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Effects of 2.45 GHz Wi-Fi exposure on sleep-dependent memory consolidation

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Abstract

Studies have reported that exposure to radiofrequency electromagnetic fields (RF-EMF) emitted by mobile telephony might affect specific sleep features. Possible effects of RF-EMF emitted by Wi-Fi networks on sleep-dependent memory consolidation processes have not been investigated so far. The present study explored the impact of an all-night Wi-Fi (2.45 GHz) exposure on sleep-dependent memory consolidation and its associated physiological correlates. Thirty young males (mean ± standard deviation [*SD*]: 24.1 ± 2.9 years) participated in this double-blind, randomized, sham-controlled crossover study. Participants spent five nights in the laboratory. The first night was an adaptation/screening night. The second and fourth nights were baseline nights, each followed consecutively by an experimental night with either Wi-Fi (maximum: psSAR10g = <25 mW/kg; 6 min average: <6.4 mW/kg) or sham exposure. Declarative, emotional and procedural memory performances were measured using a word pair, a sequential finger tapping and a face recognition task, respectively. Furthermore, learning-associated brain activity parameters (power spectra for slow oscillations and in the spindle frequency range) were analysed. Although emotional and procedural memory were not affected by RF-EMF exposure, overnight improvement in the declarative task was significantly better in the Wi-Fi condition. However, none of the post-learning sleep-specific parameters was affected by exposure. Thus, the significant effect of Wi-Fi exposure on declarative memory observed at the behavioural level was not supported by results at the physiological level. Due to these inconsistencies, this result could also be a random finding.

KEYWORDS
declarative memory, EEG power, emotional memory, procedural memory, sleep spindles, slow oscillations

1 | INTRODUCTION

Although the use of wireless communication networks has increased, studies that address possible Wi-Fi exposure effects on brain electrophysiology and/or neurocognitive function in humans are scarce (see, for example, Foster & Moulder, 2013). So far, there is an ongoing discussion about possible mechanisms and non-thermal effects of radio frequency electromagnetic fields (RF-EMF)

(SCENIHR, 2015). The human experimental research on possible short-term RF-EMF effects is mainly driven by the concerns in parts of the population that exposure might affect health. Thus, human studies in this area are often designed to investigate many outcomes (exploratory approach) instead of testing specific hypotheses (confirmatory approach).

Effects of exposure to other RF-EMF resulting from mobile phones on objective sleep parameters were investigated in various human experimental provocation studies with mixed results (for an overview see Danker-Hopfe et al., 2016). Within the studies that used RF signals and reported variations in sleep physiology, effects on the duration of rapid eye movement (REM) sleep and non-REM (NREM) sleep (Danker-Hopfe et al., 2011) were shown, as well as effects on the electroencephalogram (EEG) power in the delta (Lustenberger et al., 2013; Schmid, Murbach, et al., 2012), theta and spindle frequency ranges (e.g., Schmid, Loughran, et al., 2012; Schmid, Murbach, et al., 2012). Although the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020) states that "Studies analyzing frequency components of the EEG have reliably shown that […] the 10–14 Hz 'sleep spindle' frequency range in sleep EEG, [is] affected by radiofrequency EMF exposure with specific energy absorption rates (SAR) <2 W/kg […]" (ICNIRP, Appendix B page 518), results are less consistent at a deeper level (SCENIHR, 2015). Although some studies did not find an effect on the EEG in the spindle frequency range during NREM sleep (Fritzer et al., 2007; Hinrichs et al., 2005; Lowden et al., 2019; Lustenberger et al., 2013, 2015; Mann & Röschke, 1996; Nakatani-Enomoto et al., 2013; Wagner et al., 1998, 2000), other studies did report such an effect (Borbely et al., 1999; Huber et al., 2000, 2002; Loughran et al., 2005, 2012; Lowden et al., 2011; Regel et al., 2007; Schmid, Loughran, et al., 2012; Schmid, Murbach, et al., 2012). However, results are also quite heterogeneous with regard to the considered sleep stages (NREM, including and/or excluding stage S1/N1, stage S2/N2, and/or stage S3/S4/N3/slow-wave sleep), the considered time window (e.g., first 30 min of NREM sleep, first hour of NREM sleep, second hour of NREM sleep, whole night, and different sleep cycles), timing of exposure (prior to sleep or during sleep), the definition of the spindle frequency range (which according to the standards of the American Academy of Sleep Medicine [AASM] is defined as the range from 12 to 14 Hz for the narrow sleep spindle frequency range and from 11 to 16 Hz for the wide sleep spindle frequency range (Berry et al., 2018)), and the direction of the effects (increase or decrease). Nevertheless, evidence suggests that either sleep stages or their associated characteristics of the EEG (sleep spindles, slow oscillations (SO) and theta frequencies) are closely linked to sleep-dependent declarative and non-declarative memory consolidation processes (Diekelmann & Born, 2010; Rasch & Born, 2013). Specifically, slow-wave sleep, SO and sleep spindles have been proposed to facilitate the consolidation of declarative memory, whereas NREM sleep and sleep spindles are relevant for procedural memory, and features of REM sleep and theta frequencies are thought to be involved in the consolidation of emotional memory (Ackermann & Rasch, 2014; Rauchs et al., 2005).

Linking the previously mentioned observations, Lustenberger et al. (2013) investigated whether sleep-dependent memory consolidation processes might also be affected by an exposure to RF-EMF. They found that RF-EMF signals (900 MHz) pulsed at frequencies that matched the endogenous repetition rate of sleep spindles (0.25 Hz) and SO (0.8 Hz) affected brain activity during sleep and impaired motor memory consolidation (Lustenberger et al., 2013). Based on these findings, the question arose whether a Wi-Fi exposure, which can be the most prominent RF-EMF source in a home setting during the night (Roser et al., 2017; Tomitsch et al., 2010), may also interact with endogenous brain activity and affect sleep-dependent memory consolidation processes. In a recent project, the impact of a whole-night Wi-Fi exposure on sleep was investigated in a sample of 34 young healthy male volunteers (Danker-Hopfe et al., 2020). For a subsample of 30 subjects, data on sleep-dependent memory consolidation were also available, which will be considered in the present paper. The aims of the present study were to explore possible Wi-Fi exposure effects on (a) sleep-dependent memory consolidation and (b) learning-associated sleep parameters (sleep stages, power spectra in the SO frequency range [0.5–1 Hz] and power spectra in the spindle frequency ranges [sigma wide 11–16 Hz and narrow 12–14 Hz]).

2 | MATERIALS AND METHODS

2.1 | Participants

Overall, 34 healthy young male volunteers aged 20–30 years (mean ± standard deviation [*SD*]: 24.12 ± 2.91 years) participated in a project of our group that investigated the effect of Wi-Fi exposure on sleep and memory consolidation. The impact of Wi-Fi exposure on sleep is reported in Danker-Hopfe et al. (2020) based on the recruited sample of 34 participants. The present analysis focuses on possible Wi-Fi exposure effects on memory consolidation and associated sleep parameters. Due to protocol deviations in the memory tasks (same version of the task was conducted on both experimental nights), four participants had to be excluded from statistical analysis. Therefore, the final sample size was $n = 30$, with a mean age (± *SD*) of 24.13 (±2.91) years (for participant recruitment and randomization, see Figure S1). The basis for the sample size determination of the Wi-Fi research project was medium-sized RF-effects on sleep parameters frequently observed in other RF-EMF studies from the same research group. In these former studies, a total sample of 30 participants was enrolled and the data were statistically analysed using *t*-tests for paired observations with a two-sided significance level of 5% and a power of 80%. An increase of the number of participants to 34 as realized in Danker-Hopfe et al. (2020) allowed therefore for the detection of even smaller effects by using the same input parameters for statistical power and significance level.

Participants were non-smokers, right-handed and native German speakers. Exclusion criteria were the presence of any sleep disorder, a regular intake of medication that could affect the central

nervous system, an excessive daily consumption of caffeine (>5 cups per day) and/or alcohol (>3 glasses per day), substance abuse, and having any metallic implants. Additionally, subjective sleep quality, daytime sleepiness and chronotype, as well as possible depressive symptoms and somatic pain, were assessed (see Table S1). Participants also needed to have and to maintain a regular sleep–wake schedule, as documented by a 14-day sleep diary (Liendl & Hoffmann, 1999) with median bedtimes that varied from 22:30 PM to 00:22 AM from Sunday to Thursday. To control for appropriate individual bedtimes, participants spent the night before an experimental night in the sleep laboratory. All participants underwent a medical examination to rule out possible neurological and psychiatric disorders. Aspects of general intelligence and fluid intelligence were assessed for sample characteristics (see Table. S1).

The ethics committee of the Charité - Universitätsmedizin Berlin (Germany, EA4/071/17) approved the study. All participants gave their written informed consent and were compensated financially; each participant received 350 € for their participation.

2.2 | Experimental design

All experiments and night-time recordings were performed in a shielded room. The first night in the sleep laboratory served as a screening and adaptation night. Subjects with a periodic leg movement arousal index > 10/h, an apnea–hypopnea index > 5/h, a sleep latency > 30 min, and/or a sleep efficiency index < 80% were excluded and therefore not randomized. Altogether, 41 young men spent an adaptation night in the sleep laboratory; four of them had to be excluded, one due to an apnea–hypopnea index > 5 and three due to an insufficient sleep efficiency index. Two subjects who passed the adaptation night quit the study before and one after the first experimental night. Participants included in the study, spent four more nights in the laboratory, divided into two blocks each, consisting of two consecutive nights. The first block started within 7 days from the adaptation night. The second block followed exactly 1 week later. The first of the two consecutive nights was always a baseline night, whereas the second was the experimental night, during which either a Wi-Fi or a sham exposure was applied. In this double-blind crossover study, participants were randomly assigned to the two possible exposure sequences (Wi-Fi exposure on the first experimental night and sham exposure on the second experimental night, or vice versa) in a fully counterbalanced design (see Figure 1a and Appendix S1 *Exposure design*). Participants were asked to avoid the intake of caffeine and alcohol on any of the 5 days preceding the nights in the sleep laboratory. Additionally, personal electronic devices (laptops, smartphones, E-books, etc.) were not allowed from the time when participants arrived at the laboratory until they left (see Figure 1b).

2.3 | Sleep recordings

On all study nights, participants went to bed as close as possible to their usual bedtimes (around 22:45–23:45 PM) and time in bed (TIB) was restricted to 8 h. Polysomnographic monitoring of the adaptation nights followed the recommendations of the AASM (Berry et al., 2018). However, EEG was recorded from 19 instead of six scalp electrodes. Electrodes were placed according to the international 10/20 system (Jasper, 1958). Sleep recordings of the baseline and experimental nights were restricted to EEG, recording of eye movements (vertical and horizontal) and chin (mental and submental) electromyographic activities. All recordings were performed using a Neurofax EEG-9200 device (Nihon Kohden, Tokyo, Japan). Impedances of electrodes were kept below 10 kΩ. Sleep was scored manually according to the standard criteria of the AASM (Berry et al., 2018) by three experts, who are CLINILABS-certified scorers and who were blind to the exposure condition. To reduce effects of interrater variability in scorings, all nights from one subject were scored by the same expert. Thus, each dataset was scored by the same independent expert. Analysis of the sleep macrostructure focused on the following learning-associated parameters: N2, N3 (slow-wave sleep), NREM and REM sleep. Sleep microstructures of interest, the spectral power in the sleep spindle frequency range (sigma frequency range in the wide [11–16 Hz] and narrow [12–14 Hz] bands (Berry et al., 2018) and in the SO frequency range [0.5–1 Hz]; (Achermann & Borbely, 1997)), were analysed during sleep stages N2 and N3 at all EEG electrode sites. For these analyses, electrode locations were topographically grouped into six brain regions: frontopolar (Fp1, Fp2), frontal (F7, F3, Fz, F4, F8), central (C3, Cz, C4), temporal (T3, T4, T5, T6), parietal (P3, Pz, P4) and occipital (O1, O2). Artifacts were excluded from the final analysis (for a description of the artifact exclusion process, see Appendix S1 *Artifact exclusion* and Danker-Hopfe et al., 2020). Additionally, a MATLAB-based (MathWorks Inc.) automatic spindle detection algorithm (Lacourse et al., 2019) that emulates human scoring was used in order to analyse sleep spindle density. This algorithm identifies spindles in the frequency range (11–16 Hz) with a maximum spindle length of 2.5 s (Lacourse et al., 2019). Spindles were detected from six electrode locations grouped into three regions: frontal (F3, F4), central (C3, C4) and parietal (P3, P4). Spindle density was calculated as the mean number of sleep spindles per 30-s epoch during sleep stage N2 and N3, respectively.

2.4 | Memory tasks

Three learning tasks were administered prior to experimental nights and following the experimental nights in the morning (30 min after lights on to control sleep inertia) to assess declarative, emotional and procedural memory. The order of the memory tasks was the same in the evening and in the morning and kept constant across subjects and experimental nights. All memory tasks were presented using E-Prime 2 (Psychology Software Tools) on a 19-inch colour monitor with a viewing distance of 60 cm.

Declarative memory was assessed using a word-pair association task (WPT). In this task, participants learned a list of word pairs in the evening, followed by an immediate recall and a delayed recall in the morning. The

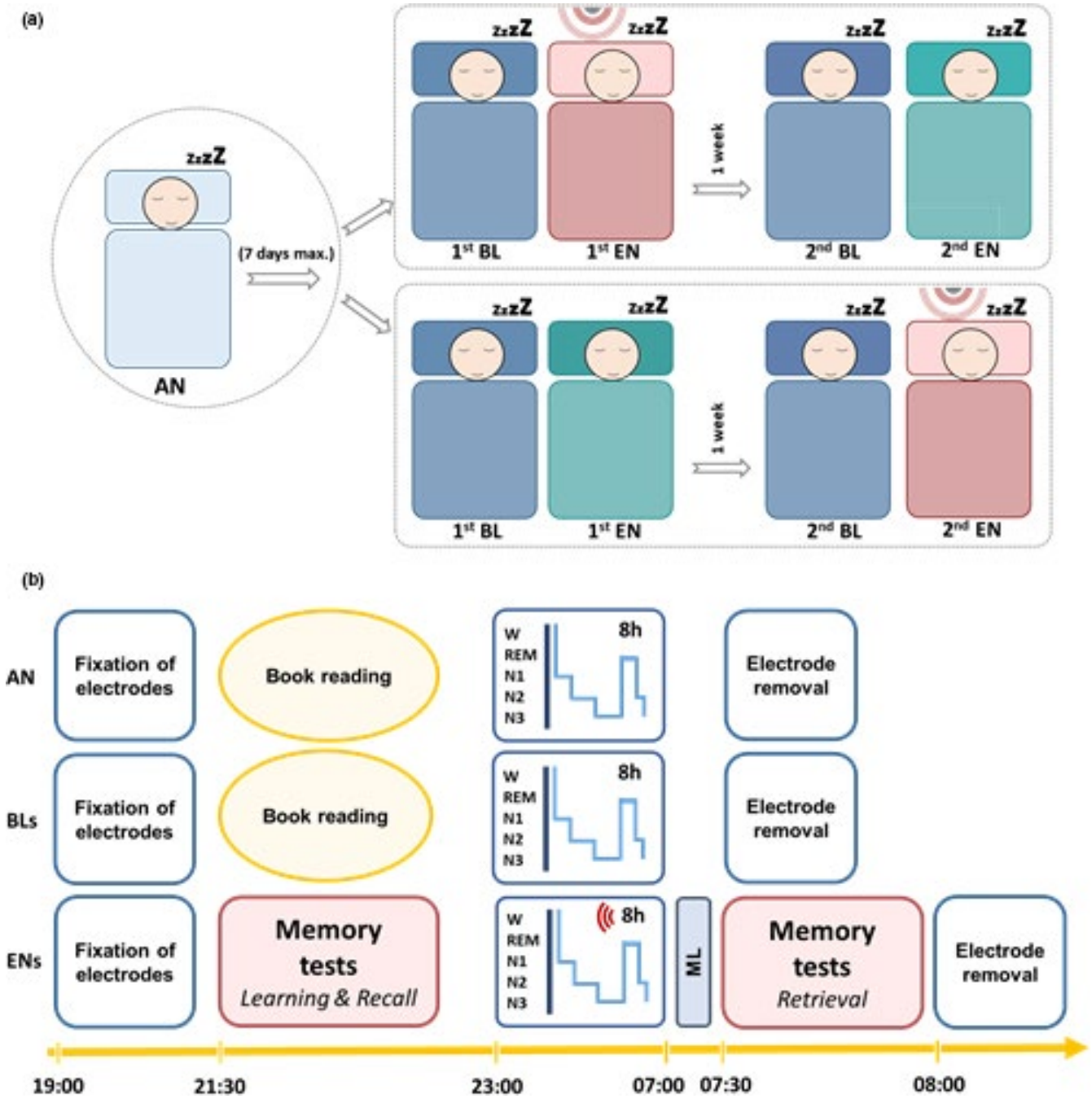

FIGURE 1 Study design. (a) The first night was an adaptation and screening night (AN). The second and fourth nights were baseline nights (BLs) with no intervention. The third and fifth nights were experimental nights (ENs), where a Wi-Fi (in red) or a sham exposure (in green) was applied in a double-blind, randomized, counterbalanced crossover design. The first BL followed the AN within a maximum of 7 days, and the second BL was scheduled 1 week after the first BL, followed by the last EN. (b) Participants arrived at the laboratory around 19:00 PM. The first procedure was an alcohol test performed with a portable breath-alcohol tester (Dräger Alcotest 6810 med). Only if the test was negative (0.00 mg/L) subjects were allowed to proceed. In the AN and BL nights, participants were allowed to read a book until going to bed. In the EN, the memory tasks were applied in the same order for all subjects; the word pair task was followed by the face recognition task and the sequential finger tapping task was the last one. This order was also kept in the morning. After time in bed (8 h), participants filled out a morning log (ML), which included a question related to the blinding of the exposure condition in the EN. The retrieval of the memory tasks started 30 min after awakening, following the same task order as in the evening. Finally, electrodes were removed and participants were allowed to have breakfast

outcome parameter for the declarative memory task was the number of correctly retrieved words at immediate and delayed recall (see Figure 2a; for detailed description, see Appendix S1 *Memory tasks*).

For the evaluation of emotional memory, a face recognition task (FRT) was administered. This test was carried out analogously to Wagner et al. (2007) and all data were corrected according to

Snodgrass and Corwin (1988). The outcome parameter for the emotional task was memory accuracy, which was defined as the difference between the conditional probability to answer "old" to a target stimulus (hit rate; Hr) and to answer "old" to a distracter stimulus (false alarm rate; FAr) (memory accuracy = Hr − FAr) (for detailed description, see Appendix S1 *Memory tasks*) (see Figure 2b).

Finally, procedural memory was evaluated using a sequential finger tapping task (SFTT) (Walker et al., 2002). Performance in this task was measured by calculating the mean of the number of correctly tapped sequences from the three last trials of the learning period in the evening and the mean of all three trials from the retrieval period in the morning (for detailed description, see Appendix S1 *Memory tasks*).

2.5 | Exposure conditions

A specially designed Wi-Fi exposure system was used on the experimental nights (for more detailed information, see Appendix S1 *Exposure system* and Schmid et al., 2020). In the Wi-Fi condition, participants were exposed to wireless local area network signals at a carrier frequency of 2.45 GHz (peak spatial specific absorption rate $psSAR_{10g}$ = <25 mW/kg maximum or <6.4 mW/kg for an average over 6 min); in the sham exposure condition, no exposure was applied. In this experimental study exposure levels reflect a realistic worst-case scenario, which implies that usually in the home setting, exposure levels are (much) smaller.

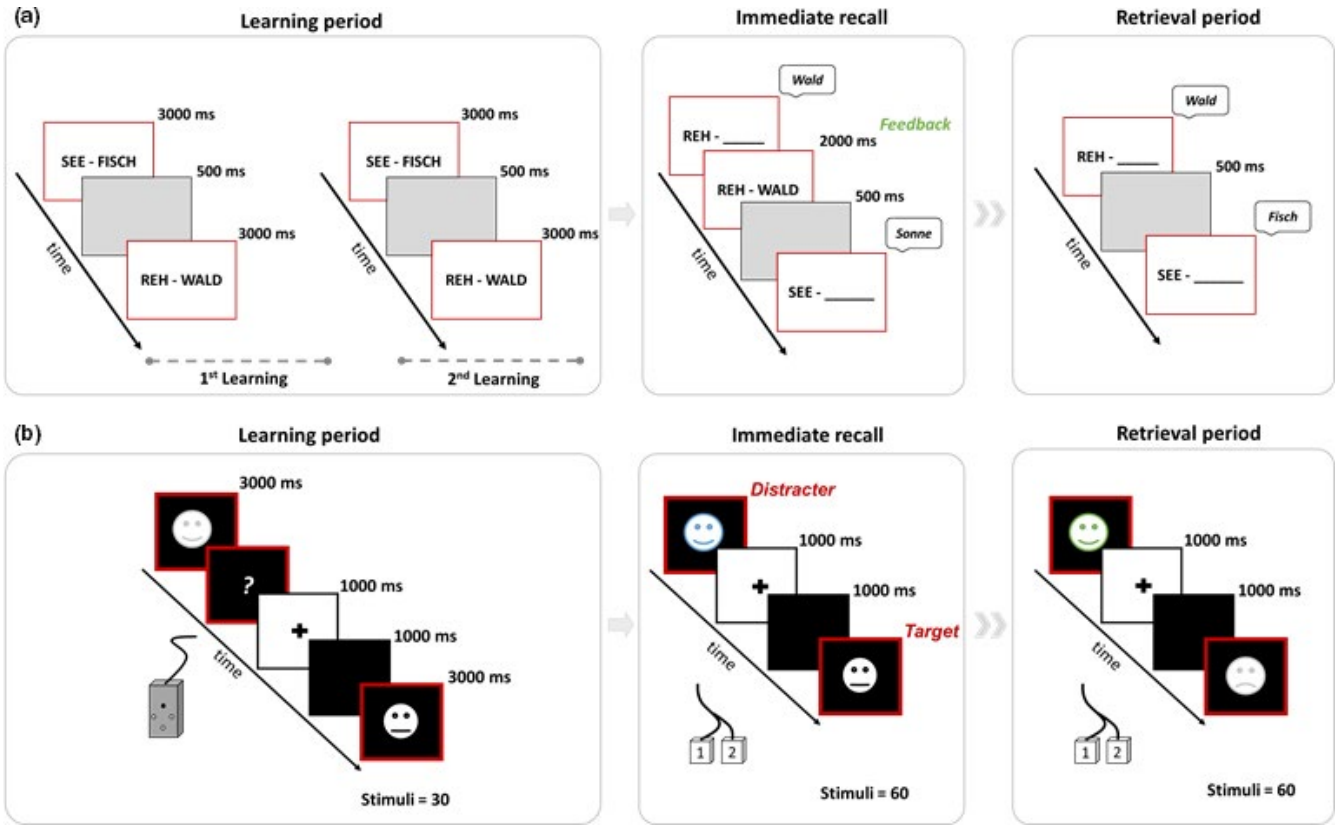

FIGURE 2 Memory tasks. (a) Word pair task (WPT). Word pairs were presented in black colour and on a white background for 3,000 ms, followed by 500 ms of blank screen. Participants were exposed twice to 101 word pairs in the same order, with 1-min break between the first and the second learning run. During the immediate recall and the retrieval period, the cue words were presented in a new randomized order and subjects were instructed to say out loud the corresponding word of the word pair. Answers were always followed by feedback during the immediate recall in the evening, but not during the retrieval period in the morning. (b) Face recognition task (FRT). Coloured pictures of facial expressions of emotions from women and men, representing positive, negative or neutral emotional expressions, were presented on a computer screen. The learning period consisted of the presentation of 30 pictures (target) of five male and five female faces, with the three distinct emotional expressions of equal number. Each face was presented for 3,000 ms, followed by a blank screen (1,000 ms). Then, participants had to indicate the emotional valence of the presented face by pressing one of three response buttons. Once the participant answered, a fixation-cross appeared for 1,000 ms, followed by a blank screen (1,000 ms), and the next stimulus was presented. Immediately after, the same set of stimuli was presented intermixed with 30 additional faces (distracter) and participants had to indicate whether this stimulus had been presented before or whether it was a new face by pressing one of two response keys. The retrieval period in the morning consisted of the presentation of 30 target faces (presented during the learning period) intermixed with 30 new distracter stimuli. Then, participants were asked to indicate whether each face was "new" or "old" by pressing one of two response keys, similarly to during the immediate recall in the evening. All stimuli were presented on a black background

2.6 | Blinding to exposure

Blinding of participants was tested by asking the subjects about their guesses with regard to the exposure condition after each experimental night. Answer possibilities were: "yes", indicating Wi-Fi exposure; "no", indicating sham exposure; and "don't know". From these answers, the James Blinding Index (BI; James et al., 1996) and its 95% confidence interval were computed. The values of this index vary from 1.0 to 0.0, corresponding to success of blinding (BI = 1.0), random guessing (BI = 0.5) or lack of blinding (BI = 0.0) (James et al., 1996).

2.7 | Statistical analyses

The impact of Wi-Fi exposure on memory performances in all three memory tasks was analysed by a repeated measures analysis of variance (rmANOVA) with the within-subject factors TIME (evening vs. morning), EXPOSURE (Wi-Fi vs. sham) and their INTERACTION. To analyse sleep spindle density and spectral power values a rmANOVA with the within-subject factors EXPOSURE (Wi-Fi vs. sham), REGION (frontopolar vs. frontal vs. central vs. temporal vs. parietal vs. occipital for EEG power, and frontal vs. central vs. parietal for sleep spindle density) and their INTERACTION was performed. The natural logarithm of absolute EEG power values was used for analyses in order to approximate normality of the data and overcome distorted spectral parameter problems, following the suggestion of Gasser et al. (1982).

Exclusion of four subjects from statistical analysis led to an unbalanced distribution of exposure sequences (first, "Wi-Fi – Sham", or second, "Sham – Wi-Fi") among the participants (13 participants were assigned to the first exposure sequence, whereas 17 participants received the exposure conditions in the order of the second sequence) (see Figure S1). Although it is unlikely that, due to a washout period (1 week), effects of the first exposure condition had a direct impact on the results observed under the second exposure condition (i.e., the carryover bias was diminished), it is conceivable that possible exposure effects may have been confounded additionally by order effects such as habituation or practice. As these effects should compensate one another in a fully counterbalanced study design, it is difficult to disentangle different effects if the number of exposure sequences is not equal. Therefore, the sequence of exposure was additionally used as a between-subject factor (EXPOSURE SEQUENCE) in the statistical models. RmANOVAs were performed with SAS procedure *Proc Mixed*. In the case of a statistically significant interaction effect, post-hoc *t*-tests were performed. The significance level reported for the analysis of the EEG power was based on a bootstrap permutation test for matched pairs (Wicklin, 2010). As outlined in the introduction, there is a considerable inconsistency in the (supposed) consistency of RF-EMF effects on EEG power in the sleep spindle frequency range. Therefore, a hypothesis-driven approach in this context is not justified so far. For this reason, an explorative approach has been used instead, without correcting the *p*-values for multiple testing. Partial eta-squared (η_p^2) and generalized eta-squared (η_G^2) (Olejnik & Algina, 2003) were used as effect size measures for rmANOVAs. Lakens (2013) recommended the comparison of the η_G^2 with the benchmarks proposed by Cohen (1988): no effect ($\eta^2 < 0.010$), small effect ($0.010 \le \eta^2 < 0.060$), medium effect ($0.060 \le \eta^2 < 0.140$) or large effect ($\eta^2 \ge 0.140$). Paired *t*-tests were carried out to investigate possible effects of Wi-Fi exposure on learning-associated sleep stages. The effect size estimator Cohen's d_{av} and its corresponding 95% CIs were calculated according to a SAS macro published by Kadel & Kip (2012). Cohen's d_{av} was interpreted as no effect ($|d_{av}| < 0.2$), small effect ($0.2 \le |d_{av}| < 0.5$), medium effect ($0.5 \le |d_{av}| < 0.8$) or large effect ($|d_{av}| \ge 0.8$) (Cohen, 1988). Moreover, Bayesian *t*-tests were used for dependent samples as implemented in SPSS (version 25), in order to quantify the relative plausibility of alternative hypotheses H1 and H0 (Keysers et al., 2020). Results were reported using the Bayes factor BF_{01} that represents $p(\text{data}|H_0)/p(\text{data}|H_1)$ and were interpreted according to Lee and Wagenmakers (2013) (see Table S6).

All statistical analyses were carried out with IBM SPSS (version 25) and SAS (version 9.4) considering a double-sided significance level of 0.05 for all analyses.

3 | RESULTS

3.1 | Exposure blinding

The James' Blinding Index indicated that participants had a successful blinding (BI = 0.78; 95% CI: 0.68; 0.87).

3.2 | Memory tasks

The rmANOVA related to the declarative memory task revealed that the between-subject factor EXPOSURE SEQUENCE and the within-subject factor EXPOSURE did not have a statistically significant effect on the number of correctly recalled word pairs, whereas the within-subject factor TIME was statistically significant ($F_{1,29} = 82.03$, $p < .0001$; $\eta_p^2 = 0.739$; Table 1). Univariate analyses showed that the number of correctly recalled word pairs was significantly higher in the morning than in the evening under both exposure conditions (sham: $|t_{(29)}| = 8.02$, $p < .0001$; $|d| = 0.46$, 95% CI [0.31;0.61]; Wi-Fi: $|t_{(29)}| = 8.64$, $p < .0001$; $|d| = 0.62$, 95% CI [0.42;0.81]; Figure 3A). Furthermore, the interaction between the two within-subject factors EXPOSURE and TIME proved to be statistically significant ($F_{1,29} = 7.71$, $p = .0095$; $\eta_p^2 = 0.210$; Table 1). Post-hoc analyses revealed that the overnight change in the number of correctly recalled word pairs was significantly more pronounced under Wi-Fi exposure than under sham exposure ($|t_{(29)}| = 2.78$, $p = .0095$; $|d| = 0.40$, 95% CI [0.11;0.70]; Table 2 and Figure 3a.i).

The memory accuracies for all emotional stimuli, as well as for positive, neutral and negative faces separately as outcome parameters

of the emotional memory task, were not significantly affected by the between-subject factor EXPOSURE SEQUENCE, nor by the within-subject factor EXPOSURE. For three of the four task conditions, however, a significant effect of the within-subject factor TIME could be observed (all faces: $F_{1,29} = 4.95$, $p = .0341$; $\eta_p^2 = 0.146$; neutral faces: $F_{1,29} = 8.05$, $p = .0082$; $\eta_p^2 = 0.217$; positive faces: $F_{1,29} = 5.93$, $p = .0212$; $\eta_p^2 = 0.170$; Table 1). Univariate analyses showed that there was an overnight increase in memory accuracy for neutral faces (sham: $|t_{(29)}| = 2.19$, $p = .0365$; $|d| = 0.40$, 95% CI [0.03;0.76]; Wi-Fi: $|t_{(29)}| = 2.25$, $p = .0324$; $|d| = 0.41$, 95% CI [0.04;0.79]) under both experimental conditions, whereas for positive faces this effect was only observed under sham exposure (sham: $|t_{(29)}| = 2.09$, $p = .0457$; $|d| = 0.31$, 95% CI [0.02;0.60]; Figure 3D,E). For all faces no differences in memory accuracy between evening and morning were observed at the univariate level (Figure 3C). However, Table 2 shows that there were no interaction effects between the two within-subject factors EXPOSURE and TIME. Accordingly, accuracy of overnight memory retention for all faces and the three subcategories did not differ significantly between the experimental conditions (Table 2 and Figure 3c. i; d. i; e. i; f. i).

Finally, the analysis of the outcome parameter of the procedural memory task by using an rmANOVA with EXPOSURE SEQUENCE as between-subject factor and EXPOSURE and TIME as well as their interaction as within-subject factors revealed that the number of correctly typed sequences per 30 s varied only significantly with TIME ($F_{1,29} = 35.32$, $p < .0001$; $\eta_p^2 = 0.549$; Table 1). Univariate analyses showed that improvements in overnight retention could be observed for both exposure conditions (sham: $|t_{(29)}| = 2.94$, $p < .0064$; $|d| = 0.55$, 95% CI [0.17;0.93]; Wi-Fi: $|t_{(29)}| = 6.77$, $p = .0001$; $|d| = 0.92$, 95% CI [0.57;1.28]; Figure 3B). Although the overnight improvement was slightly larger under the Wi-Fi exposure condition, this difference was statistically not significant (Table 2 and Figure 3b.i).

3.3 | Sleep stages

Paired *t*-test analyses showed that the amount of sleep stages N2 and N3, NREM sleep and REM sleep did not differ significantly between Wi-Fi and sham exposure conditions (Table 3).

TABLE 1 Repeated measures analysis of variance (rmANOVA) results for memory performance

Word pair task (WPT)	**Correctly recalled word pairs**			
Factor	***F***	***p***	η_p^2	η_G^2
Exposure sequence	0.22	.6463	0.008	0.007
Exposure	0.23	.6334	0.008	<0.001
Time	82.03	**<.0001**	0.739	0.069
Exposure*Time	7.71	**.0095**	0.210	0.001

Face recognition task (FRT)	**MA – *All faces***				**MA – *Negative faces***			
Factor	***F***	***p***	η_p^2	η_G^2	***F***	***p***	η_p^2	η_G^2
Exposure sequence	0.09	.7632	0.003	0.002	0.52	.4789	0.018	0.009
Exposure	1.33	.2582	0.044	0.017	1.1	.3031	0.037	0.013
Time	4.95	**.0341**	0.146	0.014	0.01	.9306	<0.001	<0.001
Exposure*Time	1.28	.2666	0.042	0.004	0.54	.4664	0.018	0.001
	MA – *Neutral faces*				MA – *Positive faces*			
Exposure sequence	0.01	.9302	<0.001	<0.001	0.01	.9391	<0.001	<0.001
Exposure	1.44	.2395	0.047	0.017	1.11	.3006	0.037	0.014
Time	8.05	**.0082**	0.217	0.036	5.93	**.0212**	0.170	0.017
Exposure*Time	0.94	.3409	0.031	0.004	1.74	.1972	0.057	0.005

Sequential finger tapping task (SFTT)	**Correctly typed sequences per 30 s**			
Factor	***F***	***p***	η_p^2	η_G^2
Exposure sequence	0.04	.8359	0.002	0.001
Exposure	0.74	.3968	0.025	0.004
Time	35.32	**<.0001**	0.549	0.116
Exposure*Time	0.91	.3475	0.030	0.003

Note: MA = memory accuracy: difference of the hit rate and the false alarm rate. Bold indicates statistical significant value ($p < 0.05$). Degrees of freedom for "Exposure sequence" = 1,28 and for the other factors = 1,29; *F* = test statistic *F*; *p* = significance level; η_p^2 = partial eta-squared; η_G^2 = generalized eta-squared. Cohen (1988): no effect ($\eta^2 < 0.010$), small effect ($0.010 \leq \eta^2 < 0.060$), medium effect ($0.060 \leq \eta^2 < 0.140$) or large effect ($\eta^2 \geq 0.140$).

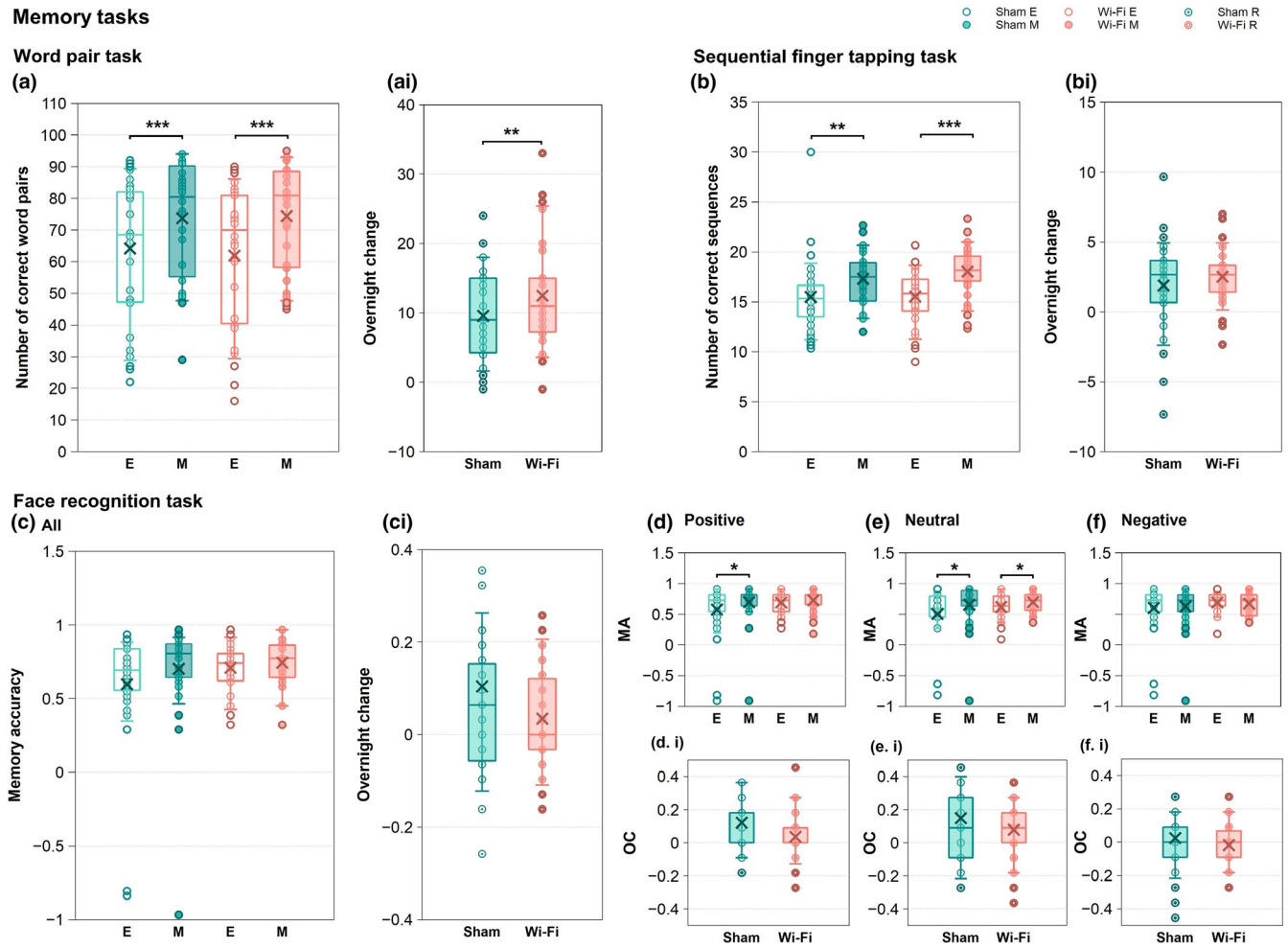

FIGURE 3 Performance in the memory tasks. Performance in the three memory tasks. Memory performance in the declarative, procedural and emotional memory tasks in the Wi-Fi (red) and sham (green) conditions. (A) Number of correctly recalled word pairs in the word pair task (WPT) and the overnight change (OC) (a. i). (B) Number of correctly typed sequences in the sequential finger tapping task (SFTT) and the OC (b. i). (C–F) Memory accuracy (MA) expressed as the difference between the hit and the false alarm rates in the face recognition task (FRT) for all categories ["all faces" (C); "neutral faces" (D); "positive faces" (E); "negative faces" (F)] and the OC in the FRT for all categories ["all faces" (c. i); "neutral faces" (d. i); "positive faces" (e. i); "negative faces" (f. i)]. OC, overnight change; E, immediate recall in the evening; M, retrieval in the morning. Memory retention (*R*) is expressed as the differences between the morning (M) and the evening (E) recalls. (*$p < .05$; **$p < 0.01$; ***$p < 0.001$)

3.4 | Sleep microstructure

An rmANOVA with the between-subject factor EXPOSURE SEQUENCE and the within-subject factors EXPOSURE and scalp REGION as well as their interaction revealed that the EEG power in the SO frequency range and in the two sigma bands (wide, 11–16 Hz; narrow, 12–14 Hz) for sleep stages N2 and N3 varied significantly with the factor REGION (SO-N2: $F_{5,145} = 77.49$, $p < .0001$; $\eta_p^2 = 0.729$; SO-N3: $F_{5,145} = 78.74$, $p < .0001$; $\eta_p^2 = 0.731$; SFA-W-N2: $F_{5,145} = 203.51$, $p < .0001$; $\eta_p^2 = 0.875$; SFA-W-N3: $F_{5,145} = 175.81$, $p < .0001$; $\eta_p^2 = 0.858$; SFA-N-N2: $F_{5,145} = 173.03$, $p < .0001$; $\eta_p^2 = 0.856$; SFA-N-N3: $F_{5,145} = 153.53$, $p < .0001$; $\eta_p^2 = 0.841$; Table 4). In both sleep stages, EEG power in the SO frequency range was highest at frontopolar sites and lowest at occipital and temporal sites, whereas sigma activity (wide and narrow) was highest at central sites and lowest at temporal sites (Table S2). Additionally, EEG power values in all analysed frequency bands were slightly smaller in N2 than in N3 for all scalp regions. The rmANOVA yielded an EXPOSURE SEQUENCE effect on the EEG power in the wider sigma frequency range observed in stage N2 sleep (SFA-W-N2: $F_{1,28} = 4.32$, $p = .0470$; $\eta_p^2 = 0.134$; Table 4). Participants who received Wi-Fi exposure on the first experimental night and sham exposure on the second experimental night showed smaller EEG power values averaged over both experimental nights and all regions (mean ± *SD*: 1.72 ± 0.58 μV^2) than those who were exposed in the opposite direction (mean ± *SD*: 1.97 ± 0.63 μV^2).

Finally, results indicate that sleep spindle densities were also not affected by exposure. The rmANOVA with the within-subject factors EXPOSURE and scalp REGION as well as their interaction revealed that spindle density varied significantly only with the factor REGION in stage N2 sleep but not in stage N3 ($F_{5,145} = 5.20$,

TABLE 2 Performance in the memory tasks

Word pair task (WPT)	Sham		Wi-Fi						
	Mean	*SD*	Mean	*SD*	$\lvert t_{(29)} \rvert$	*p*	|*d*|	95% CI	BF_{01}
Evening recall	64.2	22.7	61.9	22.7	1.15	.2587	0.10	−0.27; 0.07	3.762
Morning recall	73.7	18.9	74.4	17.5	0.46	.6465	0.04	−0.12; 0.19	6.379
Retention	9.6	6.5	12.5	7.9	2.78	**.0095**	0.40	0.11; 0.70	0.254
Face recognition task (FRT)									
All faces									
Evening recall	0.60	0.42	0.71	0.17	1.36	.1844	0.35	−0.16; 0.86	2.985
Morning recall	0.70	0.36	0.74	0.17	0.65	.5225	0.15	−0.28; 0.57	5.719
Retention	0.10	0.32	0.03	0.11	1.13	.2666	0.29	−0.81; 0.22	3.931
Neutral faces									
Evening recall	0.51	0.39	0.62	0.21	1.42	.1657	0.36	−0.14; 0.87	2.751
Morning recall	0.66	0.36	0.70	0.17	0.62	.5395	0.15	−0.32; 0.62	5.884
Retention	0.15	0.37	0.08	0.19	0.97	.3409	0.24	−0.72; 0.24	4.538
Positive faces									
Evening recall	0.58	0.44	0.69	0.19	1.32	.1962	0.34	−0.17; 0.85	3.088
Morning recall	0.70	0.33	0.73	0.19	0.47	.6438	0.11	−0.34; 0.55	6.319
Retention	0.12	0.32	0.04	0.16	1.32	.1972	0.34	−0.86; 0.17	3.155
Negative faces									
Evening recall	0.60	0.40	0.69	0.17	1.12	.2736	0.29	−0.22; 0.80	3.930
Morning recall	0.63	0.35	0.67	0.19	0.75	.4595	0.16	−0.24; 0.56	5.330
Retention	0.02	0.30	−0.02	0.14	0.74	.4664	0.19	−0.69; 0.31	5.527
Sequential finger tapping task (SFTT)									
Evening recall	15.5	3.8	15.5	2.8	0.06	.9525	0.01	−0.34; 0.36	7.070
Morning recall	17.3	2.8	18.0	2.6	1.38	.1771	0.27	−0.12; 0.65	2.851
Retention	1.8	3.4	2.5	2.0	0.95	.3475	0.24	−0.26; 0.75	4.539

Note: Descriptive statistics and results of pairwise analyses (*t*-tests) between Wi-Fi and sham exposure conditions.

Memory retention (overnight change) was calculated for all memory tasks as the differences between the morning and evening recall. Bold indicates statistical significant value ($p < 0.05$). *SD* = standard deviation; *t* = *t*-statistic (degrees of freedom are given in parenthesis); *p* = significance level; *d* = Cohen's *d* (|*d*| < 0.2: no effect; 0.2 ≤ |*d*| < 0.5: small effect; 0.5 ≤ |*d*| < 0.8: medium effect; |*d*| ≥ 0.8: large effect (Cohen, 1988)); 95% CI = 95% confidence interval; BF_{01} = Bayes factor, ratio of likelihood of null hypothesis (H_0) to likelihood of alternative hypothesis (H_1): BF_{01} = 3–10: moderate evidence for H_0; BF_{01} = 1–3: anecdotal evidence for H_0; BF_{01} = 1–0.33: anecdotal evidence for H_1; BF_{01} = 0.33–0.10: moderate evidence for H_1. For a more detailed evaluation see Table S6.

$p = .0084$; $\eta_p^2 = 0.152$; Table 4). Sleep spindle density in stage N2 sleep was higher at parietal sites compared to frontal and central sites independently of the exposure condition (Figure 4 and Table S3).

4 | DISCUSSION

The present provocation study, which can only address acute effects, analysed whether a Wi-Fi exposure during TIB (8 h) might affect sleep-dependent memory consolidation processes (declarative, procedural and emotional memory) and their learning-associated brain activity during sleep in young healthy male volunteers.

4.1 | Sleep-dependent memory consolidation: Behavioural level

Results show that although Wi-Fi did not affect retention in the procedural and emotional memory tasks, the data reveal that retention in the declarative memory was increased after Wi-Fi as compared to sham exposure.

In the WPT, overnight performance gain was higher after Wi-Fi exposure compared to sham (see Figure 3a.i), with an effect size of 0.40. According to Cohen (1988) this is a small effect, which, however, has a large uncertainty (95% CI [0.11; 0.70]). This observed difference in overnight retention of correctly recalled word pairs between sham and Wi-Fi exposure conditions represented moderate evidence for the alternative hypothesis when evaluated based

TABLE 3 Effects of all-night exposure on sleep macrostructure

		Sham		Wi-Fi						
Parameter	**Unit**	**Mean**	***SD***	**Mean**	***SD***	$\|t_{(29)}\|$	***p***	$\|d\|$	**95% CI**	BF_{01}
Stage N2 sleep	min	236.3	26.4	238.1	30.3	0.35	.7292	0.06	−0.29; 0.42	6.672
Stage N2 sleep of TST	%	54.2	6.0	54.0	5.7	0.28	.7842	0.04	−0.31; 0.23	6.822
Stage N3 sleep	min	63.5	29.5	65.5	30.1	0.75	.4565	0.07	−0.11; 0.24	5.379
Stage N3 sleep of TST	%	14.4	6.4	14.7	6.4	0.57	.5701	0.05	−0.13; 0.23	6.034
NREM sleep	min	339.5	30.4	348.6	38.3	1.51	.1407	0.26	−0.08; 0.60	2.414
NREM sleep of TST	%	77.7	5.2	78.9	6.0	1.64	.1114	0.22	−0.05; 0.48	2.016
Stage REM sleep	min	97.9	25.1	92.4	25.4	1.56	.1294	0.22	−0.50; 0.06	2.266
Stage REM sleep of TST	%	22.3	5.2	21.1	6.0	1.64	.1114	0.22	−0.48; 0.05	2.017

Note: Descriptive statistics and results of pairwise analyses (*t*-tests) between Wi-Fi and sham exposure conditions.

TST = total sleep time; NREM = non-rapid eye movement; REM = rapid eye movement; *SD* = standard deviation; *t* = *t*-statistic (degrees of freedom are given in parenthesis); *p* = significance level; *d* = Cohen's *d* ($|d| < 0.2$: no effect; $0.2 \leq |d| < 0.5$: small effect; $0.5 \leq |d| < 0.8$: medium effect; $|d| \geq 0.8$: large effect (Cohen, 1988)); 95% CI = 95% confidence interval; BF_{01} = Bayes factor, ratio of likelihood of null hypothesis (H_0) to likelihood of alternative hypothesis (H_1): BF_{01} = 3–10: moderate evidence for H_0; BF_{01} = 1–3: anecdotal evidence for H_0; BF_{01} = 1–0.33: anecdotal evidence for H_1; BF_{01} = 0.33–0.10: moderate evidence for H_1. For a more detailed evaluation see Table S6.

on the corresponding Bayes factor (BF_{01} = 0.254) (see Table 2). However, the interaction of several factors needs to be taken into account in order to interpret this result accurately. Small differences in the number of correctly recalled word pairs during immediate recall might have affected performance gains in the WPT. That is, the number of correctly recalled word pairs in the evening was slightly, but not significantly, higher in the sham nights as compared to Wi-Fi, whereas the opposite was observed in the morning (see Table 2). The lower "reference level" in the evening preceding the Wi-Fi condition might explain why overnight change was significantly higher under Wi-Fi compared to sham. On the other hand, as both versions of the WPT had the same level of difficulty, it is unlikely that encoding difficulties could explain this finding. Regardless of the exposure condition, the performance on the evening of the two experimental nights did not differ, which supports the absence of a learning effect between experimental nights (see Table S5). Moreover, the data did not reflect the presence of floor or ceiling effects.

Wi-Fi exposure did not affect performance in the FRT. Overnight retention was similar between Wi-Fi and sham exposure. Bayes factors showed that overnight retention in all categories presented moderate evidence for the absence of a decline or improvement after exposure (all faces: BF_{01} = 3.931; neutral faces: BF_{01} = 4.538; positive faces: BF_{01} = 3.155; negative faces: BF01 = 5.527) with effect sizes (Cohen's *d*) that vary from no (negative faces) to small effects (all, neutral and positive faces; see Table 2). Thus, recognition memory in the emotional task did not differ between exposure conditions.

Performance improvements in the SFTT after sleep were not affected by Wi-Fi exposure. The results for the overnight retention in this memory task did not differ between exposure conditions. Moreover, retention in this task showed moderate evidence for the null hypothesis (BF_{01} = 4.539), which is supported by a small effect size (see Table 2). In contrast, Lustenberger et al. (2013) reported a reduction of the performance improvement, measured as the variance of the reaction time, in a similar SFTT under RF-EMF exposure compared to sham (with an effect size of $|d| = 0.57$ representing a medium effect; effect size calculated from data presented in Lustenberger et al., 2013). This effect could not be confirmed by our results. The variance in reaction time performance in the present study did not differ significantly between the exposure conditions, the effect size indicates no effect ($|d| = 0.13$) and the Bayes factor indicates moderate evidence for the null hypotheses (BF_{01} = 6.355) (see Table S4, and Figure S2). However, beside different signal characteristics, Lustenberger et al. (2013) used substantially higher intensities of RF-EMF exposure, whereas in the present study the applied RF-EMF intensities represent realistic worst-case exposure from real Wi-Fi installations.

Irrespective of exposure, the present results confirmed the beneficial role of sleep for memory consolidation. Performance in the three memory tasks improved after a night of sleep, reflecting small (FRT, 0.014) to medium effect sizes (WPT, 0.069; SFTT, 0.116) as indicated by generalized η^2 values. Sleep-dependent improvements in memory consolidation have been extensively discussed using different declarative and non-declarative memory tasks showing that post-sleep memory retention is better than retention after a wake period (Rasch & Born, 2013). This sleep-specific beneficial effect is assumed to be reflected in the present results. In particular, in the WPT, declarative memory enhancements after a night of sleep under both experimental conditions are in line with multiple other studies (for reviews, see Diekelmann et al., 2009; Rasch & Born, 2013). Regarding the FRT, recognition memory performance for all faces, regardless of their emotional valence, improved after

TABLE 4 Results of the repeated measures analysis of variance (rmANOVAs) for the EEG power and spindle densities in sleep stages N2 and N3

	Stage N2 sleep				Stage N3 sleep			
	Slow oscillations (0.5–1.0 Hz)				Slow oscillations (0.5–1.0 Hz)			
Factor	*F*	*p*	η_p^2	η_G^2	*F*	*p*	η_p^2	η_G^2
Exposure sequence	0.17	.6821	0.006	0.003	0.71	.4067	0.025	0.016
Exposure	1.90	.1791	0.061	0.004	1.85	.1848	0.060	0.002
Region	77.94	**<.0001**	0.729	0.525	78.74	**<.0001**	0.731	0.444
Exposure*Region	1.04	.3972	0.035	0.003	1.31	.2613	0.043	0.002
	SFA-W				**SFA-W**			
Exposure sequence	4.32	**.0470**	0.134	0.101	0.93	.3424	0.032	0.025
Exposure	0.91	.3483	0.030	<0.001	2.10	.1583	0.067	0.001
Region	203.51	**<.0001**	0.875	0.612	175.81	**<.0001**	0.858	0.540
Exposure*Region	1.21	.3084	0.040	0.002	0.85	.5146	0.029	0.001
	SFA-N				**SFA-N**			
Exposure sequence	3.31	.0797	0.106	0.072	0.61	.4418	0.021	0.015
Exposure	0.09	.7645	0.003	<0.001	1.08	.3079	0.036	0.001
Region	173.03	**<.0001**	0.856	0.632	153.53	**<.0001**	0.841	0.561
Exposure*Region	1.22	.3005	0.041	0.002	0.75	.5878	0.025	0.001
	Sleep spindle density				**Sleep spindle density**			
Exposure sequence	1.64	.2103	0.055	0.041	1.32	.2601	0.045	0.035
Exposure	0.01	.9121	<0.001	<0.001	0.59	.4480	0.020	0.001
Region	5.20	**.0084**	0.152	0.035	1.36	.2651	0.045	0.007
Exposure*Region	0.30	.7433	0.010	<0.001	0.65	.5236	0.022	<0.001

Note: Bold indicates statistical significant value ($p < 0.05$).

SFA-W = spindle frequency activity wide (11–16 Hz); SFA-N = spindle frequency activity narrow (12–14 Hz); degrees of freedom for "Exposure sequence" = 1,28, for "Exposure" = 1,29 and for the other factors = 5,145; *F* = test statistic *F*; *p* = significance level; η_p^2 = partial eta-squared; η_G^2 = generalized eta-squared. Cohen (1988): no effect ($\eta^2 < 0.010$), small effect ($0.010 \leq \eta^2 < 0.060$), medium effect ($0.060 \leq \eta^2 < 0.140$) or large effect ($\eta^2 \geq 0.140$).

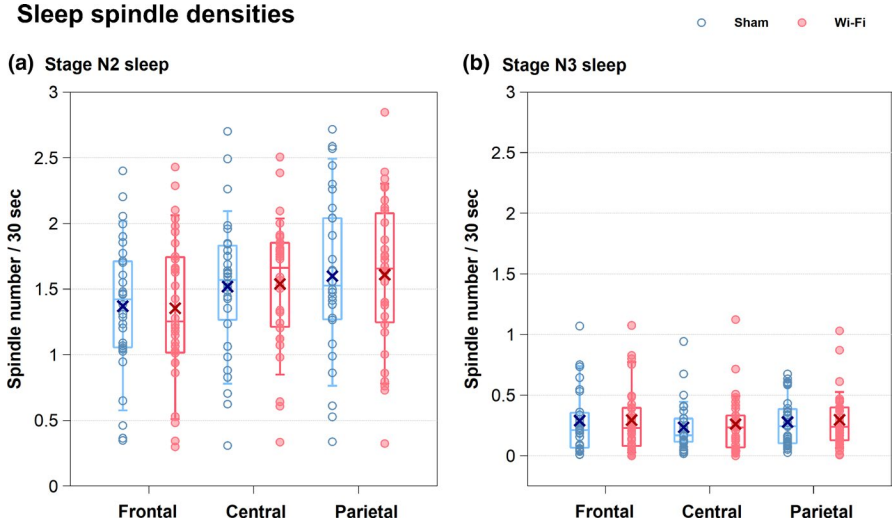

FIGURE 4 Sleep spindle densities by brain region. Sleep spindle density (spindle number per 30 s) was calculated for the sleep stages N2 and N3 in the sham (blue) and Wi-Fi (red) conditions. Average spindle densities were calculated for frontal (F3, F4), central (C3, C4) and parietal (P3, P4) scalp regions

a night of sleep, which is in agreement with previous findings (Solomonova et al., 2017; Wagner et al., 2007). Additionally, memory performance was better after sleep for neutral and positive facial expressions. These findings are consistent with the results of a recent meta-analysis (Schäfer et al., 2020), which revealed an enhancement of recognition memory for both emotional and neutral stimuli. In contrast, recognition for negative stimuli did not improve after sleep in the present study. In this respect, only the neutral faces were recognized during the evening recall phase more effectively on the second experimental night when compared with the first night, regardless of the exposure condition (see Table S5). Finally, results of the SFTT are in line with the evidence of the contribution of sleep to procedural memory consolidation (for review, see King et al., 2017).

4.2 | Sleep-specific features related to memory consolidation: Physiological level

There is compelling evidence that depending on the type of memory, certain sleep stages and sleep EEG characteristics are related to the previously mentioned memory consolidation processes. With regard to the macrostructure of sleep, overnight improvements in declarative memory have been related to slow-wave sleep (N3) (e.g., Diekelmann et al., 2012), whereas overnight improvements in procedural memory have been proposed to be related to time spent in stage N2 sleep (e.g., Walker et al., 2002). Additionally, REM sleep has been associated with both procedural and declarative memory consolidation (Fogel et al., 2007). Finally, the consolidation of emotional memory has been proposed to be dependent on both REM sleep and NREM sleep (Tempesta et al., 2018).

The present analysis revealed that Wi-Fi exposure had no effect on time spent in sleep stages N2, N3 (slow-wave sleep), NREM or REM sleep. Bayes factors for N2 and N3 sleep supported this interpretation by providing moderate evidence for the absence of an exposure effect on these two sleep stages (N2, BF_{01} = 6.672; N3, BF_{01} = 5.379). The corresponding Cohens' *d* values indicated also no effect. However, Bayes factors for NREM and REM sleep indicated only anecdotal evidence for the H_0 (NREM, BF_{01} = 2.414; REM, BF_{01} = 2.266), with Cohens' *d* values representing small effects (see Table 3). In other words, these results pointed out that N2 and N3 sleep were rather unlikely to be affected by Wi-Fi exposure, but that an exposure effect on NREM and REM sleep cannot be excluded. It could be speculated that the evaluation of these two effects, whether they are supportive of the null or alternative hypothesis, would have been more convincing if the sample size had been larger. Then, if this supported the tendency observed in NREM sleep at the descriptive level under Wi-Fi exposure compared to sham (see Table 3), this possible change in NREM could explain at least partially the improvement of declarative memory consolidation.

The literature shows that RF-EMF effects on sleep architecture are quite heterogeneous. Although some studies found effects in the discussed sleep parameters, others did not (for detailed overview, see Danker-Hopfe et al., 2016). Therefore, the present results can be assigned to the group of studies that reported null findings with regard to effects of exposure on sleep macrostructure. The same applies to the study by Danker-Hopfe et al. (2020), which examined the impact of Wi-Fi exposure on a large number of objective sleep parameters in addition to some subjective sleep variables. This previous study, however, considered sleep data from all 34 recruited participants and disregarded deliberately some of the sleep-specific variables that are thought to be associated with memory consolidation processes. Thus, the present study fills this gap and complements this previous publication, but with results restricted to a subsample of 30 subjects for whom behavioural data were available.

With regard to sleep microstructure, sleep spindle frequency ranges, as well as slow-wave activity (0.1–3.5 Hz), have been associated with both declarative and procedural memory improvements (Fogel et al., 2007; Holz et al., 2012). However, other studies did not find a clear association between performance improvements and related sleep stages or EEG power in declarative (Gais et al., 2002) or procedural memory (Rångtell et al., 2017). Sleep spindle density has been proposed to be involved in declarative (e.g., Gais et al., 2002)

and in procedural (e.g., Barakat et al., 2011) memory consolidation. Additionally, emotional memory has been positively correlated with fast spindle densities (13–16 Hz) and negatively with slow spindle (10–13 Hz) densities (Solomonova et al., 2017).

The present results did not reveal any Wi-Fi exposure effect on the EEG power in the ranges of slow oscillations (0.5–0.1 Hz) and narrow (12–14 Hz) and wide (12–16 Hz) sleep spindles. Nor was the sleep spindle density in stages N2 and N3 sleep affected by exposure (see Table 4). This is supported by Cohen's *d* values, which indicate small or no effects (see Table S2). Bayes factors revealed moderate evidence for the absence of a Wi-Fi effect on the narrow sleep spindle frequency range at all regions in N2 and N3. Similarly, Bayes factors indicated moderate evidence for the absence of a Wi-Fi effect on the EEG power in the wide spindle frequency range and in the range of slow oscillations in all cortical regions in both sleep stages, except for the occipital region in N2 and N3. In these cases, Bayes factors revealed only anecdotal evidence for the absence of Wi-Fi effects. As mentioned above, a larger sample size could have provided stronger evidence for the presence or absence of the reduced EEG power under Wi-Fi exposure that can be observed at the descriptive level (see Table S2). Furthermore, Bayes factors revealed moderate evidence for an absence of an exposure effect on sleep spindle densities in both sleep stages, with Cohen's *d* values indicating no effects (see Table S3).

In this respect, Lustenberger et al. (2013) reported that pulsed RF-EMF induced an increase of slow-wave activity at the end of the sleep period, whereas spindle activity remained unchanged and sleep-dependent procedural memory gains were downscaled. Similarly, other RF-EMF studies did not report effects on the EEG in the spindle frequency range (Fritzer et al., 2007; Hinrichs et al., 2005; Nakatani-Enomoto et al., 2013; Wagner et al., 1998, 2000) or for spindle density (Lustenberger et al., 2015), in line with the present results. However, as pointed out previously, RF-EMF effects on the sleep EEG power show mixed results.

In summary, the results at the physiological level did not reveal an impact of Wi-Fi exposure on any of the sleep parameters that are generally associated with sleep-dependent memory consolidation processing, such as NREM sleep, specifically slow-wave sleep, as well as EEG power values in the SO and spindle frequency ranges, and sleep spindle densities. Accordingly, the positive effects that Wi-Fi exposure had on memory retention in the declarative task were not supported by physiological changes associated with memory consolidation processes during sleep. Thus, the present behavioural and neurophysiological findings did not provide evidence that night-time Wi-Fi exposure affects sleep-dependent memory consolidation, so the positive exposure effect on declarative memory should be classified as inconclusive.

5 | CONCLUSIONS

After a night of sleep, participants showed better performances in all memory tasks independent of the experimental condition. These findings are in line with the notion that sleep plays an active role in sleep-dependent memory consolidation. Procedural and emotional memory were not affected by RF-EMF exposure. The observation that the overnight increase in memory performance in the declarative memory task was more pronounced under Wi-Fi exposure as compared to sham was not supported by the results at the physiological level. Sleep spindle densities and power spectra, which are commonly thought to be involved in declarative memory processes, were not affected. Due to these inconsistencies, the observed results may be interpreted to be just by chance. A replication study would be needed to further clarify whether this is a chance or an exposure effect. If the exposure effect could be confirmed, it would seem to have a beneficial effect on memory.

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CONFLICT OF INTEREST

The authors declare no competing financial interests. The sponsor (FSM) did not have any influence on the study design, the data analysis or the manuscript. The manuscript reflects the opinions of the authors only.

AUTHOR CONTRIBUTIONS

HD-H and HD conceptualized the study. GS and RH developed the exposure system. AB-L, TE, HD and HD-H designed and prepared the study. AB-L conducted the study. HD processed the data. AB-L and TE performed statistical analysis. AB-L drafted the manuscript. AB-L, TE, HD and HD-H discussed the results and wrote the manuscript. All authors contributed to and approved the article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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