongst others, they could show that indoor RF-EMF sources resulted in an increased exposure in the frequency range of Wi-Fi over the years. Bolte and Eikelboom (2012) analyzed 24 h personal exposimeter measurements from 98 volunteers aged between 19 and 81 years, which were recorded during 39 everyday activities. Though exposure from cordless phones was the main contributor for most activities at home, sleeping was dominated by Wi-Fi exposure. For homes in general and bedrooms in particular, Markakis and Samaras (2013) also reported highest Wi-Fi exposure levels during the night in the course of the day.

A Eurobarometer survey revealed that a part of the population is concerned about possible health effects resulting from RF-EMF sources related to mobile communications systems, i.e. mobile phones and mobile phone base stations (TNS Opinion and Social, 2010). At the symptom level, sleep problems are among the most commonly reported complaints (Huss et al., 2004; Roosli et al., 2004). Several human experimental studies have been performed to investigate effects of RF-EMF exposure (mainly emitted from mobile phones) on sleep. Results of these studies were, however, quite heterogeneous. While some observed RF-EMF effects on selective sleep parameters, others did not (for a summary, see Danker-Hopfe et al. (2016)). For Wi-Fi, in contrast, survey data as well as studies that specifically addressed Wi-Fi exposure on sleep are lacking. However, there are lots of commentaries, forum postings and some anecdotal evidences on the Internet suggesting that a Wi-Fi exposure may affect human health in the same way as other RF-EMF sources do. For example, the nonprofit organization *Environmental Health Trust* has published strategies to reduce the level of RF-EMF exposure in sleep areas, which are expected to have a positive impact on nocturnal sleep. Among other things, they recommend to turn off the Wi-Fi router at night and to avoid placing the router, and other electrical devices, close to the bedroom (Web Page: https://ehtrust.org/five-strategies-improving-sleep/; Last access date: April 25, 2020).

Given that there is similar public concern about Wi-Fi exposure as there is about mobile telephony, and that Wi-Fi exposure contributes more to total exposure at night than during the day, it was obvious to address this problem in an experimental study. To the best of our knowledge, this is the first study that explored experimentally possible effects of Wi-Fi exposure on sleep. The present study specifically aimed to answer the following questions: Does a whole night Wi-Fi exposure affect (1) subjective sleep quality, (2) the macrostructure of sleep (i.e. outcome parameters related to sleep-wake times, sleep initiation and sleep architecture), (3) arousals and stage shifts during sleep (sleep maintenance parameters) and (4) the power spectra of the sleep EEG? Furthermore, the study addressed the question whether unconscious concerns related to Wi-Fi exposure may affect sleep.

2. Materials and methods

2.1. Sample size considerations

The sample size was calculated based on previous work of the same research group. It was shown that statistical analysis of data from 30 participants using parametric statistical approaches for paired comparisons with a two-sided significance level of 5% and a power of 80% revealed predominantly medium-sized exposure effects. To be able to detect even smaller exposure effects it was intended to recruit at least 34 participants for the present study.

2.2. Participants

The sample comprised 34 healthy young male participants from Berlin or the surrounding area in the age range from 20 to 30 years (mean ± SD: 24.1 ± 2.9 years). They all had a school graduation entitling them to study at university. Nine of the participants had already completed their studies, eight of them were employed and one was job-seeking. The remaining twenty-five participants were still university students. Irrespective of employment status, however, all activities were predominantly office work with light physical activity. Only right-handed non-smokers were included. Individuals with a history of a psychiatric, neurological and/or sleep disorder were excluded. At the time of inclusion, participants (1) were good sleepers [Pittsburgh Sleep Quality Index (PSQI) score < 5; Buysse et al. (1989).], (2) had no extreme morning/evening preference [Morningness-Eveningness Questionnaire (MEQ) score ≥ 31 or ≤ 69; Horne and Östberg (1976)], (3) had no excessive daytime sleepiness [Epworth Sleepiness Scale (ESS) score < 10; Johns (1991)] and (4) had no indication of depression or somatic symptoms as assessed by a medical examination and validated questionnaires [Patient Health Questionnaires (PHQ-9 and PHQ-15) scores ≤ 5 and ≤ 10, respectively; Spitzer et al. (1999)]. Participants had a regular sleep-wake schedule as assessed by a sleep diary (Liendl and Hoffmann, 1999), which was filled out for two weeks prior to inclusion. Furthermore, a regular intake of medication that affects the central nervous system, excessive caffeine and/or alcohol consumption, regular and occasional drug use, as well as metal implants were considered as exclusion criteria. To include the estimated number of eligible participants various recruiting strategies were followed. Amongst others, these strategies comprised posted flyers, electronic advertisements and word-of-mouth advertising (for numbers of excluded subjects, see Fig. S1).

The study was approved by the ethics committee of the Charité - Universitätsmedizin Berlin (EA4/071/17). All participants gave their written informed consent and received a monetary compensation for participation.

2.3. Experimental design

The double-blind, sham-controlled, randomized fully counterbalanced cross-ever study comprised five nights in the sleep laboratory (see Fig. 1). An adaptation and screening night was followed latest one week later by two consecutive nights: the first experimental night (EN), which was preceded by a baseline night (BL) to control sleep quality prior to experimental interventions. Exact one week later (to ensure that ENs were performed at the same day of the week) the last two nights (again a BL followed by an EN) were scheduled. Subjects were told to avoid caffeine and alcohol intake at the days preceding a night in

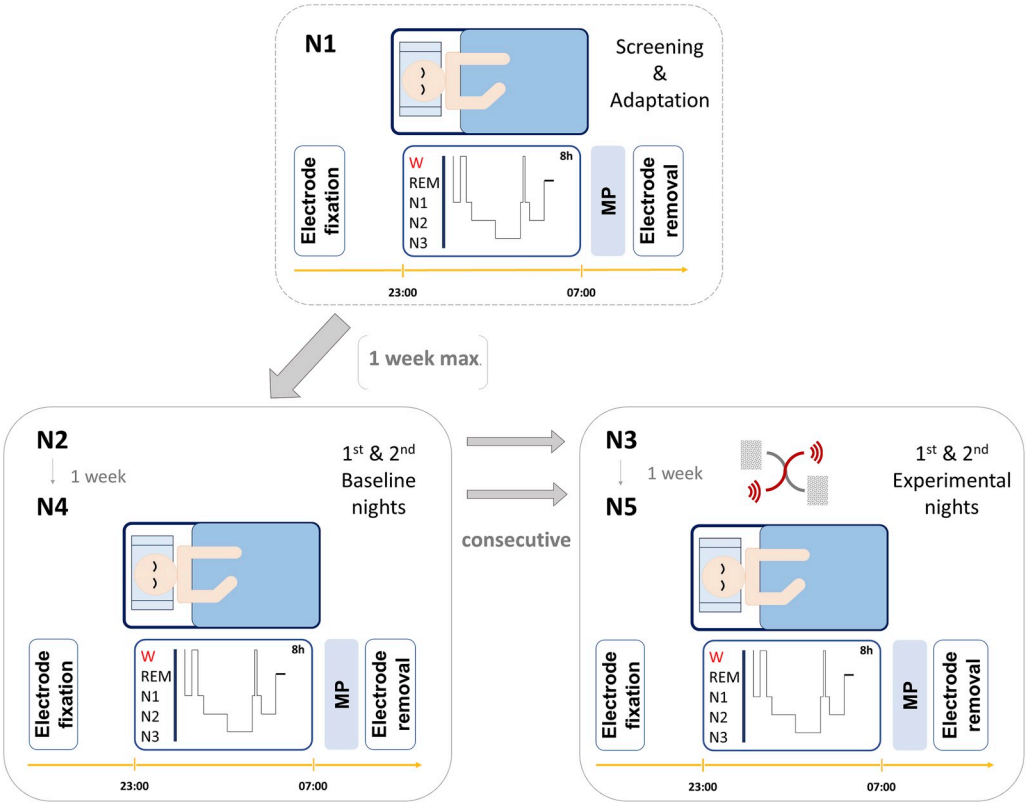


Fig. 1. Study design. The first night (N1) served as an adaptation and screening night. The second (N2) and fourth night (N4) were baseline nights (BLs) with no intervention. They were immediately followed by the experimental nights (ENs) N3 and N5, respectively, in which Wi-Fi ("Wi-Fi" symbol in red) and sham (grey square) exposure were applied in a double-blind counter-balanced cross-over design. N2 took place latest seven days after N1, and the second set of a BL and EN (N4/N5) was scheduled exactly one week later. For all nights, participants arrived at the laboratory at 19:00 h and the electrodes were fixed. Light out times varied slightly according to the individual bedtimes between 22:25 h and 23:45 h. Time in bed (from lights out to lights on) was exactly 8 h. After awakening, participants filled out a morning protocol (MP). Finally, electrodes were removed and participants were allowed to have breakfast and to leave the lab. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the sleep laboratory. Immediately after arrival at the sleep laboratory, alcohol consumption was controlled by a breathalyzer test. The cut-off to proceed was 0.00 mg/L. In addition, the participants were asked to hand in all their personal electronics upon arrival. This was to ensure, firstly, that they were not exposed to any additional RF-EMF source from the time they arrived at the lab and, secondly, that no electronic devices were inadvertently brought into the study room, which could have compromised the double-blind procedure. Furthermore, this measure also served to control the use of electronic media during the stay in the laboratory, so that an evening or night-time exposure to blue light emitted from the screens of the electronic devices could be excluded. For each participant, "lights out" time was adjusted to the individual bedtime (approximately between 22:45 and 23:45) and kept constant during the study. Since the duration of each sleep recording was set to 480 min, individual "lights on" time was accordingly between 06:45 and 07:45 in the morning.

The sequences of the two exposures for the EN (verum-sham or sham-verum) were randomly assigned to participants by a list implemented in the software. To keep the counterbalanced design, the software for the double blind control of the exposure system provided a function for correction when participants dropped out of the study. Their sequences were re-used for new participants in a randomized manner to assure blinding.

2.4. Sleep recording and evaluation

Sleep recordings took place in a room that was completely shielded from daylight. Sleep was evaluated at a subjective and at an objective level. Subjective data was collected by means of a standardized morning protocol (Hoffmann et al., 1997). Subjective information comprised total sleep time (sTST [min]), sleep onset latency (sSOL [min]), wake after sleep onset (sWASO, [min]), absolute number of awakenings (sAWA) and restfulness of sleep. The latter was assessed using the five categories: (1) very restful, (2) quite restful, (3) moderately restful, (4) hardly restful, and (5) not at all restful.

Objective data were obtained by polysomnography (PSG) recorded and analyzed according to the international standard of the American Academy of Sleep Medicine (AASM; Iber et al., 2007). A PSG requires the placement of electrodes for the recording of the electroencephalogram (EEG), the electromyogram and the electrooculogram during sleep. The six mandatory EEG electrodes of this standard were complemented by 13 additional electrodes placed to cover all positions of the international 10/20 system (Jasper, 1958). Sleep was registered with a Polysmith recording system (Neurofax EEG-9200, Nihon Kohden, Tokio, Japan). Subjects with a periodic leg movement arousal index > 10/h (which is indicative of a sleep related movement disorder) and/or an apnoe-hypopnoe-index > 5/h (which is indicative of a sleep related breathing disorder) in the AN were excluded from further participation. In the BLs and ENs, only those bio-signals essential to sleep scoring were recorded.

PSG data were evaluated by experienced human scorers according to the AASM standard published by Berry et al. (2018). From these evaluations, 24 parameters describing the macrostructure of sleep [e.g. sleep onset latency (SOL), total sleep time (TST), sleep efficiency index (SEI), distribution of sleep stages] as well as six arousal parameter could be derived. In addition, to explore time varying effects during the night, 15 macrostructure variables were analyzed separately for the first and the second half of the night. All parameters considered in this paper are listed in Table S1 of the Supplement together with a brief description.

To test whether a Wi-Fi exposure affects the microstructure of sleep spectral power of the sleep EEG was analyzed. Whole night power spectra were averaged for each sleep stage separately. Frequency resolution was 0.25 Hz. A frequency range of 0.50 Hz–19.75 Hz was investigated. Additionally, mean spectral power densities were analyzed for EEG frequency bands defined according to the recommendations by Jobert et al. (2013): Delta [0.50–4.00 Hz[, Theta [4.00–8.00 Hz[, Alpha [8.00–12.00 Hz[, Beta1 [12.00–16.00 Hz[and Beta2 [16.00–20.00 Hz[.

Power spectral values were calculated for each 30 s epoch and for 19 EEG signals derived from locations Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1 and O2 to the averaged mastoids

as the common reference. Within each epoch, spectral values were averaged according to Welch's method (Welch, 1961): Segments of 4 s, overlapping 2 s, were used, resulting in 14 segments per epoch. A von-Hann taper function was applied on each segment. For the exclusion of segments contaminated by artifacts two different criteria were used. The first criterion was related to the amplitude of the signal. If the difference between the absolute maximum and absolute minimum values exceeded a certain limit, the respective segment was excluded. To prevent K-complexes and delta waves from triggering the artifact detection while maintaining sufficient sensitivity of the artifact criterion in lower amplitude EEG, the amplitude limits were set to different values depending on the sleep stage assigned to the epoch. Hypnogram data for the PSGs were used to set a limit of 300 μV peak-to-peak for stage N2 and N3 and a limit of 150 μV peak-to-peak elsewhere. Disturbances from the utility grid (50 Hz) interfere with the artifact detection as they shift the sensitivity towards lower amplitudes. To prevent this interference, a notch filter (IIR 2nd order, Q = 5) was applied on all PSG data prior to further processing. The second criterion referred to the extraordinary power for higher frequencies in the EEG. This indicates muscle artifacts and noise from other disturbances and is similar to an artifact detection method used by Adamczyk et al. (2015); if the average (root mean square) signal in the frequency range 19.8–45.5 Hz exceeded a limit of 5.75 μV, the referring segment was excluded.

Epochs were only included into analysis if at least 10 of the 14 segments were present after artifact removal. As a check against technical problems in recordings, log-transformed spectra of stage N2 sleep were visually inspected for all locations in all PSGs prior to unblinding. Qualitatively deviating curves indicating a dominating non-EEG content of the signals were identified in a few recordings at single locations (overall 6 cases). The data recorded from these locations were excluded from further analyses.

2.5. Shielding measures

The PSG recording input device was housed in a specifically designed screening case with EEG signal lines fed through RF blocking filters to prevent RF interference of experimental exposure signals with the bio-signal recording. RF interference may compromise blinding and can lead to false-positive results (Fouquet et al., 2013). Presence of electrode leads modifies the RF field distribution (Angelone et al., 2010). To reduce these effects, electrode cables featuring a high RF impedance were constructed and used for PSG recording.

Experiments were done in a shielded room equipped with wooden furniture. External electromagnetic fields in the 75 MHz–3 GHz range were below the measuring threshold of 0.03 V/m (at 100 kHz resolution bandwidth). The residual electric field strength at 50 Hz (power grid) was 1–2 V/m.

2.6. Exposure conditions

In ENs there was either a sham exposure (no signal at all) or the head region of participants was exposed to 2.45 GHz Wi-Fi signals delivered by a specially designed exposure facility using six antennas positioned around the head in a hexagonal arrangement (see Fig. 2). 2.45 GHz Wi-Fi signals were used as they have significantly higher penetration depths compared to 5 GHz Wi-Fi radiation, and therefore higher absorption can be expected in deeper brain regions. A particular timing scheme simulating varying network utilization was repeated every 6 min. The peak spatial specific absorption rate was set to < 25 mW/kg for the maximum. The time average over 6 min was < 6.4 mW/kg. This represents a scenario of comparably “strong” Wi-Fi exposure, but is still realistic in a home setting. The basis for the determination of the exposure parameters was a standard access point at a distance of 1 m working at high capacity. Exposure (verum or sham) was applied for the whole night (8 h from lights out to lights on). For further exposure related details please refer to Schmid et al. (2020).



Fig. 2. Structure containing the antennas. Six commercially available Wi-Fi patch antennas were positioned every 60° along a circle of 0.6 m radius in order to meet the requirement of an almost uniform exposure of the head regardless of the subject's position.

2.7. Study blinding

The present study was performed double-blind, i.e. neither the participants nor the persons involved in data collection and in data pre-evaluation (sleep scorer) knew the exact exposure condition (verum or sham). In order to evaluate whether blinding of the participants was successful, they were asked after both ENs whether they thought that a real Wi-Fi exposure (verum) or no exposure at all (sham) took place. Three response options were given: “*yes*”; “*no*” and “*I don't know*”. Based on these responses, James Blinding Index (BI; James et al., 1996) and its 95% confidence interval (95% CI) were computed. The degree of blinding is given by a standardized value between 0 and 1 provided that weights of 0 and 1 are assigned to correct and “*I don't know*” responses, respectively, and that the weight for wrong guesses is a value something in between (here: 0.75). A BI of zero corresponds to a complete lack of blinding, a BI of 0.5 indicates random guessing and a BI of one constitutes perfect blinding. Blinding can be considered as unsuccessful if the upper 95% confidence limit of the BI is smaller than 0.5.

2.8. Assessment of concerns

Participants were asked to complete a questionnaire on concerns about several environmental factors, including some sources of RF-EMF exposure. Information was assessed by the same questions as used in surveys commissioned by the German Federal Office for Radiation Protection. A question on concerns about Wi-Fi was added with the same response options as for the other environmental factors: (1) seriously concerned, (2) fairly concerned, (3) little concerned, and (4) not concerned at all. Additional information on Wi-Fi in the home environment was collected, and if present, subjects were asked to estimate the distance of the Wi-Fi router from the bed.

2.9. Statistical analyses

As this is the first Wi-Fi study related to sleep, the statistical analysis was not hypothesis-driven but rather of an exploratory nature. Wi-Fi exposure effects on subjective and objective sleep parameters as well as possible variations between the two baseline conditions were investigated performing within sample pairwise analyses based on individual differences by means of t-tests for paired observations. To provide an estimate of effect size Cohen's d_{av} with the average standard deviation of both repeated measures as standardizer was computed. Additionally, corresponding 95% CIs were calculated using a SAS

macro (Kadel and Kip, 2012). Cohen's d_{av} can be interpreted according to the following benchmarks: no effect = $|d_{av}| < 0.2$, small effect = $0.2 \leq |d_{av}| < 0.5$, medium effect = $0.5 \leq |d_{av}| < 0.8$, large effect = $|d_{av}| \geq 0.8$ (Cohen, 1988).

The same statistical approach was used to address the questions whether unconscious concerns about the upcoming (unknown) exposure affect sleep. This was tested by pooling subjective and objective sleep parameters for BLs (participants were aware that no exposure was applied) and ENs (participants did not know whether sham or verum exposure was applied).

To explore possible Wi-Fi exposure effects on the spectral sleep EEG power, repeated measures analyses of variance (RM-ANOVA) were carried out with the within-subject factors EXPOSURE (Wi-Fi vs. sham) and REGION as well as their INTERACTION. The 19 electrodes were aggregated to six topographic brain regions, for which EEG power values of the following electrode positions were averaged: Fp1, Fp2 (Frontopolar); F7, F3, Fz, F4, F8 (Frontal); C3, Cz, C4 (Central); T3, T4, T5, T6 (Temporal); P3, Pz, P4 (Parietal); O1, O2 (Occipital). To overcome the problem of distorted spectral parameters the suggestion of Gasser et al. (1982) was followed to use the natural logarithm of absolute EEG power values for further analyses in order to approximate normality of the data. RM-ANOVAs were performed for each of the five sleep stages (N1, N2, N3, NREM and REM) separately. The factor REGION was introduced to address the problem of multiple testing in case of a statistically significant effect by reducing the number of post-hoc tests. However, since it turned out that post-hoc analyses in case of a statistically significant REGION effect are not directly related to the topic of the present paper, these analyses were deliberately omitted. Partial eta squared (η_p^2) and generalized eta squared (η_G^2) (Olejnik and Algina, 2003) point estimates were given as measures of effect size. According to Lakens (2013) the latter can be interpreted against the following benchmarks also provided by Cohen (1988): no effect = $\eta^2 < 0.010$, small effect: $0.010 = \eta^2 < 0.060$, medium effect: $0.060 = \eta^2 < 0.140$, large effect: $\eta^2 \geq 0.140$. Due to the fact that the sphericity was more or less violated in all cases, Greenhouse-Geisser adjusted p values were reported. For exploratory purposes, sleep stage- and brain region-specific follow-up tests based on univariate pairwise analyses [bootstrap permutation tests for comparing the means of paired data; Wicklin and Nc (2010)] between verum and sham exposure conditions were conducted for each of the five frequency bands separately.

As mentioned above, the standardized morning protocol uses a 5-point scale to measure the restfulness of sleep. As two of the five categories were inadequately represented, responses were collapsed into three categories [(1) very restful, (2) quite restful, (3) moderately restful]. The remaining categories were statistically analyzed using the Stuart-Maxwell marginal homogeneity test.

A double-sided significance level of 0.05 was considered for all statistical analyses, which were carried out with SAS (version 9.4).

3. Results

While 54 volunteers had to be excluded from study participation throughout recruitment, all but one of the participants, who dropped out due to time constraints, completed the study after randomization. For the flow of participants from enrollment to analysis, we refer to Fig. S1 in the Supplement.

3.1. Blinding and concerns

To test the efficacy of participants' blinding James' BI was calculated. A value of 0.78 (95% CI: 0.68; 0.87) indicates a successful blinding.

The results obtained by the questionnaire on concerns are displayed in Fig. 3. The data show that the young healthy men of the present study do not bother very much about environmental factors related to RF-EMF emissions from different sources. The use of mobile phones raised the strongest concerns among these factors (seriously concerned: 3%; fairly concerned: 6%). Worries about WLANs and mobile phone base stations were similarly low (seriously concerned: 0%; fairly concerned: 3%). Thirty-two of the 34 (94.1%) participants had a Wi-Fi rooter in their home environment. The mean distance (± SD) to the bed was 6.6 ± 3.9 m (range 2–20 m).

3.2. Impact of exposure expectation on subjective and objective sleep variables

A comparison of subjective and objective sleep parameters between pooled BLs and pooled ENs underlined that the expectation of possible adverse RF-EMF exposure effects did not result in statistically significant differences in the subjectively assessed sleep quality (see Table S2 in the Supplement). Nor was the macrostructure of sleep relevantly affected by these expectations. As can be seen in Table S2, the percentage of stage R sleep and, very probably due to this, the number of arousals during stage R sleep were slightly higher during ENs when compared to the pooled baseline conditions, while the corresponding arousal index did not differ.

3.3. Baseline nights

To control for effects due to variations in the timing and duration of sleep in the nights prior to the ENs, participants spent these nights in the controlled set-up of the sleep laboratory. As in the ENs, the time in bed was set to 480 min. The SEI in the BLs prior to sham ENs was (mean ± SD) 91.6 ± 5.4% and in the BLs prior to Wi-Fi ENs 91.3 ± 6.9%, reflecting comparably sufficient sleep before both ENs [$t(33) = -0.26$; $p = 0.7943$; $d_{av} = -0.05$ (95% CI: −0.40; 0.30)]. This is also documented by subjective total sleep times [BLs before Sham: 454.7 ± 32.6 min, which corresponds to a mean SEI of 94.7%; BLs before Wi-Fi: 463.7 ± 33.3 min, SEI: 96.6%; $t(33) = 1.51$; $p = 0.1415$; $d_{av} = 0.27$ (95% CI: −0.09; 0.63)]. BLs and ENs were scheduled to start at fixed individual bedtime between 22:45 and 23:45.

3.4. Subjective sleep parameters

T-tests for paired observations showed that subjective sleep parameters were not significantly affected by a whole night Wi-Fi exposure. A small but not significant effect was observed for the sTST, which was longer under Wi-Fi exposure (see Table 1). The Stuart-Maxwell test revealed that exposure had no statistically significant effect on overall self-assessment of restfulness of sleep [$Q(2) = 0.39$, $p = 0.8212$] meaning that individual responses to this question did not show a clear exposure-dependent assessment trend in either direction.

3.5. Sleep architecture and arousals

Table 1 further indicates that outcome parameters describing the macrostructure of sleep and arousal parameters as derived from PSG did not differ significantly between exposure conditions. Furthermore, most Cohen's d_{av} point estimates reflect no effect ($|d_{av}| < 0.2$ for 26 out of the 30 variables; 86.6%). The $|d_{av}|$ point estimates of the other four variables reflect small effects up to a maximum value of 0.28. Small, but not significant effects were observed for the SPT, which was longer under Wi-Fi exposure, and the LPS, which was shorter following Wi-Fi exposure. A non-significant small effect was also shown for stage N1 sleep (in minutes and as percentage of TST), which was increased under Wi-Fi exposure as compared to sham. Visualization of the individual hypnograms does also not reflect a systematic effect of exposure on sleep (see Fig. 4).

While statistical analyses of the outcome parameters describing the macrostructure during the first half of the night yielded overall no statistically significant results, Wi-Fi exposure resulted in an increased

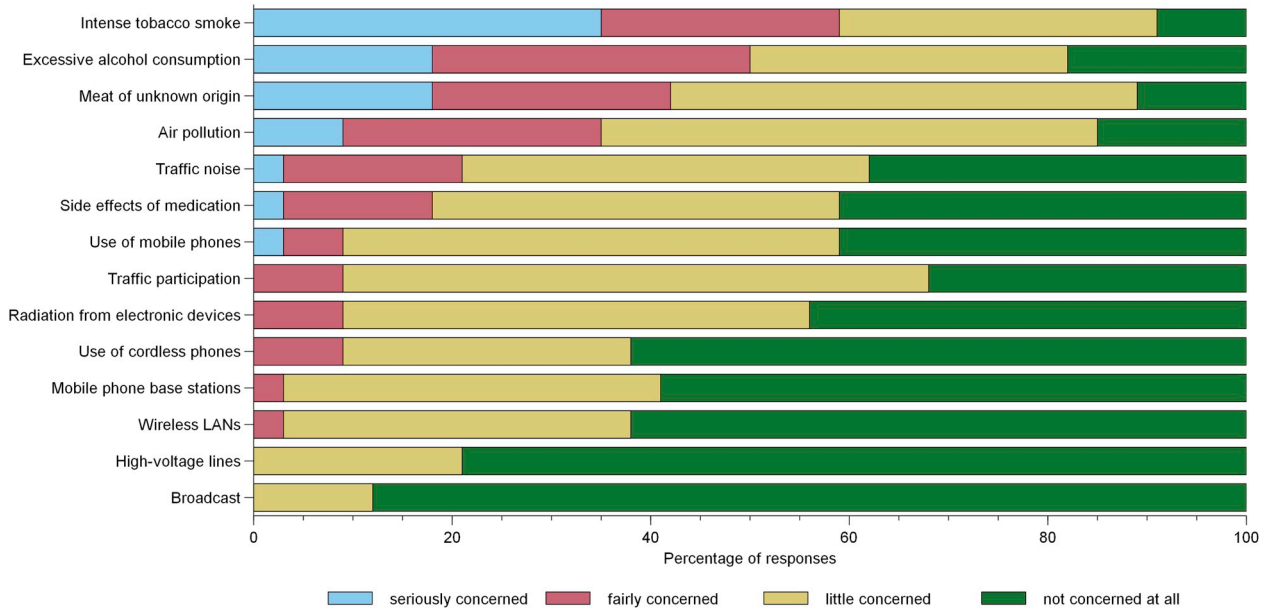


Fig. 3. Concerns about diverse environmental factors. The questionnaire was evaluated based on relative response percentages. To compare the concerns/worries related to each environmental factor response percentages were sorted in a decreasing order by the degree of concern.

amount of stage N1 sleep (in min) during the second half of the night (see Tables S3 and S4 in the Supplement).

3.6. Power spectra of the sleep EEG

Results of the RM-ANOVAs are shown in Table 2. As indicated in this Table, there was one statistically significant overall main EXPOSURE effect on brain activity affecting the EEG power in the alpha frequency band during NREM sleep. Summary Table S5 of descriptive statistics and Fig. 5 show that global EEG Power was significantly decreased under Wi-Fi exposure when compared to sham exposure. All other statistically significant main effects refer to the factor REGION indicating that EEG power values for all frequency bands differ between brain regions (see Table 2).

Follow up pairwise analyses revealed four statistically significant results (See Fig. S2 and Table S6 in the Supplement). The EEG power in the delta frequency band was affected by Wi-Fi exposure during sleep stages N1 and NREM over temporal and occipital brain regions, respectively. Furthermore, Wi-Fi exposure had an effect on the EEG power in the beta2 frequency band over temporal brain regions in sleep stage N3 and on the EEG power in the alpha frequency band over parietal brain regions in sleep stage NREM. In all cases, EEG power was reduced following Wi-Fi exposure when compared to sham.

4. Discussion

The present study was the first to investigate possible effects of acute 2.45 GHz Wi-Fi exposure on human sleep using a well-engineered and sophisticated new head exposure system designed specifically for this purpose. The main results demonstrated that there were no statistically significant acute effects of a whole-night Wi-Fi exposure on parameters describing the macrostructure of sleep and on parameters characterizing subjective sleep quality in healthy young men. On the other hand, it was shown that acute Wi-Fi exposure affected the microstructure of sleep by reducing global EEG power in the alpha frequency band during NREM sleep.

4.1. Concerns

The results obtained by the questionnaire on concerns related to several health-associated environmental factors suggest that RF-EMF emitting technologies seem to play a marginal role in risk perception in the present sample. In repeated telephone surveys comprising more than 14,500 German citizens of both sexes aged 14 years and older between 2003 and 2013, concerns related to these technologies ranked also low as compared to other non-EMF environmental factors (Lauff and Wachenfeld, 2014). Despite of the low ranking, however, the number of respondents who were seriously or fairly concerned were comparatively stable over the years at a non-negligible level of ~20% for mobile phones and of ~30% for mobile phone base stations (Lauff and Wachenfeld, 2014). In the present sample of young healthy men, less than 10% of the participants were seriously or fairly concerned about possible health risks from mobile phones, mobile phone base stations, and Wi-Fi, respectively (please note that the question related to Wi-Fi exposure was not included in the German telephone surveys). These variations in risk assessment may be due to demographic factors as data from the German telephone surveys showed that women were generally more concerned than men and that concerns were less pronounced in younger (≤24 years) than in older subjects (Lauff and Wachenfeld, 2014).

4.2. Effect of expectation of exposure on subjective and objective sleep variables

In order to figure out whether possible effects of mobile phone base stations on objective and subjective sleep quality are due to EMF exposure or are rather non-EMF-related, Danker-Hopfe et al. (2010) conducted a well-elaborated experimental field study in 10 German villages where no mobile phone service was available. A base station specifically developed for this study was set up in the middle of each village and the participating residents were randomly exposed either to a Global System for Mobile Communications (GSM) or to a sham base station signal for five nights, respectively. The study revealed that GSM exposure led to no statistically significant variation in any of the considered subjective and objective sleep parameters as compared to sham. On the other hand, if the level of concern about possible health risks resulting from base stations was also taken into account, sham exposure had a statistically significant impact on sleep in participants who considered themselves as “concerned” compared to those who considered themselves as “not concerned”. This was interpreted as a nocebo effect,

Table 1
All-night Wi-Fi exposure effects on outcome parameters characterizing the macrostructure of sleep and on subjective sleep quality. Results are based on pairwise analyses of individual differences between the Wi-Fi and sham exposure (Wi-Fi minus sham). For an explanation of parameter abbreviations, see Table S1 in the Supplement.

Parameters	Unit	Sham				Wi-Fi							
		Mean	SD	Median	P25; P75	Mean	SD	Median	P25; P75	t(33)	p	d_{av}	95% CI
related to sleep-wake times													
TST	min	436.6	31.6	442.5	427.5; 454.5	440.6	24.8	446.8	428.0; 458.5	0.75	0.4567	0.14	−0.23; 0.51
SPT	min	455.7	31.5	465.0	450.5; 471.0	461.4	14.8	467.0	455.0; 472.5	1.15	0.2592	0.23	−0.14; 0.61
WASO	min	22.7	16.5	17.0	12.5; 27.0	21.7	14.7	17.0	12.5; 27.0	−0.33	0.7401	−0.06	−0.43; 0.30
WSPT	min	19.1	10.5	16.5	11.5; 25.0	20.8	13.8	17.0	12.5; 25.5	0.58	0.5654	0.14	−0.33; 0.61
SEI	%	90.9	6.6	92.1	89.1; 94.7	91.8	5.2	93.3	89.2; 95.3	0.79	0.4351	0.15	−0.22; 0.51
related to sleep initiation													
SOL	min	20.9	20.2	15.5	9.5; 28.0	17.7	13.9	13.3	7.5; 24.5	−0.95	0.3473	−0.19	−0.57; 0.19
LPS	min	24.8	21.3	19.3	12.5; 30.0	19.8	14.6	18.0	8.5; 25.0	−1.39	0.1753	−0.28	−0.67; 0.11
RL	min	86.8	34.0	75.3	65.5; 100.5	89.8	44.9	76.8	61.5; 94.5	0.31	0.7604	0.08	−0.41; 0.56
N3L	min	19.5	9.1	16.8	14.0; 25.5	18.7	12.7	16.0	12.0; 20.5	−0.37	0.7150	−0.07	−0.47; 0.32
LN2	min	24.5	19.9	18.5	13.5; 32.0	21.6	13.6	18.3	11.0; 28.0	−0.84	0.4096	−0.17	−0.56; 0.23
LN3	min	40.4	23.4	38.0	25.5; 46.5	36.4	18.9	32.8	21.5; 41.0	−1.06	0.2986	−0.19	−0.55; 0.16
LR	min	107.7	38.8	97.0	79.5; 118.0	107.5	46.0	89.3	80.0; 113.5	−0.02	0.9821	−0.01	−0.52; 0.50
related to sleep architecture													
N1	min	39.6	16.9	35.5	29.5; 45.0	43.8	16.7	38.5	34.5; 51.5	2.01	0.0523	0.25	0.00; 0.49
N1P	%	9.1	4.0	8.3	6.8; 10.6	10.0	3.8	9.0	8.0; 11.7	1.94	0.0607	0.22	−0.01; 0.45
N2	min	236.6	25.6	236.0	216.5; 259.5	239.1	28.6	247.0	216.0; 259.5	0.53	0.6028	0.09	−0.25; 0.43
N2P	%	54.3	5.7	56.2	50.9; 57.3	54.2	5.4	55.0	50.5; 58.5	−0.16	0.8766	−0.02	−0.28; 0.24
N3	min	63.4	28.0	64.5	41.5; 79.5	64.9	28.8	61.3	43.0; 87.0	0.64	0.5257	0.05	−0.11; 0.21
N3P	%	14.4	6.2	14.5	9.4; 19.4	14.6	6.2	14.3	9.7; 19.7	0.37	0.7165	0.03	−0.13; 0.19
R	min	97.0	25.1	92.8	76.0; 115.5	92.9	25.7	91.8	79.5; 114.5	−1.24	0.2228	−0.16	−0.41; 0.10
RP	%	22.1	5.2	21.1	17.8; 26.0	21.2	6.0	21.7	17.4; 26.4	−1.35	0.1851	−0.17	−0.41; 0.08
related to sleep maintenance													
AWA-N	#	20.1	7.5	20.5	14.0; 25.0	20.9	6.0	20.0	16.0; 26.0	0.76	0.4517	0.12	−0.18; 0.41
AWA-I	#	2.8	1.1	2.8	1.9; 3.3	2.9	0.9	2.7	2.2; 3.4	0.54	0.5935	0.08	−0.21; 0.37
SSS-N	#	150.2	32.8	152.5	122.0; 172.0	150.4	34.4	146.5	126.0; 171.0	0.05	0.9634	0.01	−0.29; 0.30
SSS-I	#	20.8	4.9	20.6	17.0; 23.7	20.5	4.9	19.9	17.1; 23.2	−0.35	0.7258	−0.05	−0.31; 0.21
AR-N	#	90.7	38.4	79.0	62.0; 117.0	94.3	39.1	85.5	64.0; 116.0	0.89	0.3773	0.09	−0.11; 0.30
ARNR-N	#	71.1	33.2	61.0	51.0; 80.0	75.0	31.8	67.0	53.0; 96.0	1.02	0.3169	0.12	−0.12; 0.36
ARR-N	#	19.6	18.1	15.0	6.0; 25.0	19.3	16.5	14.0	7.0; 24.0	−0.30	0.7634	−0.02	−0.16; 0.12
AR-I	#	12.5	5.4	11.4	8.5; 15.7	12.9	5.4	11.4	9.0; 16.0	0.75	0.4575	0.07	−0.12; 0.26
ARNR-I	#	12.6	6.0	11.0	8.7; 14.7	13.0	5.6	11.9	8.9; 16.2	0.64	0.5253	0.07	−0.14; 0.28
ARR-I	#	11.6	8.8	9.6	4.0; 14.7	12.0	8.4	9.7	5.9; 15.7	0.57	0.5715	0.05	−0.12; 0.22
related to subjective sleep quality													
sSOL	min	15.8	8.9	15.0	10.0; 20.0	13.9	10.2	10.0	5.0; 20.0	−1.27	0.2122	−0.19	−0.49; 0.11
sAWA	#	1.9	1.9	1.0	1.0; 3.0	2.0	1.5	2.0	1.0; 3.0	0.83	0.4135	0.10	−0.13; 0.34
sWASO	min	14.2	24.6	5.0	1.0; 15.0	11.6	13.1	6.5	1.0; 20.0	−0.75	0.4605	−0.13	−0.44; 0.18
sTST[#]	min	456.8	31.5	470.0	450.0; 480.0	462.7	22.9	480.0	450.0; 480.0	1.18	0.2459	0.22	−0.12; 0.55

[#] = t(32) due to missing data for one participant; SD = Standard deviation; P25 = 25th percentile; P75 = 75th percentile; t = t-statistic, degrees of freedom given in brackets; p = significance level; d = Cohen's d_{av} [$|d_{av}| < 0.2$: no effect, $0.2 \leq |d_{av}| < 0.5$: small effect, $0.5 \leq |d_{av}| < 0.8$: medium effect, $|d_{av}| \geq 0.8$: large effect (Cohen, 1988)]; 95% CI = 95% confidence interval.

i.e. not the RF-EMF exposure itself but the mere negative expectations associated with the presence of the experimental base station were very likely responsible for the observed alterations in nocturnal sleep (Danker-Hopfe et al., 2010). Based on these findings, it was assumed that negative expectations towards Wi-Fi exposure would also lead to an increased sleep latency, an increased number of arousals and stage shifts, more light sleep and worse sleep quality, the latter reflected by subjective assessment. However, as the participants of the present study were overall little concerned about RF-EMF emitting technologies in general and about Wi-Fi exposure in particular, it was not surprising

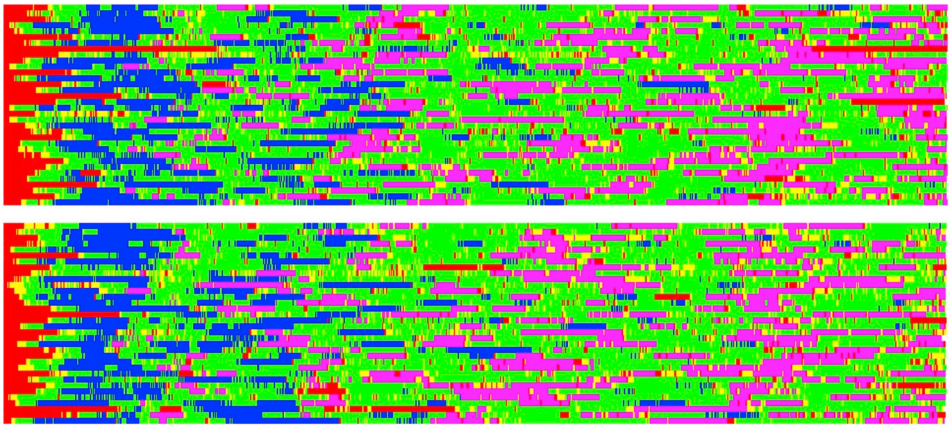


Fig. 4. Individual hypnograms illustrated as lasagna plots. Upper part: Sham exposure, lower part: Wi-Fi exposure. Color legend: red = awake, yellow = sleep stage N1, green = sleep stage N2, blue = sleep stage N3, pink = sleep stage R. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Analysis of the EEG power in the five considered frequency bands by sleep stage. Statistically significant results of the RM-ANOVAs are marked in bold. The degrees of freedom are given in brackets.

Parameter	Exposure (1, 33)				Region (5, 165)				Exposure * Region (5, 165)			
	F	p	η_p^2	η_G^2	F	pGG	η_p^2	η_G^2	F	pGG	η_p^2	η_G^2
Sleep Stage N1												
Delta	3.83	0.0588	0.104	0.007	112.17	< **0.0001**	0.773	0.399	0.94	0.4173	0.028	0.001
Theta	1.35	0.2535	0.039	0.002	153.22	< **0.0001**	0.823	0.519	1.07	0.3637	0.031	0.001
Alpha	2.83	0.1020	0.079	0.004	96.55	< **0.0001**	0.745	0.350	0.32	0.7690	0.010	< 0.001
Beta1	2.44	0.1278	0.069	0.002	147.83	< **0.0001**	0.818	0.322	0.23	0.8524	0.007	< 0.001
Beta2	0.52	0.4750	0.016	< 0.001	184.79	< **0.0001**	0.848	0.318	0.46	0.7091	0.014	< 0.001
Sleep Stage N2												
Delta	2.93	0.0962	0.082	0.005	198.41	< **0.0001**	0.857	0.662	0.97	0.3927	0.029	0.002
Theta	1.99	0.1672	0.057	0.001	212.53	< **0.0001**	0.866	0.602	0.55	0.6224	0.016	0.001
Alpha	3.93	0.0558	0.106	0.001	148.61	< **0.0001**	0.818	0.406	0.87	0.4356	0.026	0.001
Beta1	1.20	0.2816	0.035	< 0.001	259.25	< **0.0001**	0.887	0.578	0.77	0.4800	0.023	0.001
Beta2	1.27	0.2677	0.037	0.001	159.75	< **0.0001**	0.829	0.333	0.59	0.6244	0.018	< 0.001
Sleep Stage N3												
Delta	2.53	0.1209	0.071	0.002	235.41	< **0.0001**	0.877	0.587	1.94	0.1396	0.056	0.002
Theta	1.51	0.2277	0.044	0.001	207.05	< **0.0001**	0.863	0.593	0.57	0.5950	0.017	0.001
Alpha	3.64	0.0651	0.099	0.002	211.98	< **0.0001**	0.865	0.467	0.97	0.4013	0.028	< 0.001
Beta1	3.33	0.0771	0.092	0.002	209.71	< **0.0001**	0.864	0.534	0.92	0.4184	0.027	0.001
Beta2	1.54	0.2228	0.045	0.003	86.21	< **0.0001**	0.723	0.270	0.70	0.5523	0.021	0.001
Sleep Stage NREM												
Delta	2.94	0.0958	0.082	0.003	227.03	< **0.0001**	0.873	0.526	1.94	0.1435	0.055	0.002
Theta	1.88	0.1798	0.054	0.001	211.40	< **0.0001**	0.865	0.579	0.86	0.4479	0.025	0.001
Alpha	4.53	**0.0409**	0.121	0.002	153.94	< **0.0001**	0.823	0.412	0.72	0.5078	0.021	< 0.001
Beta1	3.23	0.0815	0.089	0.001	250.51	< **0.0001**	0.884	0.569	0.71	0.5078	0.021	0.001
Beta2	1.06	0.3103	0.031	0.001	158.29	< **0.0001**	0.827	0.340	0.36	0.7892	0.011	< 0.001
Sleep stage R												
Delta	1.74	0.1961	0.050	0.002	173.75	< **0.0001**	0.840	0.633	1.08	0.3530	0.032	0.002
Theta	2.15	0.1521	0.061	0.001	245.00	< **0.0001**	0.881	0.658	0.95	0.4107	0.028	0.001
Alpha	1.29	0.2639	0.038	0.001	124.45	< **0.0001**	0.790	0.406	1.36	0.2637	0.040	0.001
Beta1	0.45	0.5056	0.014	< 0.001	89.88	< **0.0001**	0.731	0.251	0.68	0.5421	0.020	< 0.001
Beta2	2.56	0.1191	0.072	0.001	179.77	< **0.0001**	0.845	0.341	0.55	0.6223	0.016	< 0.001

F = F-statistic; p = significance level; pGG = Greenhouse-Geisser adjusted significance level; η_p^2 = partial eta squared; η_G^2 = generalized eta squared [According to Lakens (2013) only η_G^2 can be compared to the following benchmarks provided by Cohen (1988) $\eta_G^2 < 0.010$ representing no effect, $0.010 \leq \eta_G^2 < 0.060$ representing a small effect, $0.060 = \eta_G^2 < 0.140$ representing a medium effect and $\eta_G^2 \geq 0.140$ representing a large effect].

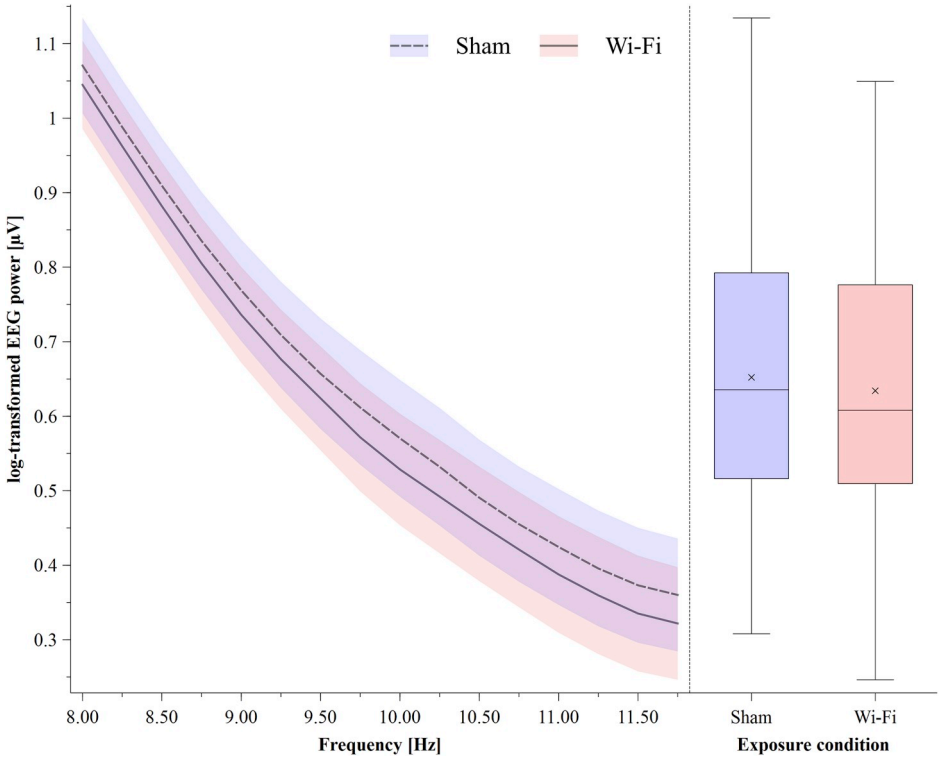


Fig. 5. Global EEG power (log-transformed) for the alpha frequency band during NREM sleep under both exposure conditions. The left side of the figure shows the EEG bin power values within the alpha frequency range (8.00–11.75 Hz) with a resolution of 0.25 Hz. Uncertainty of the values are indicated by the standard error. On the right, EEG band power values are displayed as box plots. Whiskers are defined as 1.5 times the interquartile range.

that none of these parameters was statistically significant between pooled BLs and ENs. In addition, a split of the sample according to the responses concerning Wi-Fi related worries into those, who were at least little concerned and those who were not concerned at all confirmed that possible negative expectations had not biased the results on subjective and objective sleep variables (data not shown).

Effect of Wi-Fi exposure on subjective sleep parameters as well as on the macro- and microstructure of sleep.

Whereas this was the first study specifically investigating Wi-Fi exposure effects on the macrostructure of sleep, the impact of RF-EMF exposure in general on sleep architecture has been the subject of intensive research during the last two decades. Overall, however, the data from these studies do not show a uniform picture. If effects were observed at all, they affected various selected parameters, partly with opposite effects for the same outcome parameter. For a summary, see Danker-Hopfe et al. (2016). The present results provided evidence that acute RF-EMF exposure as generated by 2.45 GHz Wi-Fi devices has no effect on the macrostructure of sleep. These findings are in line with about half of the studies carried out so far in this field of research.

Danker-Hopfe and colleagues reported effects of a whole night GSM and Wideband Code Division Multiple Access (WCDMA) exposure on stage R sleep in young healthy male subjects at both, the group (Danker-Hopfe et al., 2011) and the individual level (Danker-Hopfe et al., 2016). The authors argued that this effect could be explained by a warming of the skin. This hypothesis is based on the fact that the preoptic area (POA) of the hypothalamus, which is involved in sleep regulation, contains also neurons that are warm sensitive (Romanovsky, 2018). Tissue heating results from energy absorption and constitutes the main biophysical mechanism for possible RF-EMF-related effects. The degree of warming depends on the specific absorption rate (SAR) due to exposure. A 15 min TETRA exposure with maximum 10 g averaged SAR value of 6 W/kg emitted from a body worn antenna fixed to the left ear caused an increase in skin temperature of up to 1.1 °C (Dorn et al., 2014). In the present study, however, the maximum 10 g averaged SAR value was around 1000 times smaller than in the study mentioned above and around 300 times smaller than SAR values usually reported in mobile phone studies. Thus, an effect caused by a warming of the skin was already a priori considered as very unlikely.

Furthermore, the present results of the subjective assessment of sleep correspond to those observed for objective measures and are consistent with the results of other studies (Schmid et al., 2012a, 2012b).

With regard to the microstructure of sleep, earlier research repeatedly revealed RF-EMF exposure effects on the power spectra of the sleep EEG during NREM sleep, especially in the sleep spindle frequency range (e.g. Borbely et al., 1999; Loughran et al., 2005; Regel et al., 2007). In more recent studies, RF-EMF effects on EEG power have also been reported for other sleep stages, different time frames and varying frequency bands (e.g. Lowden et al., 2011; Schmid et al., 2012b), leading to an increased number of positive results at the expense of consistency. The exposure effect on the NREM sleep EEG in the alpha frequency range observed in the present study also contributes to this heterogeneity since, unlike most other studies, the global spectral power was reduced rather than increased under RF-EMF exposure. Given the number of tests (25) and alpha level 0.05, one significant result is expected just by chance. Thus, this observation could just be a random result. The same argument holds for the follow up pairwise analyses, which revealed four statistically significant results (see Table S6 in the Supplement). Given 150 tests (five frequency bands * six regions * five sleep stages), the number of statistically significant effects just by chance can be expected to be up to eight.

However, regardless of the frequency band and/or sleep stage affected and also irrespective of the effect direction, SCENIHR (2015) concluded that the relevance of any small physiological changes remains unclear and that there is still no mechanistic explanation for the observed effects. Thus, since there is no clear evidence for a health significance of slight alterations in brain activity, the observed effect in the alpha frequency range does not seem to be indicative of a disturbed sleep under exposure.

4.3. General considerations

Given the high penetration rate with Wi-Fi technology, it is surprising that of the large number of RF-EMF-related bio-effect studies conducted so far, only very few have specifically focused on possible biological effects from Wi-Fi exposure.

In 2013, Foster and Moulder reviewed the evidence for Wi-Fi exposure related effects in biological studies and their literature search resulted in only 13 studies of which some were either not published in a peer-reviewed journal or had obvious technical deficiencies (Foster and Moulder, 2013). With regard to human experimental studies investigating Wi-Fi effects on brain activity, they could identify just one study published in a peer-reviewed journal (Papageorgiou et al., 2011). These authors studied effects of Wi-Fi exposure on the P300 component of event-related potentials, which resulted from performing a modified version of Hayling sentence completion test. The sample consisted of 15 men and 15 age-matched females (mean age 23.8 ± 1.7 years). In one of the three Hayling conditions, a significant exposure by gender interaction was observed. In the sham condition, men had a non-significantly higher P300 amplitude while in the Wi-Fi exposure condition the amplitude in men decreased and increased in females leading to significantly higher amplitude in the verum exposure condition in females. Since then, only one new human experimental study in this context has been published. In a well-elaborated study, Zentai et al. (2015) examined effects of a 60-min Wi-Fi exposure on the resting state EEG compared to a sham condition in a double-blind design. The sample comprised 25 young healthy subjects (15 females, mean age ± SEM: 23.3 ± 0.6 years). The authors did not find any Wi-Fi exposure effect on the EEG power analyzed for several frequency bands considering midline electrode sites. This more recent study supports the conclusion by (Foster and Moulder, 2013) that the biological literature does not provide a basis to anticipate any biological effects from Wi-Fi exposures in users. Recently, however, Pall (2018) published a paper in which he doubted Foster's and Moulder's evaluation of Wi-Fi specific literature. Among others, Pall (2018) stated that Foster's and Moulder's interpretation of statistically non-significant results is wrong and that they ignored some statistically significant effects. However, this publication by Pall (2018) was subsequently heavily criticized from peers in the community (Arribas et al., 2018; Foster and Moulder, 2019; Najera, 2019).

Foster and Moulder (2013) further recommended that additional biological studies related to Wi-Fi exposure are only worthwhile, if (a) the study is performed in vivo, (b) the outcome is relevant for human health, (c) a well characterized exposure system including both currently available Wi-Fi standards is used and (d) a rigorous methodology with a special emphasis on the study design is applied. The present study contributes to the scarce literature on Wi-Fi effects from human experimental studies by fulfilling these criteria except that only one Wi-Fi standard was investigated. Furthermore, by adding BLs to the study design it was assured that results were not biased by effects due to variations in the timing and duration of sleep in the nights preceding the ENs. The selection of a sample of young healthy male volunteers of a narrow age range can be considered as both a strength and a limitation. As a strength because it minimizes data variability since it is known that brain activity during sleep varies with age and sex (Yetton et al., 2018), and as a limitation because the present results cannot necessarily be translated to older volunteers, to women and to patients with pre-existing medical conditions. A further limitation of this study is that the present results reflect only short-term effects and that it is therefore not possible to draw any conclusions about possible effects resulting from a prolonged Wi-Fi exposure.

5. Conclusions

In summary, the present study was the first to examine the impact of a whole night Wi-Fi exposure on sleep. It was highlighted that neither subjective assessment of sleep nor the macrostructure of sleep was significantly affected by Wi-Fi exposure. A statistically significant Wi-Fi exposure effect has been observed on the EEG power in the alpha frequency band during NREM sleep, but as these slight physiological changes are not reflected by other measures at the subjective and objective level, this result cannot be interpreted as an indicator for a disturbed sleep.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2020.113550.

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