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Review

Radiofrequency electromagnetic field exposure and non-specific symptoms of ill health: A systematic review☆

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Abstract

This article is a systematic review of whether everyday exposure to radiofrequency electromagnetic field (RF-EMF) causes symptoms, and whether some individuals are able to detect low-level RF-EMF (below the ICNIRP [International Commission on Non-Ionizing Radiation Protection] guidelines). Peer-reviewed articles published before August 2007 were identified by means of a systematic literature search. Meta-analytic techniques were used to pool the results from studies investigating the ability to discriminate active from sham RF-EMF exposure. RF-EMF discrimination was investigated in seven studies including a total of 182 self-declared electromagnetic hypersensitive (EHS) individuals and 332 non-EHS individuals. The pooled correct field detection rate was 4.2% better than expected by chance (95% CI: −2.1 to 10.5). There was no evidence that EHS individuals could detect presence or absence of RF-EMF better than other persons. There was little evidence that short-term exposure to a mobile phone or base station causes symptoms based on the results of eight randomized trials investigating 194 EHS and 346 non-EHS individuals in a laboratory. Some of the trials provided evidence for the occurrence of nocebo effects. In population based studies an association between symptoms and exposure to RF-EMF in the everyday environment was repeatedly observed. This review showed that the large majority of individuals who claims to be able to detect low level RF-EMF are not able to do so under double-blind conditions. If such individuals exist, they represent a small minority and have not been identified yet. The available observational studies do not allow differentiating between biophysical from EMF and nocebo effects.

Keywords: Electromagnetic hypersensitivity (EHS); Idiopathic environmental intolerance; Symptoms; Well-being; Radio frequency electromagnetic field (RF-EMF); Mobile phones

1. Introduction

The term electromagnetic hypersensitivity (EHS) relates to subjects attributing symptoms to exposure to electromagnetic fields (EMFs). Typically EHS individuals suffer from a wide range of non-specific symptoms such as neurasthenic or skin symptoms (Röösli et al., 2004; Frick et al., 2006; Eltiti et al., 2007b). Often they attribute the symptoms to one or a few specific EMF sources. In the early nineties complaints related to video display units were common, in particular, in Scandinavia (Hillert et al., 1999). With the introduction of mobile communication technologies complaints related to these sources became more prominent (Röösli et al., 2004; Eltiti et al., 2007b).

In population based surveys, prevalence of EHS was reported to be 1.5% in Sweden (Hillert et al., 2002), 3.2% in California (Levallois et al., 2002), 4% in the UK (Eltiti et al., 2007b), 5% in Switzerland (Schreier et al., 2006), and 8–10% in Germany (Infas, 2006). EHS is self-declared based on own experience. Therefore, it remains unclear whether a causal link between exposure and disease actually exists.

A substantial part (56%) among EHS individuals claim to be able to perceive radio frequency electromagnetic field

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(RF-EMF) in their daily life immediately or within a few minutes after exposure (Röösli et al., 2004). Thus, within the phenomenon of EHS, Leitgeb and Schröttner (2003) have proposed to differentiate between electromagnetic sensibility and sensitivity. Electromagnetic sensibility describes the ability to perceive low levels of EMF, whereas sensitivity refers to the development of health symptoms caused by environmental EMF exposure. In principle, these two phenomena can be considered independently, because development of symptoms does not necessarily require perception of exposure. However, afflicted individuals must have made experiences where they were convinced that EMF exposure had impaired their health in order to consider themselves as hypersensitive.

The ability to perceive low levels of EMF was repeatedly investigated by so-called provocation studies. In such a study, participants are repeatedly exposed to an active field or sham condition in a blind manner and have to detect the correct field status (presence or absence of field). Randomized trials in a laboratory as well as epidemiological studies were accomplished to investigate a potential association between symptoms and RF-EMF exposure (sensitivity).

The aim of this review is to clarify the following issues:

1. Are there individuals who are able to perceive RF-EMF at levels common for the everyday environment?
2. Does everyday RF-EMF exposure cause symptoms?
3. Are EHS individuals more susceptible to RF-EMF exposure than the general population?

2. Methods

2.1. Inclusion and exclusion criteria

A comprehensive literature research was performed to identify all relevant peer-reviewed papers published before August 2007. The primary outcome of the study had to be either the ability to perceive low level RF-EMF or any non-specific symptoms of ill health (e.g. headache, sleep disturbance, fatigue, dizziness, and concentration difficulties). Symptoms could be either asked for in an open way (e.g. did you feel anything abnormal?) or a list of symptoms could be given to rate the severity of the symptoms. The exposure of interest had to be in the RF-EMF range (300 kHz–3 GHz) and below the guidelines from International Commission on Non-Ionizing Radiation protection (ICNIRP). English or German articles were considered. Experimental studies had to be single- or double-blinded and to compare at least one sham and one active exposure. Epidemiological studies were excluded if exposure assessment as well as outcome assessment was limited to self-reported data.

2.2. Search strategy

Articles were searched for in the National Library of Medicine (PubMed) and the online database of the Institute for Scientific Information (ISI). A wide range of MeSH, free-text key words and their combinations were used including ''non-ionizing radiation'', ''environmental hypersensitivity'', ''electromagnetic hypersensitivity'', ''mobile phones'', ''base stations'', ''symptom'', ''headache'', etc. A first selection was based on the abstracts. The completeness of the literature search was checked with reference lists of review articles and with topic specific online databases ELMAR (www.elmar.unibas.ch/) and EMF portal (http://www.emf-portal.de/).

2.3. Data extraction

From all experimental studies I extracted the following information: study design, type of participants (EHS vs. non-EHS), number of participants, number of exposure conditions, duration of exposure, EMF sources, EMF intensity, type of blinding, randomization, and adequacy of data analysis. Additionally, I retrieved from provocation studies the number of observed correct and incorrect rating of presence and absence of field, and whether participants had to rate the field after each exposure condition, or whether they had to choose the active field from two or more exposure conditions. From experimental trials investigating symptoms, I additionally extracted the type of symptoms, direction of the observed association and the corresponding p-value. If p-values were not given, I calculated them from standard errors, t-, or z-values, if reported.

From the epidemiological studies I extracted the study design, number of participants, participation rate, type and intensity of exposure, exposure assessment method, duration of exposure, type of symptoms, statistical method, considered confounding factors, and the p-value of the statistical model.

2.4. Data analysis

I performed a meta-analysis of the data from the provocation studies investigating the ability to perceive low level RF-EMR. Based on the experimental setting I determined the underlying data distribution. A binomial data distribution refers to an experiment where participants had to determine the active exposure condition from two or more provocations after the end of the experiment. A Poisson distribution was assumed if participants had to rate the presence or absence of the field after each provocation. In this case the responses of the study participants are not forced to reflect a priori probabilities. If the underlying data distribution was binomial, the number of correct ratings by chance (expected hits) was obtained by multiplying the number of trials with the probability of a chance hit. Otherwise the number of correct ratings expected by chance was calculated based on the expected marginal distribution of a two by two table showing all four combinations of real and perceived exposure status. For each study the difference between observed (O) and expected (E) correct answers was calculated and normalized by the number of expected correct answers by chance ($(O-E)/E$). Exact 95% confidence intervals were calculated based on binomial or Poisson data distribution, respectively. I assessed heterogeneity across the provocation studies by means of Cochran's Q statistic and I calculated the I^2 statistic, to describe the percentage of total variation across studies that is due to heterogeneity rather than chance. In the absence of between-study heterogeneity ($p = 0.90$; $I^2 = 0.0\%$), I used fixed-effects meta-analysis to combine the relative differences between observed and expected correct ratings from different studies. Meta-regression was performed to evaluate whether correct RF-EMF detection was associated with the study collective (EHS vs. non-sensitive study participants), exposure source (mobile phone vs. base station), or exposure duration. For the meta-analysis I used the Stata procedures ''metareg'' and ''metan'' (STATA 9.2, StataCorp, College Station, TX, USA).

I abstained from a formal meta-analysis of the experimental trials on symptoms and the epidemiological studies, because the variety of methods used to measure the outcomes resulted in heterogeneous outcome scales.

3. Results

3.1. Detection of RF-EMF

Table 1 gives an overview of provocation studies in connection with RF-EMF exposure. All but one study

(Heinrich et al., 2007) were double blind and performed in a laboratory. In the field trial (Heinrich et al., 2007), a newly installed mobile phone base station on an office building was randomly turned on and off over a period of 70 working days. This study was omitted from the meta-analysis because blinding cannot be guaranteed in this everyday environmental setting. Some of the provocation studies were done with healthy volunteers while others selected study participants who declared to be EHS or to be able to perceive low level EMF. In most of these studies the study subjects were exposed to a maximum of three conditions, occasionally (Radon and Maschke, 1998; Wolf et al., 2006) the number of provocations was larger. Typically, provocation lasted between 30 and 45 min. Eltiti et al. (2007a) applied 5 min (5′) as well as 50 min (50′) provocations. In all but two studies exposure setting was chosen as to mimic a phone call with a GSM 900 mobile phone. Eltiti et al. (2007a) and Regel et al. (2006) applied an UMTS base-station like exposure resulting in a more homogenously distributed exposure over the whole body with considerably lower exposure of the head compared to the other studies. Note that different methods were applied to rate field status (presence or absence of field). In some of the studies participants had to rate the field status after each provocation. Other studies did an overall rating at the end of the experiment where the study participants had to declare which provocation was active from two or more provocations. In total 182 EHS individuals and 332 non-sensitive subjects were included in seven provocation studies. In some of the studies a few study participants did not rate the field status at all and thus were omitted from the calculation of the expected number correct answers (two EHS and 33 non-EHS individuals). In none of the studies there was evidence that the field rating was better than that expected based on chance. The pooled relative difference between observed and expected correct choices of all seven provocation studies was 0.042 (95%-CI: −0.021 to 0.105) (see Fig. 1). The correct field detection rate was slightly higher for studies with EHS study participants compared to the ones with non-EHS participants. However, according to a meta-regression neither type of study participant (EHS vs. non-sensitive) nor exposure source (mobile phone vs. base station) or exposure duration was associated with better performance in rating the correct field status (Table 2).

A slightly different issue is the question whether a small minority exists among the study participants who are indeed able to perceive low level RF-EMF. In order to identify individuals with this ability, one needs multiple provocations with the same subject to exclude chance rating with a high probability. One double-blind trial and one field study applied more than three provocations per individual. In the double-blind trial (Radon and Maschke, 1998) participants had to identify 12 times the active exposure out of three provocations ($p = 0.33$). None of study participants was successful more than seven times. Seven or more correct choices out of 12 can be expected with a likelihood of 6.7%. In the field study participants determined the operation status of a mobile phone station up to 70 times (Heinrich et al., 2007). The most successful participant achieved 69% correct answers in 42 ratings. Given the assumption that this person was unaware of the operation status, the likelihood to achieve such or a better performance by chance is 0.01. To observe one study participant out of 95 with such a success rate is compatible with chance (Bonferroni corrected significance threshold: 0.005).

EHS individuals were found to have a considerably higher false alarm rate during the sham condition compared to the general population sample in a number of studies (Frick et al., 2005; Regel et al., 2006; Eltiti et al., 2007a) but not in all (Rubin et al., 2006).

3.2. Symptoms

Two different study types have investigated a potential relation between exposure to RF-EMF and non-specific symptoms: randomized trials in laboratory settings or population based studies in the everyday environment.

An overview of the randomized trials carry out in a laboratory is given in Table 3. In total 194 EHS and 346 non-EHS individuals were included in eight trials. All but one study (Fritzer et al., 2007) used a cross-over design comparing symptoms during or after sham condition with symptoms during or after real exposure. Five studies were double blind, two studies single-blind (Koivisto et al., 2001; Wilen et al., 2006) and one study reported that subjects were "blind" to the RF conditions (Fritzer et al., 2007). Exposure duration was between 30 and 60 min except the study from Fritzer et al. (2007), where study participants were exposed during night. Most often a mobile phone GSM 900 exposure was applied, sometimes also the exposure of other mobile phones (GSM1800 or analogue NMT) or a mobile phone base station (see Table 3).

The overwhelming number of studies did not find an association between symptoms and RF-EMF exposure. In one study (Eltiti et al., 2007a) EHS individuals had an increased arousal score as well as borderline significant increased tension and anxiety scores when exposed to an UMTS base station compared to sham.

Some of the experimental laboratory studies addressed the occurrence of nocebo effects. The nocebo effect is the inverse of the placebo effect and means that adverse symptoms occur due to expectations (e.g. due to concerns). Rubin et al. (2006) reported that some study participants experienced severe reactions during sham condition. A significant increase in the symptom score was observed when EHS individuals were informed that they were exposed (Eltiti et al., 2007a) but not in control persons. Regel et al. (2006) observed a significant correlation between symptom score and perceived field intensity in both EHS and non-EHS individuals even though perceived fields were not associated with exposure levels. Likewise a strong correlation between symptom score and perceived

Table 1
Overview of provocation studies investigating detection of RF-EMF exposure

Reference	Collective	Exposure	Exposure duration	Intensity	Number of correct discriminations/expected
Radon and Maschke (1998)	11 EHS	Mobile phone: GSM 900	12 trials, each consisting of three 2-min exposures (one active and two inactive)	Incident field: 0.24 W/m	53/44
Loughran et al. (2005)	50 healthy volunteers	Mobile phone: GSM 900	2 × 30 min provocations	SAR10(max) = 0.29 W/kg	27/22
Rubin et al. (2006)	(a) 65 EHS (b) 60 non-EHS	Mobile phone: GSM 900	3 × 50 min provocations (sham, a non-pulsing carrier wave signal, GSM 900)	SAR = 1.4 W/kg	(a) 110/106 (b) 96/99.3
Regel et al. (2006)	(a) 33 EHS (b) 84 non-EHS	Base station: UMTS	3 × 45 min provocations (0, 1, 10 V/m)	SAR10(max) = 0.15 mW/kg SAR10(max) = 15 mW/kg	(a) 17/15 (b) 22/24.5
Wolf et al. (2006)	18 healthy volunteers	GSM 900 antenna	3 × 15 repeated cycles each with 20 s exposure (2 s on/2 s off alternating)	SAR10(max) = 1.2 W/kg SAR10(max) = 12 W/kg	29/26
Oftedal et al. (2007)	17 EHS	Mobile phone: GSM 900	Up to four pairs of 30 min exposures (active/inactive)	SAR10(max) = 0.8 W/kg	52/48.5
Heinrich et al. (2007)	95 non-EHS	Base station: UMTS	During 70 days, base station was randomly turned on and off	Mean = 0.1 V/m	2079/2013
Eltiti (2007a)	(a) 56 EHS (b) 44 EHS (c) 120 controls (d) 114 controls	Base station: GSM and UMTS	(a + c) 3 × 5 min provocation (b + d) 3 × 50 min provocation (Sham, UMTS, GSM)	10 mW/m^2	(a) 92/93.3 (b) 79/73.3 (c) 185/181 (d) 171/167.6

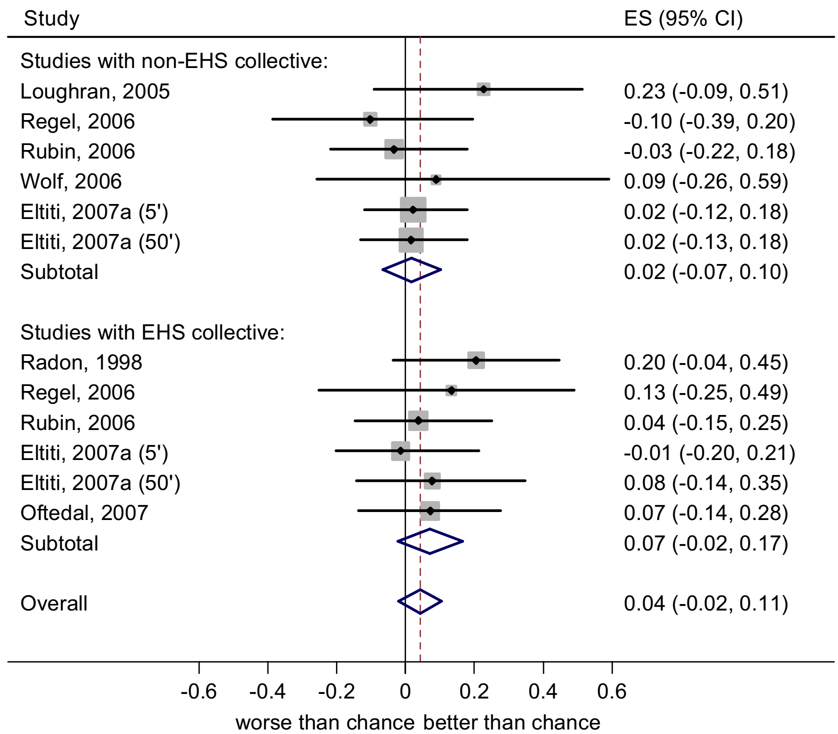

Fig. 1. Graphical representation of the results from the provocation studies. Effect size (ES) refers to the relative difference between observed and expected correct answers. The solid horizontal line represents the 95% confidence interval of each study and the size of the square is proportional to the weight of the individual study in the pooled estimate. The solid vertical line marks the expected correct answer rate based on chance. The scattered line represents the pooled estimate from all studies. The edges of the diamonds show the 95% confidence intervals of the pooled estimates (subtotal, overall).

Table 2
Meta-regression: effects of the collective (EHS vs. non-EHS), the kind of exposure (mobile phone vs. base station) and exposure duration on the correct detection rate

	Coefficient	95% Confidence interval
EHS collective	0.050	−0.078 to 0.178
Mobile phone exposure	0.067	−0.068 to 0.202
exposure duration (h)	0.010	−0.193 to 0.213

operating status was observed in the field trial of the UMTS base station ($p<0.0001$) (Heinrich et al., 2007). Evidence for nocebo effects came also from another study where 42 individuals complaining about headaches when using a mobile phone were invited to participate in the study (Oftedal et al., 2007). All of these participants were exposed in an open-blind test where they were told when they were exposed. During the open-blind provocation 24 individuals reported to develop headache and were considered eligible for a double-blind experiment. In these 17 individuals, who agreed to participate in the double-blind experiment, no association between exposure and headache was observed.

I identified four population-based studies, which investigated associations between symptoms and RF-EMF outside of the laboratory in the everyday environment (Table 4).

In the vicinity of a short-wave transmitter in Schwarzenburg (Switzerland), two cross-sectional and two panel studies were carried out between 1992 and 1998 to investigate the association between sleep disturbances and magnetic field exposure (Abelin et al., 2005; Altpeter et al., 2006). In both cross-sectional surveys about 400 adults living in differently exposed areas were asked about somatic and psycho-vegetative symptoms including sleep disturbances as well as possible confounding factors. Exposure was estimated based on 2621 measurements of magnetic field strength taken in 56 locations. In the panel studies, sleep quality and melatonin excretion was studied when the transmission was interrupted during three days in 1993 or definitively shut down in 1998, respectively. In both surveys, the prevalence of difficulties falling and remaining asleep increased with increasing short-wave frequency magnetic field exposure. In both panel studies sleep quality improved after interruption of the exposure. A chronic change of melatonin excretion following short-wave magnetic field exposure could not be shown; however, an acute increase of melatonin excretion by 26% (95% CI: 8–47%) was observed in poor sleepers after shutting down the transmitter, which may be compatible with a rebound effect.

An Austrian cross-sectional survey has focussed on subjective symptoms, sleep quality, and cognitive performance of people living in urban and rural areas for more than one year in proximity to one of 10 selected base

Table 3
Overview of randomized trials on symptoms and RF-EMF exposure in a laboratory

Reference	Collective	Exposure	Exposure duration	Intensity	Direction of the association	
					More symptoms during exposure (*p*-value)	More symptoms during sham (*p*-value)
Koivisto et al. (2001)	48 healthy volunteers	Mobile phone: GSM 900	2 × 60 min provocations	Phone's power output: 0.25 W	Headache (0.78) Dizziness (0.55)	Fatigue (<1.00) Itching/tingling of skin (0.07) Redness on skin (<1.00) Sensations of warmth (<1.00)
Koivisto et al. (2001)	48 healthy volunteers	Mobile phone: GSM 900	2 × 30 min provocations	Phone's power output: 0.25 W	Dizziness (0.58) Fatigue (0.83)	Headache (<1.00) Itching/tingling of skin (0.75) Redness on skin (0.13) Sensations of warmth (0.30)
Hietanen et al. (2002)	20 EHS	Mobile phones: analogue NMT GSM 900 GSM1800	3 to 4 × 30 min provocation	Average power output: 1 W (NMT) 0.25 W (GSM 900) 0.125 (GSM1800)		"Abnormal feelings" (no *p*-value given)
Rubin et al. (2006)	60 EHS +60 non-EHS	Mobile phone: GSM 900	3 × 50 min provocations (sham, a non-pulsing carrier wave signal, GSM 900)	SAR = 1.4 W/kg	Fatigue (0.42) Dizziness (0.46) Skin symptoms (0.37) Burning (0.62) Eye pain (0.69)	Headache (0.48) Nausea (0.55)
Regel et al. (2006)	33 EHS	Base station: UMTS	3 × 45 min provocations (0, 1, 10 V/m)	SAR10(max) = 0.15 mW/kg SAR10(max) = 15 mW/kg		Symptoms scores: (i) short questionnaire on current disposition (0.88) and (ii) Bulpitt score (0.84)
Regel et al. (2006)	84 non-EHS	Base station: UMTS	3 × 45 min provocations (0, 1, 10 V/m)	SAR10(max) = 0.15 mW/kg SAR10(max) = 15 mW/kg		Symptoms scores: (i) short questionnaire on current disposition (0.93) and (ii) Bulpitt Score (0.78)
Wilen et al. (2006)	20 EHS (+20 non-EHS)[a]	Mobile phone: GSM 900	2 × 30 min provocations	SAR10(max) = 0.8 W/kg	Symptoms, discomfort (0.39)	
Oftedal et al. (2007)	17 EHS	Mobile phone: GSM 900	Up to four pairs of 30 min exposures (active/inactive)	SAR10(max) = 0.8 W/kg		Headache (0.30) Pain/discomfort (0.22) Other symptoms (0.19)
Fritzer et al. (2007)	20 healthy volunteers	Specific antenna: GSM900	One sham night and six consecutive exposure nights	SAR(max) = 1 W/kg	Pittsburgh sleep quality index (0.21)	Zerrsen score (0.99)
Eltiti et al. (2007a)	44 EHS	Base station: GSM and UMTS	3 × 50 min provocation (sham, UMTS, GSM)	10 mW/m^2	GSM: anxiety (0.06); tension (0.09); arousal (0.03); inverse of relaxation (0.46); total number of symptoms (0.49); symptom score (0.81) UMTS:	

Table 3 (*continued*)

Reference	Collective	Exposure	Exposure duration	Intensity	Direction of the association	
					More symptoms during exposure (*p*-value)	More symptoms during sham (*p*-value)
					anxiety (0.005); tension (0.004); arousal (0.001)*; inverse of relaxation (0.03); total number of symptoms (0.10); symptom score (0.12)	
Eltiti et al. (2007a)	114 non-EHS	Base station: GSM and UMTS	3 × 50 min provocation (sham, UMTS, GSM)	10 mW/m^2		GSM: anxiety (0.53); tension (0.47); arousal (0.83); inverse of relaxation (0.25); total number of symptoms (0.96); symptom score (0.49) UMTS: anxiety (0.04); tension (0.11); arousal (0.46); inverse of relaxation (0.04); total number of symptoms (0.41); symptom score (0.87)

Note that some of the studies performed multiple experiments or analysed data from EHS and non-EHS collectives separately.
[a]None of the non-EHS study participants reported any symptoms during the exposure. Reported *p*-values refer to the EHS study participants and were calculated based on McNemar statistics.
*Statistical significant after Bonferroni correction for multiple comparisons ($p<0.0025$) (Eltiti et al., 2007a).

stations (Hutter et al., 2006). Total 365 individuals were randomly selected from the telephone directory or by random walk. They filled out a symptom questionnaire. Exposure assessment was based on a spot measurement in the sleeping room taken a few days after completion of the questionnaires. Measurements yielded field values in the high frequency range from 0.01 to 0.75 V/m; 70% of the exposure was estimated to be from mobile phone base stations. From a total of 14 different symptoms, three were found to be associated with exposure (headache, cold hands or feet, and difficulties to concentrate). After taking into account concerns about base stations sleep quality measures were not related to exposure.

A cross-sectional survey of three villages in Cyprus focussed on non-specific symptoms, birth abnormalities and mortality in relation to RF-EMF exposure (Preece et al., 2007). Two villages were close to a short-wave military antenna and one village was further away. Average exposure levels in the villages were obtained from measurements and were 0.57 V/m in the highly exposed village (thereof 0.11 V/m from the military antenna), 0.46 V/m in the medium exposed village (0.04 V/m from military antenna) and below 0.01 V/m in the village with the least exposure. Several symptoms as well as the SF-36 score were related to RF-EMF exposure. There was no evidence of a link between birth abnormalities and RF-EMF exposure. Numbers of cancer cases were too small to show differences.

In the field trial (Heinrich et al., 2007), a newly installed UMTS mobile phone base station on an office building was randomly turned on and off over a period of 70 working days. The software of the base station was programmed in such a way that the operating state could not be retrieved from the own UMTS mobile phone. The 95 individuals working in the building on which the mobile phone base station was mounted filled in a symptom questionnaire every morning and evening using an online questionnaire. There was a slight tendency of an increase of self-reported complaints on days when the mobile phone base station was operating; however, this was not statistically significant ($p = 0.08$).

4. Discussion

Surveys showed that a substantial part of EHS individuals believes to be able to perceive low level RF-EMF under everyday conditions immediately. However, the meta-analysis of the provocation studies provides strong evidence that this is not the case for the large majority under double-blind conditions in a laboratory. One cannot completely rule out that the observed slight, non-significant tendency of better field rating than expected by chance was due to a small minority who was indeed able

Table 4
Overview of population based studies on RF-EMF in the everyday environment

Reference	Study design	Collective	Exposure frequency	Exposure assessment	Exposure values	Statistical significant associations (*p*-value)	Insignificant associations (*p*-value)
Abelin et al. (2005)	Cross-sectional in 1992	404 residents of three differently exposed areas around short-wave transmitter (participation rate: 60%)	6–22 MHz	Based on distance and measurements of the magnetic field	Low: median = 1 mA/m Medium: median = 21 mA/m High: median = 28 mA/m (during 2 h per day)	Difficulties in falling asleep (<0.001); difficulties in maintaining sleep (<0.001); general weakness and tiredness (<0.001); nervousness and restlessness (<0.001); limb and joint pain (0.003)	Neck and shoulder pain (0.18); back pain (0.57)
Abelin et al. (2005)	Longitudinal study in 1993	65 residents of a short-wave transmitter (participation rate: 64%)	6–22 MHz	During a 10-day study period, transmission was stopped on the 4th to 6th day.	During the transmission stop exposure was negligible	Decrease of awakening after transmission stopped (0.02)	
Abelin et al. (2005)	Cross-sectional survey in 1996	399 residents of four differently exposed areas around the short-wave transmitter (participation rate: 77%)	6–22 MHz	Based on distance and measurements	Low: median = 1 mA/m Low: <10 mA/m Medium: median = 21 mA/m High: median = 28 mA/m	Difficulties in falling asleep (0.006); difficulties in maintaining sleep (0.001); nervousness and restlessness (0.024)	General weakness and tiredness (0.14); limb pain (0.27); joint pain (0.67)
Altpeter et al. (2006)	Longitudinal study in 1998	54 residents of a short-wave transmitter	6–22 MHz	Exposure source turned off	Before shut down (24 h average): Low: median = 0.4 mA/m High: median = 2.1 mA/m After shut down: exposure negligible	Self-rated sleep quality (0.02)	

Hutter et al. (2006)	Cross-sectional	365 random sample residents of mobile phone base station (participation rate: 60%)	900 MHz band	Measurements of the electric field	Low: $<0.1\,mW/m^2$ Medium: $0.1–0.5\,mW/m^2$ High: $>0.5\,mW/m^2$	Headache (0.02); cold hands or feet (0.02); difficulties to concentrate (0.04)	Vertigo (0.31); palpitations (0.44); tremor (0.06); hot flushes (0.74); sweating (0.46); loss of appetite (0.07); exhaustion (0.10); tiredness (0.26); feeling strained (0.45); urge for sleep (0.63); Pittsburgh Sleep Quality Index (0.28)
Preece et al. (2007)	Cross-sectional	1870 inhabitants from three differently exposed villages around a military antenna system (participation rate: 87%)	7–30 MHz and other sources "mainly cell phones")	Distance and measurements of the electric field strengths	Low: $<0.01\,V/m$ Medium: average $=0.46\,V/m$ High: average $=0.57\,V/m$	Migraine (<0.001); headache (<0.001); dizziness (<0.001); depression (0.002), SF-36-scores (0.001)	Birth abnormalities (n.s.)
Heinrich et al. (2007)	Longitu-dinal study	95 workers of a building with a mobile phone base station on the top (participation rate: 35%)	UMTS mobile phone base station	Base station randomly turned on/off during 70 days	Mean $=0.1\,V/m$ Max $=0.53\,V/m$		21 different non-specific symptoms such as headache, concentration difficulties, etc. (0.08)

to perceive low level RF-EMF. However, based on the limited data available such individuals have not been identified yet.

One may argue that perception of low-level EMF is not health relevant, in particular, if only a very small minority of the population is affected at maximum. Nevertheless, there are at least two reasons to investigate this outcome. First, if the phenomenon of field detection did exist, it would be indicative of a biological mechanism, which is not known so far. Second, it seems that this perceived ability to recognize EMF under everyday conditions is an important component for the self-diagnosis of many afflicted individuals. Thus, it is conceivable that demonstrating afflicted individuals their failure to perceive low-level RF-EMF could be a helpful therapeutic option. This has not been investigated so far. I suggest that provocation studies in such a therapeutic context may combine double-blind provocation sessions with open-blind sessions to demonstrate the face validity of the experiment to the study participants. Otherwise study participants will not trust in the experiment and search for other explanations for their failure. Typical explanations from the study participants when confronted with their failure include: exposure duration was too short, the laboratory environment was unfamiliar, they felt too distressed, or the wrong exposure signal was applied (Rubin et al., 2005).

Only one of eight randomized trials in the laboratory reported an association between acute symptoms and RF-EMF exposure. According to the authors, the observed increased arousal score during UMTS exposure is due to imbalanced order of exposure (Eltiti et al., 2007a). Sensitive individuals received UMTS exposure first in 45.5% of the cases instead of 33.3%. However, stratified analyses by sessions suggest that order of exposure is unlikely to explain the full observed difference between UMTS and sham (Röösli and Huss, 2008). An association between symptoms and UMTS base station like exposure was published in a previous report (Zwamborn et al., 2003), but contradicts the result from another study (Regel et al., 2006).

In contrast to the trials, most observational studies reported an association between symptoms and RF-EMF exposure, although these studies are widely diverse in their design and exposure sources. Various reasons may explain this striking difference compared to the trials. One reason could be the exposure duration. In randomized trials maximum exposure duration was 1 h, whereas observational studies also capture longer-term effects. Another reason could be the lack of power in the randomized trials. The number of subjects was smaller than in the observational studies. The lack of comparable outcome measures prevented me from carry out a formal meta-analysis of the randomized laboratory trials, which would have more power to detect an effect if present. However, if lack of power were an issue, one would expect to observe a non-significant increase of symptoms during exposure in the majority of the laboratory trials, which was not the case (Table 3). In addition, several studies were sensitive enough to observe nocebo effects. This allows the conclusion that for short term exposure nocebo phenomena are more important than potential biophysical effects.

One major challenge in observational research is long term RF-EMF exposure assessment. In our everyday environment, many different sources are emitting EMF, differing widely with respect to frequency and modulation. So far, laboratory research could not identify the most relevant exposure characteristics for health. Therefore, it is not known how to combine high, periodic local exposure from sources close to body (e.g. mobile phone) with lower, continuous whole body exposure from environmental fields (e.g. mobile phone base station). In two observational studies RF-EMF was determined based on spot measurements in the bed room (Hutter et al., 2006), or in the office (Heinrich et al., 2007). The measured values were low (<0.75 V/m) with the main contribution originating from mobile phone base stations. At present, it is unknown how representative such spot measurements for the total 24-h personal RF-EMF exposure are. This should be tested in validation studies.

Long term exposure assessment is less a problem in broadcast transmitter studies because of the pronounced gradients occurring in large areas in the surroundings of such transmitters (Altpeter et al., 2006; Preece et al., 2007). However, under such circumstances blinding of the participants with respect to their exposure status cannot be achieved, because electromagnetic incompatibilities can occur. Awareness of the exposure status may cause a selective symptom reporting (information bias) or a development of symptoms due to concerns (nocebo). Thus, these observational studies do not allow differentiating between biophysical and other effects, as acknowledged by the authors of these studies. In order to do so, particular sophisticated study designs are needed. A potential approach could be based on the fact that in our everyday environment with a lot of RF-EMF sources, correlation between actual exposure and self-estimated exposure is poor (Neubauer et al., 2007). This allows comparing truly exposed and unexposed individuals, by taking into account whether they perceive themselves as being exposed or not.

Selection bias is also of concern, particularly for cross-sectional studies. The participation rate in the reviewed studies lied between 60% and 87%. This is quite high, although, still allows potential for selection bias.

In summary, the research so far shows that the large majority of EHS individuals who claims to be able to perceive low-level radiofrequency EMF are not able to do so under double-blind conditions in a laboratory. Furthermore, there is no evidence that short-term low-level exposure causes non-specific symptoms in EHS or other individuals. It seems that these two issues are important components for the self-diagnosis of many EHS individuals. One could possibly make use of this obvious misconception in dealing with EHS individuals. However, this has first to be evaluated. Currently, one cannot completely rule out that a small minority exists who can indeed perceive low-level EMF. However, such individuals have not been identified yet. It is unknown how such individuals would be characterized if they existed. A meta-regression of previous studies does not suggest that self-declared EHS is a useful predictor. Regarding potential long-term effects of low-level radiofrequency exposure on symptoms there is little information provided by available studies. A sophisticated study design is needed to bridge this research gap.

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