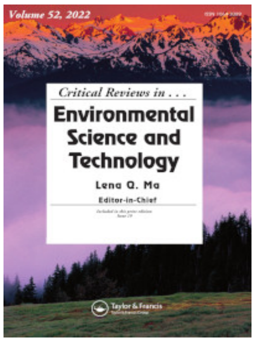


Critical Reviews in Environmental Science and Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/best20

Health effects of WiFi radiation: a review based on systematic quality evaluation

Stefan Dongus, Hamed Jalilian, David Schürmann & Martin Röösli

To cite this article: Stefan Dongus, Hamed Jalilian, David Schürmann & Martin Röösli (2022) Health effects of WiFi radiation: a review based on systematic quality evaluation, Critical Reviews in Environmental Science and Technology, 52:19, 3547-3566, DOI: 10.1080/10643389.2021.1951549

To link to this article: https://doi.org/10.1080/10643389.2021.1951549

CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY
2022, VOL. 52, NO. 19, 3547–3566
https://doi.org/10.1080/10643389.2021.1951549

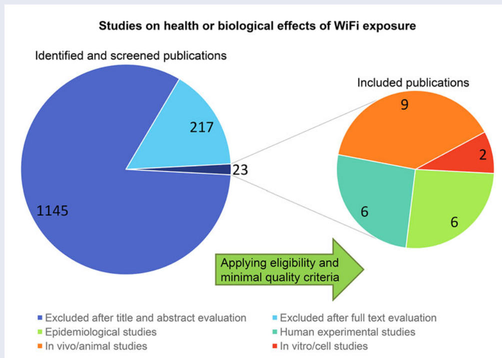
Health effects of WiFi radiation: a review based on systematic quality evaluation

Stefan Dongus[a,b], Hamed Jalilian[c], David Schürmann[d], and Martin Röösli[a,b]

[a]Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, Basel, Switzerland; [b]University of Basel, Basel, Switzerland; [c]Department of Occupational Health Engineering, Research Center for Environmental Pollutants, Faculty of Health, Qom University of Medical Sciences, Qom, Iran; [d]Department of Biomedicine, University of Basel, Basel, Switzerland

ABSTRACT

Although WiFi contributes little to total radiofrequency electromagnetic field (RF-EMF) exposure in our everyday environment, concern has raised whether this specific type of modulated RF-EMF causes health problems. The aim of this review is to evaluate all types of studies that investigated biological and health effects of WiFi exposure and fulfilled basic quality criteria. Eligible for inclusion were epidemiological, human experimental, *in vivo* and *in vitro* studies using realistic WiFi exposure settings. We conducted a systematic literature search for all papers published between January 1997 and August 2020 followed by a quality review addressing blinding and dosimetry in experimental studies and various types of biases in epidemiological studies. All studies fulfilling the quality criteria were descriptively summarized in terms of observation or absence of associations. From 1385 articles identified by the literature search, 23 fulfilled basic quality criteria: 6 epidemiological papers, 6 human experimental articles, 9 *in vivo* articles, and 2 *in vitro* articles. Whereas *in vivo* and *in vitro* studies applied exposure levels up to 4 W/kg, human studies dealt with exposure levels several orders of magnitude below the ICNIRP guidelines, which are typical for WiFi exposure situations in the everyday environment. Numerous outcomes ranging from biological markers to symptoms were mostly found not to be associated with WiFi exposure. Sporadic findings were not consistent in terms of outcomes or exposure-response associations. This review based on a systematic literature search and quality evaluation does not suggest detrimental health effects from WiFi exposure below regulatory limits.



KEYWORDS WLAN; WiFi; risk assessment; health; radiofrequency electromagnetic fields; epidemiological; in vivo; in vitro; human experimental

HANDLING EDITORS Albert Juhasz and Scott Bradford

CONTACT Martin Röösli martin.roosli@swisstph.ch Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, Socinstrasse 57, P.O. Box, Basel, CH-4002, Switzerland.

Supplemental data for this article can be accessed at publisher's website.

Introduction

WiFi, also called WLAN (Wireless Local Area Network), is commonly used to connect devices and for Internet access. Typical applications are in private homes, schools, workplaces, and WiFi hotspots in cities and public transport. WiFi is based on the IEEE 802.11 family of standards, which uses various transmission protocols mostly in the frequency range of 2.400 to 2.484 GHz and 5.150 to 5.825 GHz (IEEE, 2016). Data packets are transmitted between multiple devices and access points using various types of modulations such as the multiple-input, multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM). Consequently, WLAN devices transmit short pulses (bursts) and the burst lengths and burst repetition rates are highly dependent on the actual data traffic in the network. The duty factor is the ratio of the pulse duration to the total period, which is usually low for WiFi communication (Khalid et al., 2011). In the absence of data traffic, only the access point transmits a short beacon signal, every 100 ms, which corresponds to a pulse rate of 10 Hz. In this situation, the crest factor, defined as the ratio of peak values to the effective value, is highest (about a factor of 100) (Schmid et al., 2020).

Peyman et al. (2011) conducted systematic measurements of 15 different types of laptops and 13 different types of access points to estimate exposure of pupils in UK schools to WiFi. For these measurements, the duty factor was maximized so that the burst power was equal to the time averaged power. For laptops operating at 2.4 GHz, the maximum power flux density decreased from 22 to 0.13 mW/m^2 as the distance increased from 0.5 to 1.9 m. Similar trends were observed for laptops operating at 5 GHz with a maximum value of 15 mW/m^2 at 0.5 m distance from the device. For 2.4 GHz access points, the maximum power density value at 0.5 m from the source was 87 mW/m^2 decreasing to 0.22 mW/m^2 at 1.9 m (maximum of ca. 22 mW/m^2 in the 5 GHz band). Subsequent analyses of realistic duty factors of 146 individual laptops investigated in six primary and secondary schools during classroom lessons yielded values from 0.02 to 0.91%, with a mean duty factor of 0.08% (Khalid et al., 2011). The duty factors of access points from seven networks ranged from 1.0% to 11.7% with a mean of 4.8%. This implies that time-averaged exposure levels are considerably lower than the reported maximum values. From these observed duty factors, Khalid et al. (2011) concluded that maximum time-averaged power density from a laptop at a distance of 0.5 m would be 220 $\mu W/m^2$ (instead of 22 mW/m^2), and the peak localized specific absorption rate (SAR) in the torso region of a 10-year-old child model, at 34 cm from the antenna, was predicted to be 80 μW/kg. Findlay and Dimbylow (2010) computed a maximum whole-body averaged SAR value of 19.1 μW/kg for a 1 V/m (=2.65 mW/m^2) plane-wave incident WiFi exposure situation.

Several studies have measured typical personal exposure from WiFi emissions together with other sources of radiofrequency electromagnetic fields (RF-EMF) such as mobile phones, Digital Enhanced Cordless Phones (DECT) or radio or TV broadcasting. These studies, and also some systematic reviews of RF-EMF exposure studies from Europe, have shown that the contribution of WiFi to total RF-EMF exposure is relatively low, typically below 10% (Birks et al. 2018; Foerster et al., 2018; Gallastegi et al., 2018; Jalilian et al., 2019; Roser et al., 2017; Sagar et al., 2018).

Despite the fact that typical WiFi exposure levels in the everyday environment are several orders of magnitude below guideline values (10 W/m^2) (ICNIRP, 2020), there is concern that exposure to WiFi radiation could cause harm for the population, and individuals have reported to specifically react to this type of exposure (Andrianome et al., 2018). It has been speculated that biological effects could arise from high peak values of the WiFi signal pulsation owned to the low duty factor. Wilke (2018) evaluated more than 100 studies on RF-EMF in the 2.45 GHz frequency range and concluded that these studies document “damage to the reproductive system, impacts on the EEG and brain functions, as well as effects on the heart, liver, thyroid, gene expression, cell cycle, cell membranes, bacteria, and plants.” She mentions that many studies identified oxidative stress as a mechanism of action. According to a review of Pall (2018) oxidative stress, sperm/

testicular damage, neuropsychiatric effects including changes in the encephalogram (EEG), apoptosis, cellular DNA damage, endocrine changes, and calcium overload are established effects of WiFi exposure. However, this review was heavily criticized for selective reporting, for ignoring the quality of the studies, for ignoring the level of exposure, for including studies that did not apply WiFi signals, and for inadequate description of the study results (Arribas et al., 2018; Foster & Moulder, 2019; Najera, 2019; Pinto et al., 2020). Another review with substantially less papers, owing to more stringent inclusion criteria, concluded that several studies observed biological effects due to WiFi-type exposures, but technical limitations prevent drawing conclusions about possible health risks of the technology (Foster & Moulder, 2013).

The aim of this review was to evaluate whether WiFi signals have specific biological or health effects by conducting a systematic literature search and restricting the review to studies that adhere to basic quality criteria defined *a priori* and thus low risk of bias.

Methods

Basic eligibility criteria

All epidemiological, human experimental, *in vivo* and *in vitro* studies published between January 1997 and August 2020 referring to WiFi exposure were eligible for inclusion if peer-reviewed and written in English, German or French. We only considered studies with applied SAR values up to 20 W/kg, which corresponds to the basic restrictions for local exposure of limbs in occupational settings (ICNIRP, 2020). We did neither consider studies on plants, bacteria or fungi, nor letters, commentaries, editorials, case reports, conference proceedings, reviews or exclusively computational or modeling papers. We did not consider studies on microwave ablation, thermal treatment, diathermy, other therapeutic applications, medical implants, medical devices and electromagnetic compatibility. To be eligible, studies needed to report an effect estimate for WiFi. Studies that reported WiFi exposure effects exclusively in combination with other signals, for example DECT or mobile phone RF-EMFs, but did not report an effect estimate specifically for WiFi, were not considered.

In order to represent a realistic WiFi signal, studies had to address exposure in the RF-EMF frequency range labeled as any of the IEEE WLAN 802.11 standards (e.g. 802.11ac, 802.11n, 802.11a, 802.11 b, 802.11 g, 802.11 h). If not specifically labeled, studies with realistic WiFi-like signals had to be in the frequency range of 2.400- 2.483 and/or 5.150 – 5.725 GHz and fulfill any of the following criteria:

1. Signal was *not* a continuous wave (CW) signal, and was declared as a packet-type of data service.
2. Modulation was described as direct sequence spread spectrum (DSSS), frequency-hopping spread spectrum (FHSS) or orthogonal frequency division multiplex (OFDM) resulting in stochastic signal characteristics with a pulse rate between 10 Hz for beacon only and ca. 100 Hz at maximum data transmission rate (Schmid et al., 2020).
3. In the absence of data transmission, a pulse rate of 10 Hz was applied.
4. Signal originated from a commercially available access point or mobile terminal (e.g. laptop).

Quality criteria

In addition to the basic eligibility criteria, the following minimal quality criteria had to be fulfilled.

1. Any experimental study had to include at least one sham condition.

2. Any experimental study had to be at least single blinded.
3. The exposure levels in experimental studies were measured or modeled to demonstrate exposure differences between various conditions. Just placing a WiFi emitting device with no emission control was considered to be inadequate.
4. In *in vitro* and *in vivo* studies, an adequate dosimetry was performed.
5. Any epidemiological study had to describe how participants were selected including inclusion and exclusion criteria. For instance, recruiting study participants by an advertisement would result in strong self-selection, which would not be suitable for a cross-sectional data analysis.
6. Any epidemiological study had to consider basic confounders such as age, sex and sociodemographic factors.

Literature search

Using the Web of Science and PubMed databases, a systematic literature search was performed for relevant records between 1 January 1997 and 31 August 2020 (IEEE 802.11, the original WiFi standard, was released in 1997). Keywords referred to exposure and signal type (radiation, radiofrequency electromagnetic fields, 2.4 GHz, 2.45 GHz, 5 GHz, WLAN, WiFi, 802.11 standard), study type (epidemiology, experimental animal models, *in vitro*, *in vivo*) and study subject (human, health, animal, rat, mouse, hamster, rabbit, cell). Variations of the search terms were included as well (e.g. 2.4 GHz / 2400 MHz, WiFi/Wi-Fi, wireless LAN / WLAN, RF-EMF / radiofrequency electromagnetic fields, mouse/mice etc.). A detailed list of the search terms is provided in Table S1 (supplemental material 1). Complementary, manual search was applied to include additional publications found in reference lists of published articles on the topic.

The retrieved literature list was checked for duplicates and with respect to fulfilling the inclusion criteria based on title, abstract and full text. Subsequently, quality evaluation was independently conducted by two data assessors (SD and HJ) and any discrepancy was solved together with MR. In five cases, clarification whether the signal used was indeed a WiFi signal according to the basic eligibility criteria was sought by direct communication with the authors.

Data extraction

For each of the studies fulfilling the inclusion and quality criteria, a defined set of criteria was assessed, and the respective information that was provided in the studies was extracted into tables. The assessment criteria for included studies are listed in Table S2 (supplemental material 1).

Synthesis

The findings of all studies were narratively summarized. Both, associations and absence of associations were reported. Results were evaluated individually with respect to the strengths and limitations of the corresponding studies and potential risk of bias (NTP, 2015; Rooney et al., 2014). An important aspect was to compare exposure levels in relation to regulatory limits and actual exposure levels of the population. As the number of findings per outcome was too small and exposure situations too heterogeneous, we abstain from pooling effect estimates using meta-analysis.

Results

Literature search

After removing duplicates, the search yielded a total of 1385 publications. From these, 955 publications were excluded based on the information and terms in the title, and an additional 190

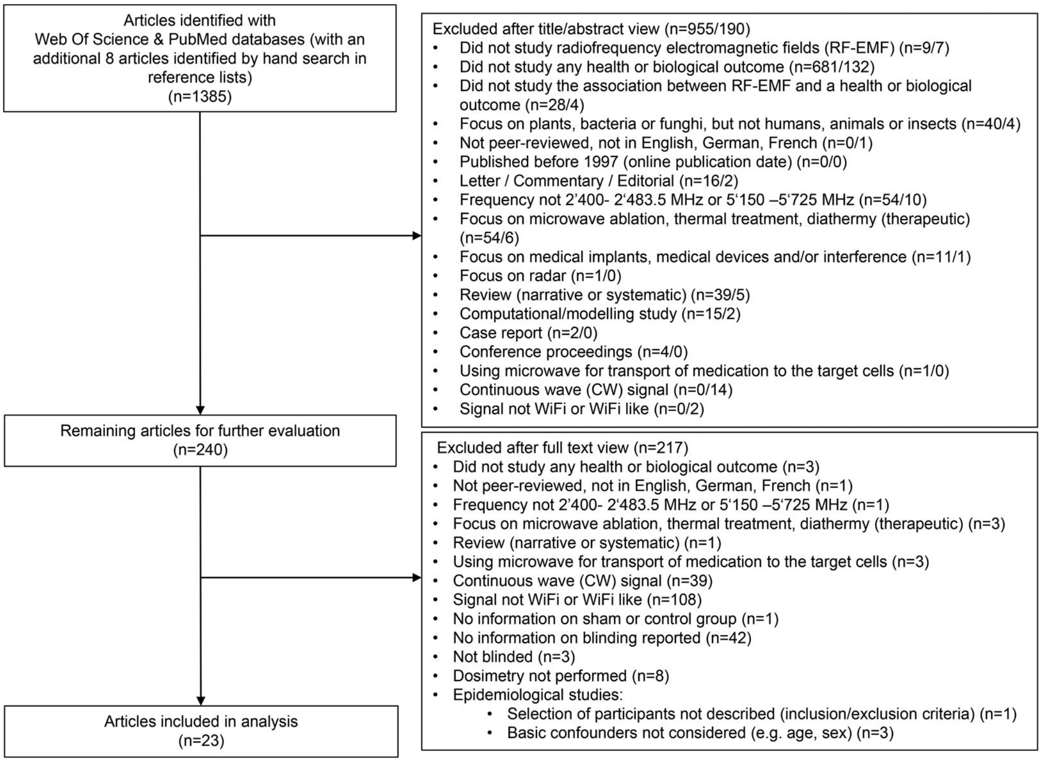


Figure 1. Identification and selection of studies on the health or biological effects of exposure to radiofrequency electromagnetic fields from WiFi.

publications after viewing their abstract (Figure 1 and supplemental material 2). After applying the basic eligibility and quality criteria, 23 publications remained for full assessment and data extraction. These comprised six epidemiological articles, six articles describing human experimental studies, nine *in vivo*, and two *in vitro* papers.

Epidemiological studies

Table 1 and Table S3 (supplemental material 1) give an overview on the six epidemiological papers fulfilling the quality criteria. Redmayne et al. (2013) conducted a cross-sectional study in 373 adolescents with a mean age of 12.3 years about occurrence of symptoms in relation to use of mobile and cordless phones and to the presence of a WiFi at home. While several symptoms were found to be related to mobile phone use, those with a WiFi at home were significantly less likely to wake up during the night. Other symptoms (headaches, feeling down or depressed, tinnitus, trouble falling asleep, tired during school, painful texting thumb) were not related to the presence of WiFi at home. A limitation is self-reported WiFi at home, which concerns also the following two epidemiological studies.

In a larger cross-sectional study involving 2,361 children at seven years of age, it was evaluated if exposure to RF-EMF was associated with reported quality of sleep (Huss et al., 2015). Together with data on other EMF sources (cordless phone base station and mobile/cordless phone use), data on presence of a WiFi at home was obtained from parental reports referring to the time when the child was five years old. In addition, modeled RF-EMF exposure from mobile phone base stations at home and at school was also considered. None of the five scales of the Child Sleep Habits Questionnaire (CSHQ), *a priori* hypothesized to be potentially related to RF-EMF

Table 1. Overview of included epidemiologic and human experimental studies.

Type of study, reference	Participants	WiFi signal	Exposure levels	Exposure duration	WiFi association observed[a]	WiFi association absent[a]
Epidemiological, Bektas et al. (2020)	149 pregnant volunteers	Self-reported exposure	Not reported	Less or more than 2 h/day	None	Biomarkers for oxidative stress in human placenta and cord blood immediately after birth, genotoxicity in cord blood cells
Epidemiological, Bolte et al. (2019); including pilot study of Bogers et al. (2018)	57 self-declared EHS in the main study; 7 in the pilot study (male & female)	2400–2500 MHz, measured by personal exposimeter	Rate of change metric, time above 0.1 mW/m^2 (pilot: number of samples above 0.1 mW/m^2)	5 days of measurements (pilot: 21 days)	Sum score of nonspecific symptoms and severity of the most relevant complaint in one participant (pilot: in two participants some symptoms decreased, in two participants some symptoms increased)	No association on various nonspecific symptoms in 56 study participants (pilot: no association in 3 participants)
Epidemiological, Guxens et al. (2019)	3102 children, aged 5 years	Presence of WiFi at home as reported by mother	Not reported	At the time of the cross-sectional survey	None	Emotional and behavioral problems
Epidemiological, Huss et al. (2015)	2361 children, aged 7 years	Presence of WiFi at home as reported by mother	Not reported	Two years prior to the cross-sectional survey	Higher sleep anxiety in children with WiFi at home (negative control outcome)	7 subscales of the Child Sleep Habits Questionnaire
Epidemiological, Redmayne et al. (2013)	373 adolescents (10-14 years)	Presence of WiFi at home as reported by mother	Not reported	At the time of the cross-sectional survey	Reduced waking in the night	Various self-reported symptoms
Human experimental, Andrianome et al. (2017)	10 self-declared EHS (male & female)	2.45 GHz, IEEE 802.11	Electric field: 1 V/m	5 min	None	Activity of the autonomic nervous system
Human experimental, Andrianome et al. (2019)	10 self-declared EHS (male & female)	2.45 GHz, IEEE 802.11	Electric field: 1 V/m	5 min	None	Salivary biomarkers (alpha amylase, cortisol, IgA)
Human experimental, Danker-Hopfe et al. (2020)	34 young healthy male participants	2.45 GHz, IEEE 802.11 b	Peak SAR: $<$25 mW/kg; average SAR over 6 min: $<$6.4 mW/kg	8 h	Reduction in global EEG power in the alpha frequency band (8.00–11.75 Hz) during NREM sleep	Subjective sleep quality, recorded macrostructure (sleep onset latency, total sleep time, sleep efficiency index, distribution of sleep stages, arousal), sleep microstructure (24 out of 25 parameters of the spectral global EEG power)

Human experimental, Hosseini et al. (2019)	45 university students (male & female), 19-43 years	2.45 GHz, IEEE 802.11 b/g/n	4.1 V/m; 0.446 W/m^2	120 min	None	Reaction time, short-term memory, reasoning ability
Human experimental, Papageorgiou et al. (2011)	30 healthy young adults (males and females)	2.45 GHz, OFDM modulation	Electric field: 0.49 V/m (not reported how value was determined)	Unclear	Gender * exposure interaction within specific condition of Hayling sentence completion test (inhibition condition)	Attention and working memory operation of the brain, EEG activity
Human experimental, Zentai et al. (2015)	30 healthy young adults (males and females)	2.45 GHz, IEEE 802.11 b/g	Peak SAR: 6.57 mW/kg	60 min	None	Spontaneous awake electroencephalographic activity, psychomotor Vigilance Test, self-reported fatigue

[a]For detailed outcomes see Tables S3–S5 (supplemental material 1).

exposure (sleep onset delay, sleep duration, night awakenings, parasomnias, daytime sleepiness), was related to WiFi exposure. Among three negative control outcomes, which were *a priori* hypothesized *not* to be associated with RF-EMF, higher sleep anxiety was observed in children with WiFi at home compared to those without. In the same study, behavioral problems were inquired at the age of five years using the Strength and Difficulty Questionnaire (SDQ) filled in by the teachers and the mothers (Guxens et al., 2019). The risk for any borderline/abnormal score was not related to the presence of WiFi at home for any of the five SDQ scales.

In the Netherlands, Bolte et al. (2019) including a pilot study from Bogers et al. (2018) aimed to directly evaluate in electromagnetic hypersensitive (EHS) individuals whether RF-EMF exposure in daily routine triggers symptoms. While the preceding pilot study (Bogers et al., 2018) comprised data of seven EHS individuals, the main study (Bolte et al., 2019) included 57 participants. In the main study, participants carried an exposimeter logging 12 RF-EMF bands for five days, and provided information on occurrence of nonspecific symptoms at random intervals about eight times a day. The pilot study lasted for 21 days, with participants providing information on symptom occurrence three times a day in 6-hour intervals. In the pilot study, based on 52 tests without multiple correction, one participant felt unsettled with increasing rate of change WiFi exposure and headache decreased in two participants with increasing WiFi exposure. In the main study, there was no statistically significant association between measured personal exposure and occurrence of symptoms at group level. Subsequently, the authors also undertook individual analysis of 36 participants that ascribed their primary complaint to sources within the measuring range of the exposimeter. Named by 22 out of 36 participants, WiFi was the most commonly attributed RF-EMF source in this collective, attributing their complaints to at least one specific source. After correction for multiple testing and confounding, two significant associations were found for one person. For this individual, the sum score of nonspecific symptoms and the severity of the most relevant complaint was associated with WiFi exposure (rate of change and time above 0.1 mW/m^2). Chance findings due to multiple testing and lack of experimental blinding are a limitation for this study. Study participants may be aware of the presence of a WiFi, which may trigger a nocebo response (Brascher et al., 2020). This might be the explanation why one participant in the pilot study reported increased lightheadedness and fatigue in relation to perceived WiFi exposure but not real WiFi exposure.

In a cross-sectional study of 149 pregnant women, self-reported use of WiFi and mobile phones was evaluated in relation to various parameters related to oxidative stress in the blood and placenta, immediately collected after birth (Bektas et al., 2020). Some parameters were associated with mobile phone use but none with WiFi exposure at workplace or at home. The small sample size and the self-reported exposure measures are limitations of this study.

Human experimental studies

In total, six papers on human experimental studies qualified for this review (Table 1 and Table S4 supplemental material 1). Papageorgiou et al. (2011) conducted a randomized experiment with 15 male and 15 female individuals with a mean age of 24 years to study the P300 component of electroencephalography (EEG), a measure of the event-related potentials (ERPs) and marker of attention and working memory operation of the brain, while performing a modified version of the Hayling Sentence Completion test. Volunteers were either sham or real exposed to a 2.45 GHz WiFi access point placed at a distance of 1.5 m from the head, resulting in an electric field strength of 0.49 V/m at the head. No exposure effect was observed except a gender*exposure interaction at some EEG recording electrodes within the response inhibition condition.

Zentai et al. (2015) included 25 volunteers in a double-blind provocation study to study the effects of a 2.45 GHz WiFi exposure for 60 minutes on the spontaneous awake electroencephalographic activity and psychomotor vigilance. The exposure system was constructed from commercial parts and peak SAR_{10g} (SAR averaged over 10 g of contiguous tissue mass) was modeled for various brain regions. The maximum level was obtained for the cerebrospinal fluid (6.57 mW/kg). Compared to a sham condition, neither spontaneous awake electroencephalographic recordings, psychomotor vigilance test (reaction time, number of lapses, variability of responses) nor self-reported fatigue was affected.

In a French human experimental study two different experiments were undertaken (Andrianome et al., 2017). First, the activity of the autonomic nervous system of 30 EHS individuals was compared with age-, sex- and BMI-matched control persons in a series of biological parameters without any EMF source present. Upon an auditory stimulus, EHS individuals had higher skin conductance activity than the control group. Heart rate variability parameters and blood pressure did not differ between the two matched study groups. Second, ten EHS individuals from the first experiment took part in a double-blind provocation study, where they were randomly sham and real exposed to four EMF signals (Global System for Mobile communications (GSM) 900, GSM 1800, DECT, and WiFi) at a level of 1 V/m (2.7 mW/m^2) for 5 min per signal with a rest period of ten minutes between the signals. None of the signals was associated with respiratory rate, heart rate variability, blood pressure or skin conductance. Further, saliva alpha amylase, cortisol and immunoglobulin A concentrations were not related to any of the signals applied (Andrianome et al., 2019).

Effects of WiFi exposure during sleep were investigated in a double-blind, sham-controlled, randomized, and fully counterbalanced cross-over study of 34 healthy young males. Study participants spent a first night in the sleep laboratory for a screening and adaptation night, and later four experimental nights, consisting of baseline nights followed by sham or real exposure nights (Danker-Hopfe et al., 2020). A whole-night 2.45 GHz WiFi (maximum peak spatial SAR_{10g} of 6.4 mW/kg) exposure was delivered by a newly developed exposure facility mimicking a strong but realistic home setting with an access point near the bed, which is well characterized in Schmid et al. (2020). No global EEG power parameters did differ between exposure and sham condition except the EEG power in the alpha frequency band (8.00–11.75 Hz) during non-rapid eye movement (NREM) sleep, which was reduced under acute WiFi exposure compared to sham. This slight physiological change in the EEG power observed under WiFi exposure was neither reflected in the subjective assessment of sleep quality nor at the level of objective measurements of the macrostructure of the sleep.

In a crossover study with 32 female and 13 male participants in Iran, effects of WiFi exposure on reaction time, short-term memory and reasoning ability were investigated (Hosseini et al., 2019). Based on one sham and one exposure session, each lasting two hours, no significant differences between the mean scores of reaction time, short-term memory, and reasoning ability were found. However, the exposure setup does not allow firm conclusions about actual WiFi exposure of the study participants.

In vivo studies

Nine publications from three different laboratories in France, Turkey and Italy reported about *in vivo* experiments in rodents with WiFi exposure (Table 2 and Table S5, supplemental material 1). In the French laboratory, pregnant female Wistar rats and their offspring were exposed in a free-roaming system to a sham or a 2.45 GHz WiFi signal, including a positive control, to assess the impact on reproduction and developing organism (Ait-Aissa et al., 2010, 2012, 2013). WiFi exposure with a whole body SAR of either 0.08, 0.4, or 4 W/kg for the adults (and up to 12 W/kg for the pups) was applied for 2 h/day during 5 days/week for the last 2 weeks of gestation, and for an additional 5 weeks after birth. In the brains of the young rats, no indication for altered gliosis (astroglia activation assessed by glial fibrillary acidic protein immunostaining) and apoptosis (TUNEL assay) were found (Ait-Aissa et al., 2010). Screening the blood of the new-borns for the

Table 2. Overview of included *in vivo* and *in vitro* studies.

Type of study, reference	Biological material	WiFi signal	Exposure levels	Exposure duration	WiFi association observed[a]	WiFi association absent[a]
In vivo, Ait-Aissa et al. (2010)	60 rats (Wistar, female, 12 per group) and offspring (3 pups per litter kept in experiment)	2.45 GHz, IEEE 802.11 b/g	SAR: dams: 0.08, 0.4, and 4 W/kg; pups: up to 12 W/kg	2 h/day, 5 days/week, day 6–21 of gestation, day 1–35 postnatal	None	Neurotoxicity (gliosis, apoptosis) in offspring
In vivo, Ait-Aissa et al. (2012)	60 rats (Wistar, female, 12 per group) and offspring (3 pups per litter kept in experiment)	2.45 GHz, IEEE 802.11 b/g	SAR: dams: 0.08, 0.4, and 4 W/kg; pups: up to 9 +/- 3 W/kg	2 h/day, 5 days/week, day 6–21 of gestation, day 1–35 postnatal	None	Immunological stress markers and growth of young rats, body mass and litter size of female rats
In vivo, Ait-Aissa et al. (2013)	60 rats (Wistar, female, 12 per group) and offspring (3 pups per litter kept in experiment)	2.45 GHz, IEEE 802.11 b/g	SAR: dams: 0.08, 0.4, and 4 W/kg; pups: up to 9 +/- 3 W/kg	2 h/day, 5 days/week, day 6–21 of gestation, day 1–35 postnatal	None	Stress markers in offspring (heat shock proteins (Hsp) and 3-Nitrotyrosine (3-NT) in rat brains)
In vivo, Dasdag et al. (2015)	16 rats (Wistar, male, 8 per group)	2.4 GHz, IEEE 802.11	1.02 mW/kg	24 h/day, 7 days/ week, 12 months	Increased sperm head defects; decreased weight of epididymis and seminal vesicles; decreased seminiferous tubules diameter and tunica albuginea thickness	Sperm motility and concentration; total morphologic and tail defects of sperms; weight of testes and prostate; Johnsen's Biopsy score
In vivo, Poulletier de Gannes et al. (2012)	100 rats (Wistar, female, 20 per group) and offspring (of 75 dams)	2.45 GHz, IEEE 802.11 b/g	SAR: 0.08, 0.4 and 4 W/kg	2 h/day, 6 days/ week, 18 days	Increase in food consumption during postexposure lactation period for rats exposed at 0.4 W/kg (but not 0.08 and 4 W/kg)	Maternal mortality, morbidity, body weight; Fertility: litter size and stillbirths Offspring: body weight, physical and functional development, behavioral abnormalities
In vivo, Poulletier de Gannes et al. (2013)	72 rats (Wistar, 9 male and 9 female per group)	2.45 GHz, IEEE 802.11 b/g	SAR: 0.08 and 4 W/kg	1 h/day, 6 days/week, 5-6 weeks	None (some incidental abnormalities observed)	Rat fertility and fetal development such as body and organ weight, food consumption, organ development, stillbirths

In vivo, Laudisi et al. (2012)	48 mice (C57BL/6)	2.45 GHz	SAR: 4 W/kg	2 h/day, starting 5 days after mating and ending 1 day before expected delivery (14 consecutive days of exposure)	Increased CD4+/CD8+ T cell population in thymus (males at 26 weeks) Reduced CD4+/CD8- T cell populations in thymus (females at week 5, males at 26 weeks)	T cell development and function (thymocyte number and proliferation, peripheral T cells, IFN-γ production)
In vivo, Sambucci et al. (2010)	48 mice (C57BL/6)	2.45 GHz	SAR: 4 W/kg	2 h/day, starting 5 days after mating and ending 1 day before expected delivery (14 consecutive days of exposure)	Higher body weight (male offspring, week 5)	Pregnancy outcome and the immune B cell compartment, including antibody production (IgM, IgG)
In vivo, Sambucci et al. (2011)	48 mice (C57BL/6)	2.45 GHz	SAR: 0.08 or 4 W/kg	2 h/day, 5 days/week, for 5 consecutive weeks starting the day after birth	Reduced IFN-γ production in CD4+ splenic T cells from exposed (SAR 4 W/kg) male (but not female) mice	Body weight, thymocyte maturation, peripheral T cell compartment, B cell proliferation, serum antibody concentrations (IgM, IgG)
In vitro, Kuzniar et al. (2017)	Cultured cells (human osteosarcomas and fibroblasts, murine embryonic stem cells)	5.8 GHz, IEEE 802.11a	Electric field: 9.5 V/m	24 h	None	Less than 1% of the quantitated human or mouse proteome is differentially regulated in response to exposure
In vitro, Schuermann et al. (2020)	Cultured cells (human fibroblasts and trophoblasts)	1.95 GHz, IEEE802.11g	SAR: 0.5, 2, 4.9 W/kg	Intermittent (5/10 min on/off) 1, 4, 24 h	None	DNA single-strand breaks and oxidative DNA damage (MRC-5 cells, HTR-8/SVneo trophoblasts)

[a]For detailed outcomes see Tables S3–S5 (supplemental material 1).

presence of markers for oxidative stress did not reveal any significant alterations and litter size by WiFi exposure, and body mass and pups anogenital distance were also not changed (Ait-Aissa et al., 2012). Furthermore, WiFi exposure did not affect the expression of the stress markers, 3-Nitrotyrosine and the heat shock proteins Hsp25 and Hsp70 (Ait-Aissa et al., 2013). In a further experiment in the same laboratory using similar exposure conditions, although no positive control was executed in this case, female Wistar rats and their pups were exposed postcoitum for 18 days 2 h/day and 6 days/week (20 animals per group) and data were obtained for both the mother and the new-borns (Poulletier de Gannes et al., 2012). Apart from an increased food consumption during the lactation period in rat dams exposed to 0.4 W/kg lacking an exposure-response correlation, no effects were observed in respect to death rate of fetuses, number of implantation sites, litter size, number of stillbirths and live births, maternal body weight and macroscopic abnormalities. In addition, the live pups did not differ in body weight, physical and functional development, or showed behavioral abnormalities. In a third experiment executed in the same laboratory, nine male and nine female Wistar Han rats per group were exposed to a 2.45 GHz WiFi signal for 1 h/day during 6 days/week at a whole body SAR of 0.08 and 4 W/kg for three and two weeks, respectively, continuing for another three weeks after mating (one couple per cage) (Poulletier de Gannes et al., 2013). Based on absence of effects for most outcomes, the authors concluded that their experiment does not provide evidence for adverse effects of WiFi exposure on the male and female reproductive organs, fertility and fetal body weight. Sporadic findings in exposed animals occurring without any consistency in terms of exposure-response associations were considered incidental and spontaneous in nature.

Dasdag et al. (2015) performed a long-term and low dose 2.4 GHz WiFi signal exposure experiment with 16 adult male Wistar rats and assessed sperm parameters and the histology of the reproductive organs. Eight animals per group were sham- or continuously WiFi-exposed for one year, but cage or positive controls were not included. An average SAR (10 g) of 1.02 mW/kg was calculated for testes and prostate, but this may involve some uncertainties due to the free roaming of rats. While neither an impact on total morphologic defects nor sperm motility and concentration was observed, the authors found an increased proportion of sperms with head defects in exposed animals. Furthermore, they reported a decreased weight of epididymis and seminal vesicles, but not of testes and prostate, and reduced thickness of the tunica albuginea and diameter of seminiferous tubules without changing the Johnsen's Biopsy score.

In experiments including a cage control group conducted in an Italian laboratory, specific-pathogen-free C57BL/6 mice were either sham- or WiFi-exposed, while being restrained in a tube. Center frequency of the WiFi signal was 2.462 GHz and the whole body SAR 4 W/kg. Exposure was applied for two hours per day, starting five days after mating and ending one day before the expected delivery. Mating success, number of newborns/mother and body weight at birth was analyzed and found to be not influenced by WiFi exposure (Sambucci et al., 2010). New-born mice were immunologically analyzed at 5 or 26 weeks of age. B cell differentiation and function (Sambucci et al., 2010) as well as cell count, phenotype, and proliferation of thymocytes including spleen cell count, CD4/CD8 cell frequencies, T cell proliferation, and cytokine production were mostly not related to prenatal exposure (Laudisi et al., 2012). The few associations observed did not show any consistency. In a follow up experiment, 16 new-born mice per exposure group were either sham- or real exposed to a 2.462 GHz WiFi signal for 2 h/day, 5 days/week for 5 consecutive weeks starting the day after birth (0.08 or 4 W/kg whole body SAR) (Sambucci et al., 2011). Body weight increase and development was not different among the groups. In the immunological analyses, a reduced IFN-γ production in spleen cells of 4 W/kg exposed male but not female mice was observed in comparison to sham-exposed mice. None of the other immunological parameters (thymocytes maturation, peripheral T and B cells) were related to exposure status.

In vitro studies

Two studies fulfilled the inclusion criteria (Table 2 and Table S5, supplemental material 1). Kuzniar et al. (2017) applied a 5.8 GHz WiFi of 9.5 V/m for 24 h on human osteosarcomas (U2OS), human fibroblasts (VH10) and mouse embryonic stem cells (IB10) to assess the proteome by mass spectrometry. The authors found that less than 1% of the detected proteins responded to EMF, which—according to the authors—does not indicate perturbed cellular processes or pathways in response to WiFi exposure. Furthermore, no proteins with consistently changed abundance in the three cell lines were identified, which could serve as biomarker for WiFi exposure. Among various tested modulated EMF signals, Schuermann et al. (2020) exposed primary human MRC-5 lung fibroblasts and immortalized human trophoblast cells (HTR-8/SVneo,) with a WiFi signal at SAR levels 0.5, 2 and 4.9 W/kg applied for 1, 4 and 24 h intermittently (5/10 min on/off). The authors concluded from genotoxicity experiments, independently conducted in two laboratories, that there is no indication for a direct or reactive oxygen species (ROS)-mediated induction of DNA damage. Therefore, both of these *in vitro* studies concluded an absence of short-term effects of WiFi exposure.

Discussion

Following a systematic literature search and quality evaluation, two *in vitro*, five *in vivo* (nine publications), five human experimental (six publications) and four epidemiological (six papers) studies remained for evaluation. The outcomes covering a broad range of biological parameters were mostly found to not be related to WiFi exposure. Sporadic findings were not consistent in terms of biological context or exposure-response associations. Whereas *in vivo* and *in vitro* studies applied in most cases exposure levels up to the guideline levels (ICNIRP, 2020) or even higher (4 W/kg), human studies dealt with levels several orders of magnitude below the ICNIRP guidelines of 10 W/m^2 for whole body exposure or 40 W/m^2 for local exposure (or SAR 2-4 W/kg), which are typical for WiFi exposure situations in the everyday environment.

Our findings for WiFi exposure are in line with other recent reviews on RF-EMF exposure. Biological effects are occasionally observed at relatively high exposure levels close to, or above, the ICNIRP guidelines in experimental studies suggesting that RF-EMF may modify—at least temporary—oxidative stress responses or membrane potentials (Barnes & Greenebaum, 2020). However, this has not been found to translate inevitably to health damage, and reviews reporting such sporadic effects could not identify consistency in terms of exposure time and intensity or other testing conditions, for instance for cognitive behavior in laboratory animals (Sienkiewicz & van Rongen, 2019) or for electrophysiological effects in humans (Danker-Hopfe et al., 2019; Wallace & Selmaoui, 2019). Various reviews concluded that the excellence of conceptional and experimental execution inversely correlates with the likelihood to report an effect; the more the quality criteria requirements were satisfied in a study, the smaller was the number of detected response in cells or animals (Elwood & Wood, 2019; Simko et al., 2016). A recent review on mobile phone use and tinnitus concluded that study quality is critical (Kacprzyk et al., 2021) and a review focusing on exposure from mobile phone base stations concluded that the more sophisticated the exposure assessment is, the less likely an effect would be reported (Röösli et al., 2010). For this reason, in our review we only included studies that met a basic set of quality criteria and thus had a lower risk of bias or experimental artifacts.

For hazard identification, epidemiological studies are most appropriate to study exposure situations occurring in our environment including long-term exposure. However, observational research is prone to bias. Exposure to WiFi radiation is likely to be correlated with several lifestyle and behavioral factors such as socioeconomic status, stressful lifestyle, internet use including problematic use and sleep displacement or blue-light exposure from screens. Thus, it is a challenge to differentiate between physical WiFi exposure and other factors related to the use of wireless communication. Three out of four epidemiological studies in this review have used a crude exposure assessment asking about the presence of WiFi at home or in school (Bektas et al., 2020; Guxens et al., 2019; Huss et al., 2015; Redmayne et al., 2013). This has a high ecological validity as it represents the situation of people who complain about WiFi effects. However, it is likely to result in considerable exposure misclassification, as the contribution of WiFi exposure to total RF-EMF exposure is relatively low. To put this statement into perspective a summary of WiFi exposure studies is given in the following.

WiFi contribution to typical total personal RF-EMF exposure has been investigated in several studies. In a personal RF-EMF exposure study with 529 children, aged 8–18 years, conducted between 2014 and 2016 using personal portable exposure meters in Denmark, the Netherlands, Slovenia, Switzerland, and Spain, WiFi in the 2.4 GHz band contributed about 2% (median: 1.8 $\mu W/m^2$) to total environmental RF-EMF exposure (median: 75.5 $\mu W/m^2$) (Birks et al., 2018). Whether children had a WiFi at home or not had only marginal influence on the personal EMF exposure in the 2.45 GHz band. In personal measurements of 8-year-old Spanish children, median exposure in the 2.4 GHz band was 12.7 $\mu W/m^2$ in living rooms and 2.3 $\mu W/m^2$ in classrooms (Gallastegi et al., 2018). These studies are in line with systematic reviews of RF-EMF exposure studies from Europe that concluded that WiFi contribution to total RF-EMF exposure is typically low and below 10% (Jalilian et al., 2019; Sagar et al., 2018). Among the few exceptions is a personal measurement study of 98 adults in the Netherlands, where WiFi from Internet use in the 2.4 GHz band contributed 11.5% to total RF-EMF exposure with highest level at home (mean: 33 $\mu W/m^2$) and at the work place (7 $\mu W/m^2$) (Bolte & Eikelboom, 2012). In personal measurements of 18 teachers in Swedish schools, WiFi in the 2.4 GHz band contributed 12% (2.8 $\mu W/m^2$) and WiFi in the 5 GHz band contributed 14% (3.1 $\mu W/m^2$) to total RF-EMF exposure (Hedendahl et al., 2017). For an indoor office environment in Belgium, Aminzadeh et al. (2016) reported an average of 166 $\mu W/m^2$ in the WiFi-5 GHz frequency band.

In a Swiss study with data collected from 90 adolescents in 2013 and 2014, WiFi in the 2.4 GHz band accounted in average for 3.5% (2.2 $\mu W/m^2$) of total personal RF-EMF exposure (Roser et al., 2017). WiFi exposure during school hours was 7.4 $\mu W/m^2$ for students with WiFi available at school and 1.0 $\mu W/m^2$ for those without. In this study, the total absorbed dose was calculated by combining measured environmental RF-EMF exposures with contributions from sources used close to body (e.g. own mobile phone). On average, WiFi in the 2.4 GHz band contributed 0.2% to the brain dose and 0.5% to the whole body dose. In an update of this study with additional exposure data from 58 adolescents collected between 2014 and 2015 and using an improved dosimetric model, environmental WiFi from access points and other people's mobile phone contributed 0.2% and WiFi from own mobile phone data traffic contributed 3.4% to total brain dose (Foerster et al., 2018).

Given the little contribution of WiFi to total exposure, the observed absence of associations in the three epidemiological studies discussed above (Bektas et al., 2020; Guxens et al., 2019; Huss et al., 2015; Redmayne et al., 2013) based on simple proxies is little informative and could also represent exposure misclassification. A more reliable exposure estimate was obtained in the fourth epidemiological study, measuring exposure during daily routine and addressing acute effects (Bogers et al., 2018; Bolte et al., 2019). However, this panel study may be affected by confounding and awareness bias, which means that knowledge about the presence of a WiFi source nearby may bias the symptom reporting of some individuals. Thus, no firm conclusion can be drawn from the observed associations in one out of 22 persons complaining about WiFi exposure in the main study (Bolte et al., 2019).

Given these limitations, the human experimental studies are considered particularly relevant for hazard identification. In the sleep study of Danker-Hopfe et al. (2020) the exposure set-up was of high quality, mimicking an extreme, but still realistic situation with a WiFi access point close to the head during sleep (Schmid et al., 2020). The randomized, double-blind experimental design is unlikely to be affected by confounding. Further, the French study on EHS individuals is important as it examined the potentially most sensitive group stating to react to RF-EMF in their daily routine (Andrianome et al., 2019). Although several orders of magnitude below regulatory limits, exposure levels of 1 V/m are still relatively high for WiFi exposure in environmental settings, and the absence of any associations is an import finding. It has been criticized that EHS individuals may be stressed in such an experiment in unfamiliar surroundings. However, in randomized tests at the home of 42 EHS individuals applying different types of RF-EMF sources according to individual attributions (16 persons requested WiFi), none of the participants was able to correctly identify when they were being RF-EMF-exposed better than chance (van Moorselaar et al., 2017). The third human experimental study passing our basic quality criteria did neither find any effects from WiFi exposure on spontaneous awake electroencephalographic activity and psychomotor vigilance (Zentai et al., 2015). No effects were found also in the fourth human experimental study, which investigated reaction time, short-term memory and reasoning ability (Hosseini et al., 2019). Thus, from these four studies acute effects of WiFi at levels typically occurring in the environment are unlikely, even in EHS individuals. The observed effect in the fifth human experimental study is most likely an incidental finding as it is restricted to a gender-exposure interaction occurring at a single component of the EEG.

In vitro and animal studies are useful to elucidate underlying biological mechanisms for any effects observed in human studies. Thus, they can be applied to confirm and to investigate health related exposure effects on the functional and molecular level, even above the regulatory limits. Applying our inclusion criteria for WiFi exposure and quality, the majority of the studies were excluded, mostly because of the lack of experimental blinding and/or sham control or the application of EMF that are unmodulated or hardly resemble a real WiFi signal. The few remaining *in vitro* and *in vivo* studies found mostly no association between WiFi exposure and the assessed readouts in respect to neuro- and genotoxicology, reproduction and immunological parameters, despite applying high exposure close or above the ICNIRP guidelines for the general population (SAR of 4 W/kg). Note that the realistic WiFi signal applied by Schuermann et al. (2020) was outside the usual frequency range.

In this review, we have focused exclusively on WiFi exposure. In principle, biological EMF effects could be a function of frequency, amplitude, and modulation. We hypothesized that WiFi signals could have different effects than other types of RF-EMF exposure including CW signals as often complained by EHS individuals (Andrianome et al., 2018). Based on our hypothesis, we have excluded many studies that addressed WiFi frequencies (e.g. 2.4 GHz) but used continuous wave signals or a different type of modulation (e.g. 217 Hz pulses as used for Global System for Mobile Communications, 2 G). These excluded studies would result in similar tissue specific SAR values for a given exposure level than the included studies. In reality, it is challenging to characterize the typical WiFi signal modulation, because it is highly variable according to amount and direction of data transmission. Thus, the included studies likely represent a mixture of different signal forms ranging from idle state with high crest factor and strong 10 Hz pulsation to almost stochastic pulsation frequency for heavy data transmission. Thus, one might be concerned that effects from very specific WiFi signal modulations or mixtures have not been captured in the research so far. Systematic research on modulation-specific effects is still inconclusive. In a human experimental study, modulation specific effects on the EEG during sleep were observed, suggesting that effects are proportional to the maximum peak during the pulse and not the average exposure levels (Schmid et al., 2012). If this were confirmed more broadly in the future, this would imply that, at the same average exposure level, WiFi would be biologically more active than most other RF-EMF sources in our daily environment due to the low duty factor of WiFi. However, exposure to WiFi is low compared to other sources, namely own use of mobile phones and emissions from mobile phone base stations (Jalilian et al., 2019; Sagar et al., 2018). Hence, even if we consider peak pulse levels, contribution from WiFi to total RF-EMF dose would be low compared to other sources. It is thus likely that complaints to have experienced detrimental effects when being exposed to WiFi are owing to a nocebo response. A recent experimental double-blind study using sham and real WiFi exposure demonstrated that negative expectations about the harmfulness of EMF may foster the occurrence of illusory symptom perceptions via alterations in the somatosensory decision criterion (Wolters et al., 2021).

In conclusion, we found little evidence that WiFi exposure is a health risk in the everyday environment, where exposure levels are typically considerably lower than ICNIRP guideline values. Observational studies on long-term effects specifically focusing on WiFi are scarce and challenging to conduct given the little exposure contribution from WiFi to overall RF-EMF exposure. Experimental studies, although limited in numbers, did not provide evidence that WiFi exposure may be more problematic than other types of RF-EMF exposure in a similar frequency and intensity range, and it is justified to conduct health risk evaluation for WiFi based on the total RF-EMF literature. Given the fact that some people state to react to specific RF-EMF sources, we recommend further experimental studies aiming to clarify the exact role of the signal characteristics by systematically exploring different aspects of RF-EMF exposure such as frequency, signal characteristics and crest factors in addition to intensity and duration of exposure. A more systematic and concerted approach would provide more reliable information for risk assessment for specific RF-EMF sources or for new exposure situations like the ongoing introduction of the fifth generation mobile radio technology (5 G). Our review has demonstrated that a substantial amount of papers did not fulfill basic quality criteria. Experimental studies should apply well-controlled exposure set-ups, consider confounders such as temperature changes and vibrations and conduct at least blinded analyses when blinded experiments are not possible. For observational studies, reliable and validated exposure assessment is a key requirement in addition to minimizing selection bias and confounding. Another aspect is reporting, which was insufficient for many studies. Thus, papers should be checked prior to publication whether they adhere to well accepted reporting guidelines such as STROBE (STrengthening the Reporting of OBservational studies in Epidemiology) (von Elm et al. 2007) or CONSORT (Consolidated Standards of Reporting Trials) (Schulz et al. 2010), ARRIVE (Animal Research: Reporting of *In Vivo* Experiments) (Kilkenny et al., 2010; Percie Du Sert et al., 2020), and MIBBI (Minimum Information for Biological and Biomedical Investigations (Taylor et al. 2008; Emmerich & Harris, 2020).

Acknowledgments

We thank the corresponding authors of studies who have provided additional information upon our request.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was funded by the Swiss Federal Office of Public Health (Dossier No. 19.020051/434.0001-22/1). Martin Röösli's research is entirely funded by public or not for profit foundations. He has served as advisor to a number of national and international public advisory and research steering groups concerning the potential health effects of exposure to nonionizing radiation, including the World Health Organization, the International Agency for Research on Cancer, the International Commission on Non-Ionizing Radiation Protection, the Swiss Government (member of the working group "mobile phone and radiation" and chair of the expert group BERENIS), the German Radiation Protection Commission (member of the committee Non-ionizing Radiation (A6) and member of the working group 5 G (A630)) and the Independent Expert Group of the Swedish Radiation Safety Authority. From 2011 to 2018, M.R. was an unpaid member of the foundation board of the Swiss Research

Foundation for Electricity and Mobile Communication, a nonprofit research foundation at ETH Zurich. Neither industry nor nongovernmental organizations are represented on the scientific board of the foundation.

ORCID

Stefan Dongus http://orcid.org/0000-0002-2761-5596
Hamed Jalilian http://orcid.org/0000-0002-5423-9442
David Schürmann http://orcid.org/0000-0003-2904-1378
Martin Röösli http://orcid.org/0000-0002-7475-1531

References

Ait-Aissa, S., Billaudel, B., Poulletier de Gannes, F., Hurtier, A., Haro, E., Taxile, M., Ruffie, G., Athane, A., Veyret, B., & Lagroye, I. (2010). In situ detection of gliosis and apoptosis in the brains of young rats exposed in utero to a Wi-Fi signal. *Comptes Rendus Physique*, *11*(9/10), 592–601. https://doi.org/10.1016/j.crhy.2010.10.005

Ait-Aissa, S., Billaudel, B., Poulletier de Gannes, F., Ruffie, G., Duleu, S., Hurtier, A., Haro, E., Taxile, M., Athane, A., Geffard, M., Wu, T. N., Wiart, J., Bodet, D., Veyret, B., & Lagroye, I. (2012). In utero and early-life exposure of rats to a Wi-Fi signal: Screening of immune markers in sera and gestational outcome. *Bioelectromagnetics*, *33*(5), 410–420. https://doi.org/10.1002/bem.21699

Ait-Aissa, S., Poulletier de Gannes, F., Taxile, M., Billaudel, B., Hurtier, A., Haro, E., Ruffie, G., Athane, A., Veyret, B., & Lagroye, I. (2013). In situ expression of heat-shock proteins and 3-nitrotyrosine in brains of young rats exposed to a WiFi signal in utero and in early life. *Radiation Research*, *179*(6), 707–716. https://doi.org/10.1667/RR2995.1

Aminzadeh, R., Thielens, A., Bamba, A., Kone, L., Gaillot, D. P., Lienard, M., Martens, L., & Joseph, W. (2016). On-body calibration and measurements using personal radiofrequency exposimeters in indoor diffuse and specular environments. *Bioelectromagnetics*, *37*(5), 298–309. https://doi.org/10.1002/bem.21975

Andrianome, S., De Seze, R., Braun, A., & Selmaoui, B. (2018). Descriptive self-reporting survey of people with idiopathic environmental intolerance attributed to electromagnetic fields (IEI-EMF): similarities and comparisons with previous studies. *Journal of Public Health*, *26*(4), 461–473. https://doi.org/10.1007/s10389-017-0886-0

Andrianome, S., Gobert, J., Hugueville, L., Stephan-Blanchard, E., Telliez, F., & Selmaoui, B. (2017). An assessment of the autonomic nervous system in the electrohypersensitive population: A heart rate variability and skin conductance study. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *123*(5), 1055–1062. https://doi.org/10.1152/japplphysiol.00229.2017

Andrianome, S., Yahia-Cherif, L., & Selmaoui, B. (2019). Effect of short exposure to radiofrequency electromagnetic fields on saliva biomarkers: A study on the electrohypersensitive individuals. *International Journal of Radiation Biology*, *95*(6), 788–792. https://doi.org/10.1080/09553002.2019.1569776

Arribas, E., Ramirez-Vazquez, R., & Escobar, I. (2018). Comment on "Wi-Fi is an important threat to human health". *Environmental Research*, *167*, 639–639. https://doi.org/10.1016/j.envres.2018.08.029

Barnes, F., & Greenebaum, B. (2020). Possible mechanism for synchronized detection of weak magnetic fields by nerve cells. *Bioelectromagnetics*, *41*(3), 213–218. https://doi.org/10.1002/bem.22251

Bektas, H., Dasdag, S., & Bektas, M. S. (2020). Comparison of effects of 2.4 GHz Wi-Fi and mobile phone exposure on human placenta and cord blood. *Biotechnology & Biotechnological Equipment*, *34*(1), 154–162. https://doi.org/10.1080/13102818.2020.1725639

Birks, L. E., Struchen, B., Eeftens, M., van Wel, L., Huss, A., Gajsek, P., Kheifets, L., Gallastegi, M., Dalmau-Bueno, A., Estarlich, M., Fernandez, M. F., Meder, I. K., Ferrero, A., Jimenez-Zabala, A., Torrent, M., Vrijkotte, T. G. M., Cardis, E., Olsen, J., Valic, B., … Guxens, M. (2018). Spatial and temporal variability of personal environmental exposure to radio frequency electromagnetic fields in children in Europe. *Environment International*, *117*, 204–214. https://doi.org/10.1016/j.envint.2018.04.026

Bogers, R. P., van Gils, A., Clahsen, S. C. S., Vercruijsse, W., van Kamp, I., Baliatsas, C., Rosmalen, J. G. M., & Bolte, J. F. B. (2018). Individual variation in temporal relationships between exposure to radiofrequency electromagnetic fields and non-specific physical symptoms: A new approach in studying 'electrosensitivity'. *Environment International*, *121*(Pt 1), 297–307. https://doi.org/10.1016/j.envint.2018.08.064

Bolte, J. F. B., Clahsen, S., Vercruijsse, W., Houtveen, J. H., Schipper, C. M. A., van Kamp, I., & Bogers, R. (2019). Ecological momentary assessment study of exposure to radiofrequency electromagnetic fields and non-specific physical symptoms with self-declared electrosensitives. *Environment International*, *131,* 104948. https://doi.org/10.1016/j.envint.2019.104948

Bolte, J. F., & Eikelboom, T. (2012). Personal radiofrequency electromagnetic field measurements in The Netherlands: Exposure level and variability for everyday activities, times of day and types of area. *Environment International*, *48*, 133–142. https://doi.org/10.1016/j.envint.2012.07.006

Brascher, A. K., Schulz, S. M., Van den Bergh, O., & Witthoft, M. (2020). Prospective study of nocebo effects related to symptoms of idiopathic environmental intolerance attributed to electromagnetic fields (IEI-EMF). *Environmental Research*, *190*, 110019. https://doi.org/10.1016/j.envres.2020.110019
Danker-Hopfe, H., Bueno-Lopez, A., Dorn, H., Schmid, G., Hirtl, R., & Eggert, T. (2020). Spending the night next to a router – results from the first human experimental study investigating the impact of Wi-Fi exposure on sleep. *International Journal of Hygiene and Environmental Health*, *228*, 113550. https://doi.org/10.1016/j.ijheh.2020.113550
Danker-Hopfe, H., Eggert, T., Dorn, H., & Sauter, C. (2019). Effects of RF-EMF on the human resting-state EEG-the inconsistencies in the consistency. Part 1: Non-exposure-related limitations of comparability between studies. *Bioelectromagnetics*, *40*(5), 291–318. https://doi.org/10.1002/bem.22194
Dasdag, S., Taş, M., Akdag, M. Z., & Yegin, K. (2015). Effect of long-term exposure of 2.4 GHz radiofrequency radiation emitted from Wi-Fi equipment on testes functions. *Electromagnetic Biology and Medicine*, *34*(1), 37–42. https://doi.org/10.3109/15368378.2013.869752
Elwood, M., & Wood, A. W. (2019). Health effects of radiofrequency electromagnetic energy. *The New Zealand Medical Journal*, *132*(1501), 64–72.
Emmerich, C. H., & Harris, C. M. (2020). Minimum information and quality standards for conducting, reporting, and organizing in vitro research. *Handbook of Experimental Pharmacology*, *257*, 177–196. https://doi.org/10.1007/164_2019_284
Findlay, R. P., & Dimbylow, P. J. (2010). SAR in a child voxel phantom from exposure to wireless computer networks (Wi-Fi). *Physics in Medicine and Biology*, *55*(15), N405–411. https://doi.org/10.1088/0031-9155/55/15/N01
Foerster, M., Thielens, A., Joseph, W., Eeftens, M., & Röösli, M. (2018). A prospective cohort study of adolescents' memory performance and individual brain dose of microwave radiation from wireless communication. *Environmental Health Perspectives*, *126*(7), 077007. https://doi.org/10.1289/EHP2427
Foster, K. R., & Moulder, J. E. (2013). Wi-Fi and health: Review of current status of research. *Health Physics*, *105*(6), 561–575. https://doi.org/10.1097/HP.0b013e31829b49bb
Foster, K. R., & Moulder, J. E. (2019). Response to pall, "Wi-Fi is an important threat to human health". *Environmental Research*, *168*, 445–447. https://doi.org/10.1016/j.envres.2018.10.016
Gallastegi, M., Huss, A., Santa-Marina, L., Aurrekoetxea, J. J., Guxens, M., Birks, L. E., Ibarluzea, J., Guerra, D., Röösli, M., & Jimenez-Zabala, A. (2018). Children's exposure assessment of radiofrequency fields: Comparison between spot and personal measurements. *Environment International*, *118*, 60–69. https://doi.org/10.1016/j.envint.2018.05.028
Guxens, M., Vermeulen, R., Steenkamer, I., Beekhuizen, J., Vrijkotte, T. G. M., Kromhout, H., & Huss, A. (2019). Radiofrequency electromagnetic fields, screen time, and emotional and behavioural problems in 5-year-old children. *International Journal of Hygiene and Environmental Health*, *222*(2), 188–194. https://doi.org/10.1016/j.ijheh.2018.09.006
Hedendahl, L. K., Carlberg, M., Koppel, T., & Hardell, L. (2017). Measurements of radiofrequency radiation with a body-borne exposimeter in Swedish schools with Wi-Fi. *Frontiers in Public Health*, *5*, 279. https://doi.org/10.3389/fpubh.2017.00279
Hosseini, M. A., Hosseini, A., Jarideh, S., Argasi, H., Shekoohi-Shooli, F., Zamani, A., Taeb, S., & Haghani, M. (2019). Evaluating short-term exposure to Wi-Fi signals on students' reaction time, short-term memory and reasoning ability. *Radiation Protection Dosimetry*, *187*(3), 279–285. https://doi.org/10.1093/rpd/ncz162
Huss, A., van Eijsden, M., Guxens, M., Beekhuizen, J., van Strien, R., Kromhout, H., Vrijkotte, T., & Vermeulen, R. (2015). Environmental radiofrequency electromagnetic fields exposure at home, mobile and cordless phone use, and sleep problems in 7-year-old children. *PLoS One*, *10*(10), e0139869. https://doi.org/10.1371/journal.pone.0139869
ICNIRP. (2020). Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). *Health Physics*, *118*, 483–524.
IEEE. (2016). IEEE Standard for Information technology—telecommunications and information exchange between systems Local and metropolitan area networks—specific requirements – Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) Specifications. IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012), pp. 1–3534. https://doi.org/10.1109/IEEESTD.2016.7786995
Jalilian, H., Eeftens, M., Ziaei, M., & Röösli, M. (2019). Public exposure to radiofrequency electromagnetic fields in everyday microenvironments: An updated systematic review for Europe. *Environmental Research*, *176*, 108517. https://doi.org/10.1016/j.envres.2019.05.048
Kacprzyk, A., Stefura, T., Krzysztofik, M., Rok, T., Rokita, E., & Tatoń, G. (2021). The impact of mobile phone use on tinnitus: A systematic review and meta-analysis. *Bioelectromagnetics*, *42*(2), 105–114. https://doi.org/10.1002/bem.22316
Khalid, M., Mee, T., Peyman, A., Addison, D., Calderon, C., Maslanyj, M., & Mann, S. (2011). Exposure to radio frequency electromagnetic fields from wireless computer networks: Duty factors of Wi-Fi devices operating in

schools. *Progress in Biophysics and Molecular Biology*, *107*(3), 412–420. https://doi.org/10.1016/j.pbiomolbio.2011.08.004

Kilkenny, C., Browne, W. J., Cuthill, I. C., Emerson, M., & Altman, D. G. (2010). Improving bioscience research reporting: The ARRIVE guidelines for reporting animal research. *PLoS Biology*, *8*(6), e1000412. https://doi.org/10.1371/journal.pbio.1000412

Kuzniar, A., Laffeber, C., Eppink, B., Bezstarosti, K., Dekkers, D., Woelders, H., Zwamborn, A. P., Demmers, J., Lebbink, J. H., & Kanaar, R. (2017). Semi-quantitative proteomics of mammalian cells upon short-term exposure to non-ionizing electromagnetic fields. *PLoS One*, *12*(2), e0170762. https://doi.org/10.1371/journal.pone.0170762

Laudisi, F., Sambucci, M., Nasta, F., Pinto, R., Lodato, R., Altavista, P., Lovisolo, G. A., Marino, C., & Pioli, C. (2012). Prenatal exposure to radiofrequencies: Effects of WiFi signals on thymocyte development and peripheral T cell compartment in an animal model. *Bioelectromagnetics*, *33*(8), 652–661. https://doi.org/10.1002/bem.21733

Najera, A. (2019). Comments on "Wi-Fi is an important threat to human health". *Environmental Research*, *168*, 514–515. https://doi.org/10.1016/j.envres.2018.07.026

NTP (2015). *OHAT: Risk of Bias Rating Tool for Human and Animal Studies.* US NIEHS NIH: National Toxicology Program, Office of Health Assessment and Translation.

Pall, M. L. (2018). Wi-Fi is an important threat to human health. *Environmental Research*, *164*, 405–416. https://doi.org/10.1016/j.envres.2018.01.035

Papageorgiou, C. C., Hountala, C. D., Maganioti, A. E., Kyprianou, M. A., Rabavilas, A. D., Papadimitriou, G. N., & Capsalis, C. N. (2011). Effects of WI-FI signals on the p300 component of event-related potentials during an auditory hayling task. *Journal of Integrative Neuroscience*, *10*(2), 189–202. https://doi.org/10.1142/S0219635211002695

Percie Du Sert, N., Hurst, V., Ahluwalia, A., Alam, S., Avey, M. T., Baker, M., Browne, W. J., Clark, A., Cuthill, I. C., Dirnagl, U., Emerson, M., Garner, P., Holgate, S. T., Howells, D. W., Karp, N. A., Lazic, S. E., Lidster, K., MacCallum, C. J., Macleod, M., … Wurbel, H. (2020). The arrive guidelines 2.0: Updated guidelines for reporting animal research. *PLoS Biology*, *18*(7), e3000410. https://doi.org/10.1371/journal.pbio.3000410

Peyman, A., Khalid, M., Calderon, C., Addison, D., Mee, T., Maslanyj, M., & Mann, S. (2011). Assessment of exposure to electromagnetic fields from wireless computer networks (wi-fi) in schools; results of laboratory measurements. *Health Physics*, *100*(6), 594–612. https://doi.org/10.1097/HP.0b013e318200e203

Pinto, R., Sambucci, M., Laudisi, F., Nasta, F., Lodato, R., Altavista, P., Lovisolo, G. A., Marino, C., & Pioli, C. (2020). Re to Wi-Fi is an important threat to human health, Environ. Research 164: 405, 2018. *Environmental Research*, *191*, 110138. https://doi.org/10.1016/j.envres.2020.110138

Poulletier de Gannes, F., Haro, E., Hurtier, A., Taxile, M., Athane, A., Ait-Aissa, S., Masuda, H., Percherncier, Y., Ruffié, G., Billaudel, B., Dufour, P., Veyret, B., & Lagroye, I. (2012). Effect of in utero Wi-Fi exposure on the pre- and postnatal development of rats. *Birth Defects Research. Part B, Developmental and Reproductive Toxicology*, *95*(2), 130–136. https://doi.org/10.1002/bdrb.20346

Poulletier de Gannes, F., Billaudel, B., Haro, E., Taxile, M., Le Montagner, L., Hurtier, A., Aissa, S. A., Masuda, H., Percherancier, Y., Ruffie, G., Dufour, P., Veyret, B., & Lagroye, I. (2013). Rat fertility and embryo fetal development: Influence of exposure to the Wi-Fi signal. *Reproductive Toxicology (Elmsford, N.Y.)*, *36*, 1–5. https://doi.org/10.1016/j.reprotox.2012.11.003

Redmayne, M., Smith, E., & Abramson, M. J. (2013). The relationship between adolescents' well-being and their wireless phone use: A cross-sectional study. *Environmental Health*, *12*(1), 90. https://doi.org/10.1186/1476-069X-12-90

Rooney, A. A., Boyles, A. L., Wolfe, M. S., Bucher, J. R., & Thayer, K. A. (2014). Systematic review and evidence integration for literature-based environmental health science assessments. *Environmental Health Perspectives*, *122*(7), 711–718. https://doi.org/10.1289/ehp.1307972

Röösli, M., Frei, P., Mohler, E., & Hug, K. (2010). Systematic review on the health effects of exposure to radiofrequency electromagnetic fields from mobile phone base stations. *Bulletin of the World Health Organization*, *88*(12), 887–896F. https://doi.org/10.2471/BLT.09.071852

Roser, K., Schoeni, A., Struchen, B., Zahner, M., Eeftens, M., Fröhlich, J., & Röösli, M. (2017). Personal radiofrequency electromagnetic field exposure measurements in Swiss adolescents. *Environment International*, *99*, 303–314. https://doi.org/10.1016/j.envint.2016.12.008

Sagar, S., Dongus, S., Schoeni, A., Roser, K., Eeftens, M., Struchen, B., Foerster, M., Meier, N., Adem, S., & Roosli, M. (2018). Radiofrequency electromagnetic field exposure in everyday microenvironments in Europe: A systematic literature review. *Journal of Exposure Science & Environmental Epidemiology*, *28*(2), 147–160. https://doi.org/10.1038/jes.2017.13

Sambucci, M., Laudisi, F., Nasta, F., Pinto, R., Lodato, R., Altavista, P., Lovisolo, G. A., Marino, C., & Pioli, C. (2010). Prenatal exposure to non-ionizing radiation: effects of wifi signals on pregnancy outcome, peripheral B-cell compartment and antibody production. *Radiation Research*, *174*(6), 732–740. https://doi.org/10.1667/RR2255.1

Sambucci, M., Laudisi, F., Nasta, F., Pinto, R., Lodato, R., Lopresto, V., Altavista, P., Marino, C., & Pioli, C. (2011). Early life exposure to 2.45 GHz WiFi-like signals: Effects on development and maturation of the immune system. *Progress in Biophysics and Molecular Biology* , *107*(3), 393–398. https://doi.org/10.1016/j.pbiomolbio.2011.08.012

Schmid, G., Hirtl, R., Bueno-Lopez, A., Dorn, H., Eggert, T., & Danker-Hopfe, H. (2020). Design and dosimetric analysis of an exposure facility for investigating possible effects of 2.45 GHz Wi-Fi signals on human sleep. *Bioelectromagnetics*, *41*(3), 230–240. https://doi.org/10.1002/bem.22256

Schmid, M. R., Loughran, S. P., Regel, S. J., Murbach, M., Bratic Grunauer, A., Rusterholz, T., Bersagliere, A., Kuster, N., & Achermann, P. (2012). Sleep EEG alterations: Effects of different pulse-modulated radio frequency electromagnetic fields. *Journal of Sleep Research*, *21*(1), 50–58. https://doi.org/10.1111/j.1365-2869.2011.00918.x

Schuermann, D., Ziemann, C., Barekati, Z., Capstick, M., Oertel, A., Focke, F., Murbach, M., Kuster, N., Dasenbrock, C., & Schar, P. (2020). Assessment of genotoxicity in human cells exposed to modulated electromagnetic fields of wireless communication devices. *Genes*, *11*(4), 347. https://doi.org/10.3390/genes11040347

Schulz, K. F., Altman, D. G., Moher, D., & Group, C, CONSORT Group (2010). CONSORT 2010 statement: Updated guidelines for reporting parallel group randomized trials. *Annals of Internal Medicine*, *152*(11), 726–732. https://doi.org/10.7326/0003-4819-152-11-201006010-00232

Sienkiewicz, Z., & van Rongen, E. (2019). Can low-level exposure to radiofrequency fields effect cognitive behaviour in laboratory animals? A systematic review of the literature related to spatial learning and place memory. *International Journal of Environmental Research and Public Health*, *16*(9), 1607. https://doi.org/10.3390/ijerph16091607

Simko, M., Remondini, D., Zeni, O., & Scarfi, M. R. (2016). Quality matters: Systematic analysis of endpoints related to "cellular life" in vitro data of radiofrequency electromagnetic field exposure. *International Journal of Environmental Research and Public Health*, *13*(7), 701. https://doi.org/10.3390/ijerph13070701

Taylor, C. F., Field, D., Sansone, S. A., Aerts, J., Apweiler, R., Ashburner, M., Ball, C. A., Binz, P. A., Bogue, M., Booth, T., Brazma, A., Brinkman, R. R., Michael Clark, A., Deutsch, E. W., Fiehn, O., Fostel, J., Ghazal, P., Gibson, F., Gray, T., … Wiemann, S. (2008). Promoting coherent minimum reporting guidelines for biological and biomedical investigations: The MIBBI project. *Nature Biotechnology*, *26*(8), 889–896. https://doi.org/10.1038/nbt.1411

van Moorselaar, I., Slottje, P., Heller, P., van Strien, R., Kromhout, H., Murbach, M., Kuster, N., Vermeulen, R., & Huss, A. (2017). Effects of personalised exposure on self-rated electromagnetic hypersensitivity and sensibility – a double-blind randomised controlled trial. *Environment International*, *99*, 255–262. https://doi.org/10.1016/j.envint.2016.11.031

von Elm, E., Altman, D. G., Egger, M., Pocock, S. J., Gotzsche, P. C., & Vandenbroucke, J. P., for the STROBE initiative (2007). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: Guidelines for reporting observational studies. *Lancet*, *370*(9596), 1453–1457. https://doi.org/10.1016/S0140-6736(07)61602-X

Wallace, J., & Selmaoui, B. (2019). Effect of mobile phone radiofrequency signal on the alpha rhythm of human waking EEG: A review. *Environmental Research*, *175*, 274–286. https://doi.org/10.1016/j.envres.2019.05.016

Wilke, I. (2018). Biological and pathological effects of 2.45 GHz radiation on cells, fertility, brain, and behavior. *Umwelt, Medizin, Gesellschaft*, *31*, 1–32.

Wolters, C., Harzem, J., Witthoft, M., Gerlach, A. L., & Pohl, A. (2021). Somatosensory illusions elicited by sham electromagnetic field exposure: Experimental evidence for a predictive processing account of somatic symptom perception. *Psychosomatic Medicine*, *83*(1), 94–100. https://doi.org/10.1097/PSY.0000000000000884

Zentai, N., Csatho, A., Trunk, A., Fiocchi, S., Parazzini, M., Ravazzani, P., Thuroczy, G., & Hernadi, I. (2015). No effects of acute exposure to Wi-Fi electromagnetic fields on spontaneous eeg activity and psychomotor vigilance in healthy human volunteers. *Radiation Research*, *184*(6), 568–577. https://doi.org/10.1667/RR13896.1