



Case report

An idiographic approach to Idiopathic Environmental Intolerance attributed to Electromagnetic Fields (IEI-EMF) Part II. Ecological momentary assessment of three individuals with severe IEI-EMF

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ABSTRACT

IEI-EMF refers to a self-reported sensitivity characterized by attribution of non-specific physical symptoms to exposure to weak EMFs. The majority of empirical results do not support the existence of a causal relationship between EMF and IEI-EMF. However, this conclusion was drawn from environmental and experimental studies that are not without methodological limitations. In the current study, as part of a complex biopsychosocial approach, an ecological momentary assessment (EMA) protocol was applied for the investigation of the temporal relationship between actual radio frequency (RF) EMF exposure and IEI-EMF, at the individual level. Continuous measurement of autonomic variables by holter electrocardiogram (ECG) monitors and the ambient RF EMF by personal dosimeters, as well as repeated (8/day) paper-and-pencil assessments of momentary internal states (symptoms, mood, perceived EMF intensity) and situational factors was conducted for 21 days with the participation of three individuals with severe IEI-EMF. Temporal relationships were examined by time series analyses. For two participants, the results did not support the association between the suspected EMF frequency range(s) and symptom reports. Nevertheless, the results revealed a reverse association with respect to another frequency range (GSM900 downlink), which contradicts the IEI-EMF condition. Autonomic activation related findings were inconsistent. For the third participant, the claimed association was partly supported, both for symptom reports and autonomic reactions (UMTS downlink, total RF; RMS values). The findings of this study suggest that IEI-EMF does not have a unitary aetiology. For certain individuals, a biophysical background cannot be excluded, whereas no such underlying factor appears to be at work for others. EMA is a useful method for the investigation of the aetiology of IEI-EMF.

1. Introduction

1.1. Idiopathic environmental intolerance attributed to electromagnetic fields

Electromagnetic hypersensitivity (aka Idiopathic Environmental Intolerance attributed to Electromagnetic Fields, IEI-EMF) is characterised by non-specific symptoms ascribed to weak non-ionizing EMFs by the impacted individuals (WHO, 2005). Aetiology of IEI-EMF, however, was explained differently by different authors and models. There are theories assuming the prominence of biophysical effects in the development and

maintenance of the condition (Belpomme et al., 2018; Redmayne and Reddel, 2021; Stein and Udasin, 2020), whereas the primary role of psychological (top-down) factors, such as expectations, attributions, is emphasized by others (Dieudonné, 2016, 2019, 2020; Dömötör et al., 2016; Szemerszky et al., 2010; Van den Bergh et al., 2017; Witthöft and Rubin, 2013). Actually, the vast majority of empirical results of environmental and experimental studies do not support a relationship between exposure to EMF and the pathogenesis of IEI-EMF (Baliatsas et al., 2012; Köteles et al., 2013; Levallois, 2002; Röösli, 2008; Röösli et al., 2010; Rubin et al., 2005, 2010, 2011; Seitz et al., 2005; Szemerszky et al., 2015; van Moorselaar et al., 2017; Verrender et al., 2018).

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1.2. Methodological approaches to IEI-EMF

The aforementioned studies, however, received criticism from a methodological point of view (Dieudonné, 2020; Frei et al., 2010; Ledent et al., 2020; Schmiedchen et al., 2019). In the lack of biomarkers specific to IEI-EMF (Belpomme et al., 2015; Rubin et al., 2011), EMF provocation test is the only accepted paradigm for experimentally testing patients' self-diagnosis. As experimental manipulation and randomization take place, this method is theoretically able to shed light on causal relationships between exposure and symptoms (Rubin et al., 2010). However, the ecological (external) validity of the paradigm is limited, as the artificial experimental conditions, lack of real-life exposure situations, potentially inadequate provocation frequency and/or inappropriate duration of the active trials may obscure existing causal relationships between symptoms and exposure to EMF (Dieudonné, 2020; Rubin et al., 2010; Verrender et al., 2018). The latter parameters should be determined individually in EMF provocation pretests, after taking into consideration (1) the frequency range claimed to evoke the symptoms, (2) the latency of the occurrence of the symptoms, and (3) possible wash-out periods necessary to avoid carry-over effects (Hocking, 1998; Röösli et al., 2004; Schmiedchen et al., 2019). Even if those participants are included who attribute their complaints to the applied provocation frequency, there remains the problem that attributions and subjective observations are often unreliable and biased. For example, in the study of Zeleke et al. (2021) the perception of personal RF-EMF exposure was not associated with objectively measured RF-EMF exposure levels. Thus participants' attributions and claims should not exclusively be used for the determination of the experimental parameters. Still, the majority of provocation studies used standard exposure and provocation sessions in which conditions might have been inappropriate to elicit symptoms for many participants (Ledent et al., 2020; Verrender et al., 2018).

Research frameworks that emphasize real-world, real-time data capture (Stone et al., 2007) represent a promising alternative to enhance ecological validity, as participants are assessed in their natural environments rather than in a laboratory setting. These research paradigms are typically referred to as ecological momentary assessment (EMA) (Stone and Shiffman, 1994) as variables of interest are measured repeatedly over time in the context of typical daily routines. Multiple measurements over a longer period of time increase the reliability of data compared to the comparatively brief laboratory experiments. EMA methodology is theoretically able to capture IEI-EMF participants' perceived EMF exposure and the related symptoms at the moment of their occurrence or shortly thereafter. This reduces retrospective recall bias, and enables the researchers to explore the effect of various contextual and situational factors on symptom reports (Wenze and Miller, 2010). Also, it makes possible the simultaneous exploration of a considerably broader EMF spectrum and complex, real life patterns of exposure than the conventional laboratory provocation tests, as well as the examination of temporal relationships (including latencies) between assessed variables. In addition, personal dosimetry makes the exact measurement of actual exposure possible, whereas the majority of environmental studies only estimate it (Bolte et al., 2019; Frei et al., 2010). Although the potential value of EMA in IEI-EMF-related research has been realized (Bogers et al., 2013), this approach has been used in only two studies to date (Bogers et al., 2018; Bolte et al., 2019).

1.3. Goals of the current study

As mentioned, aetiology of IEI-EMF was explained from two directions; certain models emphasize biophysical effects (i.e. originated from the effects of external EMF exposure on biological functions) in the background (Belpomme et al., 2018; Redmayne and Reddel, 2021; Stein and Udasin, 2020), whereas others highlight the possible psychological mechanisms (Dieudonné, 2016, 2019, 2020; Dömötör et al., 2016; Szemerszky et al., 2010; Van den Bergh et al., 2017; Witthöft and Rubin, 2013). However, these two options are not mutually exclusive. For

example, different mechanisms may play the dominant role for different individuals, which warrants the use of an idiographic approach (Bolte et al., 2019). It is also possible that both factors contribute to the condition in an additive manner or in interaction. As the phenomenon at hand appears to be quite complicated, its scientific investigation should also be complex. Therefore, the aim of the current explorative study was to test the feasibility of a multimodal approach to IEI-EMF that involves environmental, clinical, psychosocial evaluation, and the analysis of the relationship between physiology, symptoms and ambient EMF exposure in real-time, real-life conditions, at the individual level (see Table 1).

The current paper (Part II) focuses on the biophysical approach, i.e., the assessment of the associations of EMF exposure with symptoms and physiological changes, and only briefly outlines and discuss the results of the environmental, clinical and psychosocial evaluation (which are reported in detail in Part I of this study). Here, the primary aim was to apply an EMA protocol to the exploration of the temporal relationship between actual EMF exposure and symptoms attributed to it. In contrast to previous EMA studies on the field of IEI-EMF (Bogers et al., 2018; Bolte et al., 2019), we conducted continuous measurement of physiological changes characterising autonomic nervous function, as well as more frequent (8 times daily) repeated assessments of the momentary subjective states (somatic symptoms attributed to EMF, mood, perceived exposure) and potentially confounding situational factors (physical location, activity, social setting) beyond personal dosimetry. Duration of measurements was 21 days for three participants with severe self-reported IEI-EMF. Acquired data was analysed with time series analyses separately for each participants.

2. Materials and methods

2.1. Participants

The three individuals with self-diagnosed IEI-EMF voluntarily applied for participation in the present study. Inclusion criteria were (1) self-diagnosed IEI-EMF, (2) regular occurrence of symptoms in the proximity of the suspected EMF source(s), and (3) a considerable impact of the condition on everyday functioning. The only exclusion criterion was the diagnosis of recent psychotic disorder, which was evaluated by two independent clinical psychologists (for further details, see Part I of the study). Participants received a detailed written feedback on their results, but not financial compensation for their participation. The study was performed in accordance with the guidelines of the Declaration of Helsinki 4. Participants received detailed information about the purpose of the measurements and signed an informed consent form. All procedures performed in the study were approved by the Research Ethics Board of the Faculty of Education and Psychology, Eötvös Loránd University, Hungary.

Table 1. Overview of the multimodal assessment.

Modality	Assessed factors
Environmental evaluation	• physical characteristics of the living and working environment (self-reported) • self-reported and measured EMF exposure at the typical habitations of participants (see Part II) • ecological momentary assessment (see Part II)
Psychosocial evaluation	• psychiatric state: psychiatric anamnesis (self-reported), clinical interview, MMPI • life events, life conditions, social environment (self-reported) • trait and health anxiety, somatic symptom distress, somatosensory amplification, symptom attribution style, modern health worries (self-report questionnaires) • subjective sleep quality (self-report questionnaire)
Medical evaluation	• medical anamnesis (self-reported)

Note. MMPI = Minnesota Multiphasic Personality Inventory.

2.2. Procedure

As a first step before entering the study, severity of IEI-EMF, EMF source(s) assumed to evoke the symptoms, EMF-related complaints, and average latency of the appearance and the duration of symptoms were assessed with a brief questionnaire. The latter ones were open questions, while severity of IEI-EMF was evaluated based on three further questions about (1) self-diagnosed IEI-EMF (*IEI-EMF*: 0 = no, 1 = yes), (2) frequency of EMF-related symptoms (*Symptoms*: 0 = never, 1 = it happened once, 2 = rarely, 3 = often, 4 = every time), and (3) impact of the condition on everyday functioning (*Impact*: 0 = no impact at all, 1 = some impact, 2 = medium impact, 3 = high impact) (Szemerszky et al., 2019).

Upon entry to the study, as a second step, psychiatric, psychosocial, environmental and medical assessments were conducted (for the details, see Part I and Table 1). Finally, as a third step, the participants took part in a 21-day EMA. Data collection took place from September 2013 to May 2015.

2.3. Ecological momentary assessment

For 21 days, participants carried a measurement kit consisting of a portable personal dosimeter for measuring RF EMF bands, a small mobile holter ECG monitor and a paper-based “diary” (a series of short questions). The conductors of the study met with the participants every three days in their home or in the laboratory for downloading the data and charging the devices.

Dosimeters. Participant #1 and #2 wore a Maschek ESM-140 dosimeter (Maschek Elektronik, Bad Wörishofen, Germany), and Participant #3 wore a Satimo EME SPY 121 dosimeter (Satimo©, Microwave Vision S.A.). The dosimeters did not display information on actual exposure. It was worn at hip level in a belt pack during the day, and was placed on a bedside table during sleep. Participants were required to record periods when they did not wear the dosimeter.

The frequency ranges measured by both dosimeters were up- and down-link frequencies for mobile phone cellular networks: GSM900 (Global System for Mobile Communications, 880–915 MHz and 925–960 MHz), GSM1800 (1710–1785 MHz and 1805–1880 MHz) and UMTS (Universal Mobile Telecommunications System, 1920–1980 MHz and 2110–2170 MHz), as well as DECT (Digital Enhanced Cordless Telecommunications, 1880–1900 MHz, used by cordless landline phones and baby phones) and WLAN (Wireless Local Area Network, 2400–2500 MHz, the protocol for wireless internet and for microwave ovens). In addition, the Satimo EME SPY 121 recorded in FM radio (Frequency Modulation, 88–108 MHz), TV3, TV4&5 (174–223 MHz and 470–830 MHz, for analog television broadcasts) and TETRA (Terrestrial Trunked Radio, 380–400 MHz, for emergency services) frequency bands. The aforementioned frequency ranges cover the frequency bands of operating mobile and emerging technology at the time of measurements of the current study.

The dosimeters registered the momentary strength of the electric field 24 h a day (except when taking a bath/shower and during sports activities) for the entire duration of the EMA. One value per 30 s was chosen as sampling frequency to ensure the variability of physiological and EMF data which is necessary to detect potential associations. Effective root mean square (RMS) values were used for characterisation of the exposure.

Physiological measurements. A mobile ECG device (Firstbeat Bodyguard 2, Firstbeat Technologies Ltd, Jyväskylä, Finland) was used to record heart rate (HR), high frequency (HF; 0.04–0.14 Hz) domain of heart rate variability representing parasympathetic (vagal) activation (HRV-HF), and respiratory rate (RR). The ECG device registered the momentary physiological data 24 h a day (except when taking a bath/shower) for the entire duration of the EMA. The sampling frequency was one value per 30 s. Raw physiological data were analyzed and transformed into HR, HF, and RR by use of Firstbeat Sports software (v4.5.0.2).

Paper-and-pencil diary. A diary was used by participants to record somatic symptoms they attributed to EMF exposure (referred to as symptoms or complaints throughout this paper), the assumed intensity of actual EMF exposure, mood, and contextual variables (location, the social environment, and type of activity in which they were engaged in right before the actual assessment). They were prompted for recording via a beeper 8 times a day with 90 ± 30 min between alarms, between 8 AM and 8 PM. The exact times of alarms were arranged in a quasi-random pattern, thus unpredictable to the participants. They were instructed to always record their momentary state to avoid retrospective bias. If the participants were unable to complete the assessment at the moment of the alarm signal for whatever reason, they were asked to make the assessment as soon as possible, and register the time of the event.

Symptoms. Symptoms were assessed using a free symptom reporting paradigm. The major benefit of pre-determined symptom checklists is comparability of data within and between participants. On the other hand, they might be suggestive with respect to symptoms (i.e. lead to more symptom reports) (Ferrari, 2015; Ferrari and Russell, 2010), and certain symptoms that characterize the minority of individuals may not be included (Avery et al., 1967; Barsky et al., 2002; Rosenzweig et al., 1993).

Participants rated the intensity of symptoms on a 4-point scale ranging from *mild* to *very strong*. The momentary *total symptom score* was calculated as the sum of the ratings of symptoms: $\sum_{i=0}^n \text{symptompresence}(0 - 1) \times \text{intensity}(1 - 4)$. The participants had no acute disease or symptoms of premenstrual syndrome during the EMA measurements.

Perceived EMF exposure, mood, activity, location and social context. Believed intensity of EMF exposure (1: *not at all* ... 5: *very strong*) and mood state (−2: *definitely bad mood* ... 0: *neutral* ... 2: *definitely good mood*) were measured on a 5-point scale. Participants marked their activity and their location freely; the responses were later categorized individually by the study's conductors. The response categories for social environment were ‘*alone*’, ‘*among 1–3 people*’, ‘*among a lot of people*’ and ‘*talking on the phone*’.

2.4. Statistical analysis

Time series analyses (Faes and Nollo, 2010; Kettunen et al., 1998; Kettunen and Ravaja, 2000) were performed on the obtained data for each participant separately to evaluate temporal associations of actual exposure to EMF with (1) physiological changes and (2) symptom reports. The association between RF-EMF and physiological variables was examined with different models, for which HR, RR or HRV-HF were used as outcome variables, and the involvement of EMF values of different frequency bands measured during the preceding up to 2 min as predictors (Figure 1). The analysis of association between RF-EMF and symptoms was more complex, as control variables (physiological state, other EMF bands, EMF perception, mood, hour of the day and situational variables) in different combinations were used in each model (Figure 2). The models allowed a delay of 0–20 min at maximum between exposure and the appearance of symptoms. For higher accuracy, only full data sets without missing values were used. Standard R-3.4.0 (<https://www.r-project.org/>) functions and libraries were used for all statistical analyses. The complete detailed description of the statistical analysis is presented in Section 1 of the Supplementary material. The program code is available from the authors upon request.

3. Results

3.1. Characteristics of the participants

Concerning basic (self-)diagnostic questions, (1) all participants diagnosed themselves having IEI-EMF, and (2) they experienced physical complaints “every time” when the suspected EMF source was present and at work (*Symptoms*: 4 out of 4). Furthermore, (3) Participant #1 and #2

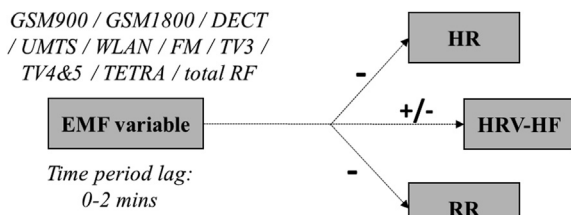


Figure 1. Model versions for testing the association between physiological variables and electromagnetic field strength, and their results. The dependent variable was one of three physiological measures: heart rate (HR), respiration rate (RR), and high frequency domain of heart rate variability (HRV-HF). The predictor variables included the EMF intensities at different frequency ranges: GSM900 up- and downlink, GSM1800 up- and downlink, UMTS up- and downlink, DECT, WLAN, an FM, TV3, TV4&5, TETRA, total RF (the sum of electric fields over the entire bands of RF sources) for only Participant #3. Abbr: + and - = positive and negative significant association between the variables in all model versions; +/- = positive significant associations between the variables in some model versions and negative in others.

reported that their condition influenced their everyday functioning very much (*Impact*: 3 out of 3), whereas Participant #3's rating was "medium impact" (2 out of 3). In summary, all three participants were characterized by severe IEI-EMF. Reported latency time of symptom formation was 0–5 min for Participant #2 and #3, and 0–20 min for Participant #1.

Participant #1 attributed her symptoms to a claimed device in the neighbourhood emitting EM radiation in a non-specified RF frequency range. Symptoms of Participant #2 were attributed exclusively to the radiation of mobile phones. Participant #3 attributed her symptoms to smartphones, laptops, and wireless networks. Further information about the social context and subjective aetiology of the participants' IEI-EMF is presented in Part I of the study.

3.2. Compliance in EMA

Participant #1, #2 and #3 did not complete their diaries in 2.98 %, 19.64 % and 0 % of the cases, respectively. Participant #2 explained her relatively large percentage of missing completions with her difficult life situation (working and looking after her young son alone).

3.3. Reported symptoms during the EMA

Complaints attributed to EMF were predominantly ear-related sensations (mainly tinnitus, Table 2) for all three participants. Beyond this, Participant #2 and #3 also perceived sensations on the area of the head and neck quite frequently, especially pain and tingling, whereas Participant #1 often experienced various sensory perceptions (primarily tingling and burning sensations on the skin). Pain in other parts of the body and neuroathenic symptoms (fatigue, nervousness, etc.) were also mentioned.

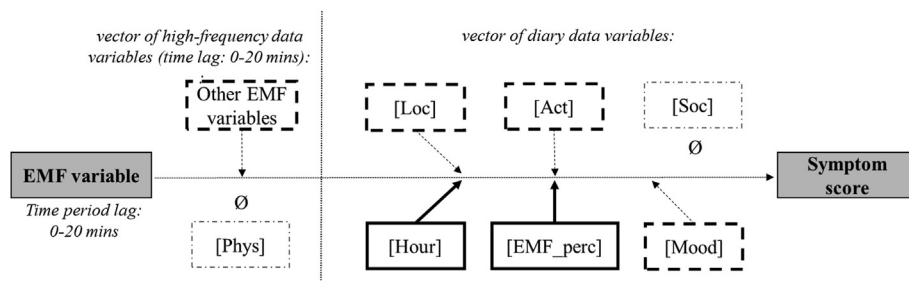


Table 2. Characteristics of participants' symptom reports and their symptom pattern during the 21-day EMA.

	Participant #1	Participant #2	Participant #3
Total number of diary completions	167	139	172
Total number of reported symptoms	157	358	55
Average number of symptoms per completion	0.94	2.58	0.32
Type of symptom	% of total symptoms		
Ears: tinnitus, tingle, whisper, chirp, growl, pain, pressing, smarting in and around the ears, gorged ears	52.2	35.2	37.0
Other sensory symptoms: tingling and burning sensations on the skin, patches in the field of vision, metallic taste, nasal discharge	22.8	2.8	0
Headache, droning in the head and pain in other parts of the head: jaw, teeth, face, throat, temple, forehead, eyes	12.7	37.7	49.7
Pain in other parts of the body: neck, scruff, waist, back, leg, sole, joints	3.2	14.5	0
Neuroathenic symptoms: fatigue, nervousness, dizziness, nausea, loss of equilibrium, speech difficulty, shivering, cold sensation, palpitation, obdormition	8.8	9.8	13.3

3.4. Measurement of everyday ambient EMF exposure

Exposure levels measured by personal dosimeters during the 21 day-long EMA were of the same order of magnitude or lower as measured in other European countries in earlier studies (Gajšek et al., 2015; Joseph et al., 2010; Thuróczy et al., 2008; Tomitsch and Dechant, 2015), and were well below the international exposure limits. 96% or more of the RF EMF values were lower than 0.05 V/m, and only 0.38% or less were higher than 0.5 V/m in all measured frequency ranges for Participant #1 and #2. Values of Participant #3 were higher in downlink ranges. Details about time proportions spent in a range of electric field strength of different frequency bands are presented in Section 3 of the Supplementary material.

3.5. Association between physiological functioning and electric field strength

Partial effects were tested in, altogether, 78 [participant; physiological measure; EMF] triplets, which entails a high compounded probability of committing type I error, i.e., obtaining false non-zero effects. For this reason, and due to the very large sample size ($N \approx 50,000$ for all participants), the accepted level of significance was set at $p < 0.005$. In Table 3 only those long range effects are reported that were statistically

Figure 2. A preliminary step in the EMF - symptom analyses aimed to select an optimal set of control variables. Abbr.: Phys = a one-dimensional indicator of the individual's general physiological state calculated by Firstbeat software; Hour = hour of the day; Act = activity the participants were engaged in right before filling of diary; Loc = their whereabouts; Soc = their social environment; EMF_perc = the perceived intensity of EMF exposure; Mood = self-rated mood. Marked with continual lines = statistically significant effect for all subjects; marked with hatch lines = statistically significant effect in only some cases; marked with faint lines and Ø = no statistically significant effect in any case.

Table 3. The significant ($p < 0.005$) long range partial effects (LRPE) of EMF variables on the participants' heart rate (HR), respiration rate (RR) and the logarithmic high frequency component of participants' heart rate variability (I_HRV-HF).

Participant	EMF variable (logarithmic)	coeff.	std. err.	t stat.	p value	semi-std. LRPE	std. LRPE of 10× increase	physiological variable
#3	I_FM	-1.359	0.409	-3.327	0.001	-0.085	-0.196	HR
#2	I_WLAN	-0.576	0.149	-3.868	<0.001	-0.035	-0.080	HR
#2	I_GSM900u	-0.051	0.017	-2.985	0.003	-0.022	-0.051	RR
#2	I_UMTSu	-0.062	0.020	-3.046	0.002	-0.026	-0.061	RR
#1	I_GSM900u	0.012	0.003	4.214	0.000	0.0047	2.81 %	I_HRV-HF
#2	I_GSM1800u	0.005	0.001	4.618	0.000	0.0029	1.18 %	I_HRV-HF
#1	I_UMTSd	-0.015	0.005	-2.971	0.003	-0.0059	-3.45 %	I_HRV-HF
#3	I_RF_total	0.022	0.007	3.234	0.001	0.0139	5.11 %	I_HRV-HF

Note. FM = 88–108 MHz; GSM900u = Global System for Mobile Communications uplink, 880–915 MHz; GSM1800u = Global System for Mobile Communications uplink, 1710–1785 MHz; UMTSu = Universal Mobile Telecommunications System uplink, 1920–1980 MHz; UMTSd = Universal Mobile Telecommunications System downlink, 2110–2170 MHz; WLAN = Wireless Local Area Network, 2400–2500 MHz; RF_total = the sum of electric fields over the entire bands of RF sources.

significant at this level. In addition to the linear coefficients, we calculated semi-standardized regression coefficients as well as a numerical measure quantifying the long range partial effects (LRPE) of a 10× increase in the intensity of electric field strengths. In the case of HRV-HF, effect sizes were interpreted in terms of percentage change due to the logarithmic form of the dependent variable.

We found statistically significant, although typically very weak LRPEs for 8 out of 78 triplets (see Table 3 and Figure 1). The effects of different EMF frequencies on HR and RR were consistently negative, i.e. higher exposures predicted lower HR and RR. The direction of the effect on HRV-HF was rather inconsistent, across both individuals and frequencies of EM radiation. Effect sizes for HR and RR were very small for Participant #2, in the range of 0.05–0.08 standard deviations for a 10× increase in EM field strengths, but substantially larger for Participant #3. Effect sizes for HRV-HF were very small for all three participants, ranging (in absolute value) between 1.18% and 5.11% for a 10× increase in EMF intensity.

3.6. Association between symptom score and electric field strength

A preliminary step in the analyses was to select an optimal set of control variables. This was necessary due to the limited sample sizes of diary data ($N = 135$ – 168), which would have resulted in overfitted regression models with low degree of freedom if using the full set of controls.

Out of the four extra-person control variables, we found hour of the day [Hour] to have a statistically significant effect for all three participants; ongoing daily activity [Act] was significant for Participant #1 only, whereabouts [Loc] was significant for Participant #3 only, and the social environment [Soc] was non-significant for all participants. Furthermore, the explanatory power of [Hour], [Act], and [Loc] largely overlapped (causing high degrees of multicollinearity), so we chose to include them as controls separately (rather than jointly) in parallel model versions.

Concerning the intra-person control variables, we found that general physiological state [Phys] was statistically non-significant, whereas perceived EM radiation [EMF_perc] was highly significant in the models. Interestingly, self-rated mood [Mood] appeared to be significant in some cases and non-significant in others (depending on the individual as well as on the set of statistical controls). For the sake of consistency, we chose to include [Mood] in all final model versions. In contrast, we estimated the model with and without the inclusion of [EMF_perc]. Besides intending this to serve as a robustness check, we did so to explore whether some part of the total effect of various EMF frequencies on the participants' self-reported health symptoms was mediated by their perception of EMF intensity. Furthermore, to carry out another robustness check, we estimated the partial effect of each EMF frequency with and without the inclusion all other EMF variables as controls. Figure 2 shows the set of control variables for the various model versions.

Section 2 of the Supplementary material presents estimated LRPE coefficients, which may reflect non-zero effects beyond the margin of sampling error. Cases in which the p-value is above 0.05 show statistically significant partial effects, either for the 2-segment model or for at least one of the two short term effects (β_0 and β_1). Similar to the high frequency analyses, we also calculated semi-standardized regression coefficients.

Concerning Participant #1, partial effects were statistically non-significant for all EMF variables with one exception. For [GSM900d], the regression coefficients and the p-values in some of the model versions pointed in the direction of GSM900 downlink EMF possibly having a *negative* partial effect on symptom score, i.e., higher exposure was associated with less symptoms. The estimated LRPE coefficients were fairly close to each other, with and without controlling for other EMF intensities, and they were slightly larger when ongoing daily activity [Act] rather than hour of the day [Hour] was used as an extra-person control. Effect sizes were somewhat reduced after the inclusion of [EMF_perc], which indicates that the association between low symptom scores and GSM900 downlink field strengths was partially mediated by the believed intensity of EM radiation. A path analysis confirmed that this mediation resulted from (1) a small negative effect of [GSM900d] on [EMF_perc] (semi-standardized LRPE = -0.120) and (2) a substantial positive effect of [EMF_perc] on [Sympt] (standardized coefficient = 0.559) (Figure 3A).

The overall picture for Participant #2 was similar to that of Participant #1. Partial effects were statistically non-significant for all EMF variables, with GSM900 downlink frequency band being the only exception. The estimated LRPE coefficients on [GSM900d] were relatively close to each other in all four model versions, i.e. whether or not the participant's perception of EM radiation and all other registered EMF intensities were controlled for (Figure 3B). It is to be noted that effect sizes were far from negligible, in the range of 0.55–0.89 standard deviations for a 10× increase in EMF intensity.

Concerning Participant #3, partial effects were statistically non-significant for all EMF variables with one exception. For [UMTSd] only, the regression coefficients and the p-values pointed in the direction of the UMTS downlink frequency EMF having a substantial *positive* effect on the symptom score, i.e., high exposure predicted more symptom reports. The estimated LRPE coefficients on [UMTSd] were fairly close to each other whether or not [EMF_perc] was controlled for, and irrespective of whether we used the participant's whereabouts [Loc] or hour of the day [Hour] as extra-person control variables. In contrast, effect sizes (calculated for a 10× increase in EMF intensity) were of very different magnitudes depending on the set of EMF controls: in the range of 2.26–2.78 standard deviations with, and 0.47 to 0.68 without the inclusion of all other registered EMF variables in the model. We interpreted this as a case of strong multicollinearity, clearly reflected in a substantial increase (by a factor of 3.3–3.7) in standard error. As a consequence, the inflated estimates should be considered exceedingly noisy and thus unreliable. It is to be noted, however, that the smaller (and more plausible)

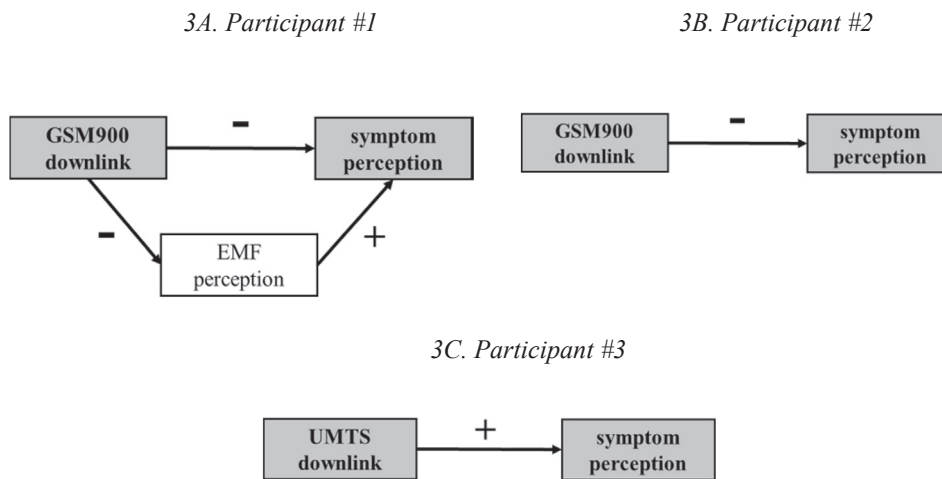


Figure 3. A - C. Summary of the results from low frequency time series analyses of EMA data. In the parallel model versions, other EMF variables, hour of the day [Hour], activity the participants were engaged in right before filling of diary [Act], whereabouts [Loc], believed EMF intensity [EMF_perc] and self-rated mood [Mood] were included in different combinations, according to the results of preliminary analysis (see the detailed description in the text). Abbr: + = positive significant association between the variables; - = negative significant association between the variables.

effect sizes obtained for the model without additional EMF controls were not practically trivial, either.

4. Discussion

In this paper, we report the findings of an EMA study, which assesses the biophysical aspects (i.e. the psychophysiological effects of ambient EMF exposure) of a novel multimodal approach to IEI-EMF. (Further findings of the multimodal study are presented in detail in a separate paper, i.e., Part I of the study). EMA involved continuous measurement of different frequency ranges of ambient RF EMF exposure, physiological changes (heart rate, HF component of heart rate variability, respiration rate), subjective states (somatic symptoms attributed to exposure to EMF, mood, perceived exposure) and situational factors (physical location, activity, social setting) for 21 days. Separate time series analyses were performed for each IEI-EMF participant to explore those EMF frequency ranges that are associated with physiological changes and symptom perception. Overall, only a small number of significant associations were found. Some of these indicated a negative association (contrary to the expectations, higher exposure was associated with less symptoms, lower HR and RR), others were inconsistent across participants and frequency ranges. A weak positive association between EMF exposure and symptoms were found only for one participant; however, even in this case the involved frequency domain differed from the frequency band the participant attributed her symptoms to.

4.1. Feasibility of the applied EMA protocol

The sampling frequency (30 s for EMF and physiological data, and 90 ± 30 min for subjective and situational variables) was high enough for time series analysis of data, and this enabled us to assess the temporal relationships among variables, even allowing a delay between exposure and symptoms. As the latency of the appearance of symptoms reported by our participants was within this range, the assessment was theoretically able to capture the existing associations. Long-term measurements provided data series large enough for complex statistical analysis at the individual level.

Real-time recordings of subjective data, including symptoms, reduced the retrospective bias characterizing the usual assessments. Recording under everyday conditions considerably increased the ecological validity of the findings. Also, autonomic state was recorded beyond self-reports. Actual exposure to EMF over a broad RF range was recorded, including complex, real life exposure patterns, instead of only one suspected provocation frequency. EMA also enabled us to take into account the impact of various external and internal factors on symptom perception, instead of completely excluding them in a laboratory setting.

In comparison with previous IEI-EMF studies using a similar method (Bogers et al., 2018; Bolte et al., 2019), the EMA protocol used in the current study (1) provides additional information on the potential effects of EMF exposure on physiological function, besides self-reports, (2) applied a more frequent assessment of momentary subjective variables and contextual factors, and (3) it also controlled for more potential confounding factors in the statistical analysis (see Table 4). Together with the environmental, medical, and psychosocial evaluation, the applied EMA represents a valuable part of a novel multimodal approach to IEI-EMF (see Part I and Part II of this study together).

However, as experimental manipulation did not take place, the possibility of uncontrolled environmental and/or lifestyle factors as third variables, showed up as a limitation of EMA. For example, visual and other cues can (both consciously and non-consciously) inform individuals about changes of EMF exposure in real life situations. It is also practically impossible to acquire sufficiently high frequency and fully comprehensive data on situational factors and subjective states to achieve more conclusive results. Completing diary in about every 90 min already was fairly demanding on the participants. Therefore, although we have found some evidence for a weak relationship between physiological measures and certain frequency bands of EMF, as well as for a moderate association between EMF and ill health, these are not conclusive concerning causality. Nevertheless, considering the extremely large sample size in the case of relationship between EMF exposure and physiological function, we can make a firm claim about the lack of causal effects when statistical results were negative. Overall, because of the possibility of uncontrolled environmental and/or lifestyle factors as third variables, the design of EMA *per se* is not appropriate to establish causal relationships between EMF exposure and symptom reports. Thus we suggest applying EMA in the future as a useful complementary method beside the experimental provocation tests more than an alternative approach.

4.2. Interpretation of the results from EMA

Although our results from EMA cannot be generalized, but in order to represent the applicability of the EMA protocol, the results of the analyzes are discussed here.

Our analysis showed that EMF exposure in the GSM900 downlink frequency band (925–960 MHz, Base to Mobile) had a negative effect on symptom reports for two of our three participants, whereas UMTS downlink frequency range (2110–2170 MHz, Base to Mobile) had a positive effect on symptom perception for the third participant (Figure 3C), even after controlling for perceived EMF exposure, mood, activity, location, time of the day and other measured EMF frequencies. Nevertheless, no significant association was revealed for the vast majority (23 out of 26) of 'participant – EMF band' pairs.

Table 4. Comparative table of various aspects of IEI-EMF studies using EMA protocol.

	Bogers és mtsai, 2018	Bolte és mtsai, 2019	Current study
IEI-EMF participants (n)	7	36	3
Duration of EMA (days)	21	5	21
Measured EMF exposure	• RF EMF • 12 frequency bands • 3 types of metric: TWA¹, „timeabove”², RCM³	• RF EMF • 12 frequency bands • 3 types of metric: TWA¹, „timeabove”², RCM³	• RF EMF • 8–12 frequency bands • RMS⁴ values for the previous 0–2 min for physiological variables, and 0–20 min for subjective variables
Diary logs	• electronic • 3/day; about every 6 h • retrospectively for the last 6 h	• electronic • every 2–3 h • synchronous	• paper-based • every 90 ± 30 min • synchronous
Assessed physiological variables	-	-	HR ⁵ HRV-HF ⁶ RR ⁷
Assessed subjective (self-report) variables	• non-specific symptoms (personalized symptom list) • perceived intensity of EMF exposure	• non-specific symptoms (list of 9 general and 1 personalized symptom)	• self reported symptoms • perceived intensity of EMF exposure • mood
Assessed contextual variables	• location	#	• location; • activity; • social context; • hour of the day
Statistical analysis	#	time series analysis	time series analysis
time period lag⁸	-	1 and 4 h	• 0–2 min for physiological variables; • 0–20 min for subjective variables
Results			
negative EMF exposure – symptom score association	for 2 of 7 participants	-	for 2 of 3 participants
positive EMF exposure – symptom score association	for 2 of 7 participants	-	for 1 of 3 participants
positive association between perceived EMF exposure and symptom score	for 1 of 7 participants	for 1 of 36 participants	for 1 of 3 participants
association between perceived and actual EMF exposure	no	no	no

Abbr.: ¹TWA = time weight average; ²„timeabove” = the time above a limit if the exposure tends to manifest in peaks; ³RCM = rate of change metric; ⁴RMS = root mean square; ⁵HR = heart rate; ⁶HRV-HF = high frequency domain of heart rate variability; ⁷RR = respiration rate; ⁸time period lag = the lag time in the time series analysis model between the value of outcome variable and EMF value measured during a certain period before.

Surprisingly, higher exposure to GSM900 downlink exposure was associated with less symptoms for two of the three participants. There may be a third variable problem behind the negative association. Participant #1 and #2 lived on the countryside during the measurements, thus they were exposed to remarkably higher EMFs when occasionally travelling to an urban environment. These trips, at the same time, might have distracted their attention from their body, resulting in less perceived symptoms. This issue was not relevant for Participant #3, as she stayed in the capital city for the entire duration of the EMA. The negative association between GSM900 downlink exposure and symptom perception was partially mediated by the perception of intensity of EMF exposure for Participant #1. Perceived EMF exposure was strongly and positively associated with symptom perception, however, it showed a weak negative association with actual field strength. This means that Participant #1 actually tended to report lower perceived EMF exposure when exposed to higher intensities of GSM900 downlink radiation, which in turn reduced her symptom report (Figure 3A).

Nevertheless, the negative association between GSM900 downlink radiation and symptom perception for Participant #2, as well as the positive association between UMTS downlink EMF and complaints for Participant #3 were not mediated by their EMF perception or any other control variable. Thus, these effects might have been genuine effects of the respective EMF exposure (effect sizes were moderate, though nontrivial), or may be explained by statistical error, or uncontrolled confounding factor(s) in the participants' external or internal environment.

Results of previous studies using similar EMA measurements (Bogers et al., 2018; Bolte et al., 2019) are in accordance with our findings

(Table 4). Bogers et al. (2018) found a negative association between EMF exposure and symptom perception for two of seven participants, and positive association for another two participants, while in the study of Bolte et al. (2019) only one out of 36 participants showed a positive EMF-symptom relationship, and there was no association at the level of the entire group. Overall, these findings highlight the existence of individual patterns and the relevance of the use of an idiographic approach to IEI-EMF.

The most frequently reported complaints were remarkably similar for all three participants, but different from symptom patterns typically obtained with the use of symptom checklists in other studies. Whereas the most frequent symptoms described in the literature are neurasthenic and dermatological symptoms (Leitgeb, 2009; Nordin et al., 2014; Tseng et al., 2011; Verrender et al., 2018), complaints reported by our participants were predominantly related to the ears and audition (tinnitus, pain, pressing, smarting in and around the ears), and the area of the head (pain and droning in the head) (Table 2). Auditory sensations do not belong to typical non-specific symptoms, thus they are usually not included in symptom checklists. It is important to note that ear- and audition-related complaints were found to be associated with exposure to RF EMF in the general population in a number of studies (Hutter et al., 2010; Panda et al., 2010; Szykowska et al., 2014). More typical IEI-EMF complaints, such as impaired sleep quality, fatigue, nervousness, dizziness, nausea, pain in several parts of the body were also reported, but less frequently.

Although IEI-EMF is defined as symptoms attributed to EMF source(s), we also aimed at examining the relationship between EMF exposure and autonomic activation proposed by a number of authors

(Andrianome et al., 2017; Lyskov et al., 2001; Redmayne and Reddel, 2021; Sandström et al., 2003). We found evidence for a weak relationship between physiological measures and EM radiation at certain frequencies (8 out of 78 'participant - physiological measure - EMF band' triplets at $\alpha = 0.005\%$). These EMF effects were consistently negative on HR and RR, which means that HR and RR values were lower when the actual exposure to EMF was higher. This direction of physiological changes is not in accordance with hypotheses that assume a sympathetic activation behind IEL-EMF. Concerning the vagal component of heart rate variability (HRV-HF), the direction of significant associations was inconsistent across both individuals and frequencies of EM radiation, which also does not support the sympathetic activation hypothesis. Moreover, the frequency ranges significantly associated with physiological changes (WLAN, GSM900 uplink, GSM1800 uplink, UMTS uplink and downlink in Participant #1 and #2; FM and total RF in Participant #3) were not identical with those associated with the reported symptoms (GSM900 downlink for Participant #1 and #2, and UMTS downlink in Participant #3). Further, physiological state was not a significant predictor of symptom reports in the time series analysis.

In summary, for two of three participants, the findings clearly did not support the claimed association between the suspected frequency range(s) and symptom reports. Nevertheless, the results revealed a reverse association with respect to another frequency range (GSM900 downlink), which contradicts the IEL-EMF condition. Physiological findings were inconsistent and also not in accordance with the autonomic activation hypothesis. Thus, in the lack of supporting findings from this EMA measurement, the condition might be explained by another approach that assumes top-down (psychological) factors, including trait-like characteristics, such as negative affectivity, introspection, paranoid tendencies, and a pre-psychotic state in the background of symptom reports for Participant #1 and #2. This option was supported by the results of the environmental-medical-psychosocial evaluation (see Part I) For the third participant, however, the claimed association cannot be excluded, both for symptom reports and autonomic reactions. However, due to the possibility of third variable problem in EMA, this association would need to be confirmed in an experimental laboratory situation. At the same time, her psychological profile showed no pathology or deviation from the average.

Also, for all three participants, we found such traumatic life event(s) in their life history that coincided with the onset of symptoms attributed to EMF, and which might have caused remarkably high psychological distress at the time of their occurrence. According to their medical evaluation, mistaken attribution of symptoms evoked by other (i.e. non EMF-related) medical problems and by their general poor health status cannot be excluded either (for details see Part I).

4.3. Limitations

As our participants definitely rejected the use of an extra electronic device (i.e. electronic diary), paper-based assessment remained the only option in the current study despite of its well-known limitations (Stone et al., 2002). However, we can suppose their proper compliance, since they voluntarily participated in the study for the feedback on their results (without financial compensation). There may be limitations related to exposure characterization. It is possible that rates of change or peak values of EMF exposure are more relevant for IEL-EMF individuals than RMS values (Bogers et al., 2018; Bolte et al., 2019). A further possible limitation of our results is that no correction was applied to the values below the measurement limit of dosimeters; such a correction is strongly recommended by a number of authors (Röösli, 2008; Najera et al., 2020). Similarly, the possible effect of the body in the measurements was not controlled for. It is important to note, however, that the influence of the body depends on the azimuth angle of arrival, thus it may lead to an over- or underestimation.

It is worth mentioning as a limitation that two types of dosimeters were used in the study: Maschek ESM-140, used for Participant #1 and #2, was replaced with Satimo EME Spy 121 for Participant #3, because

of changes of the EMF environment (i.e. appearance of novel frequency domains). In the future, the EMA method developed in the present study should always use personal exposimeters that are able to monitor all possibly relevant new frequency bands, including 5G technology.

The most important limitation of the present study is the sample size, which is limited by the huge time and resource demand of the multi-modal protocol (environmental, medical, psychiatric, psychosocial evaluations (Part I), and the 21-day EMAs). Thus this explorative study aimed at exemplarity rather than representativity.

5. Conclusion

Primarily, this study demonstrates that EMA can be a useful complementary exploratory method beside the experimental provocation tests for the investigation of the aetiology of IEL-EMF. It would be worthwhile for future studies to use different methods simultaneously; for example, collecting comprehensive data on the association between of EMF and symptoms with EMA, and, if a potential triggering EMF frequency can be identified, confirming the causal EMF - symptom association with provocation tests in a controlled, blinded laboratory setting.

The findings of this study also suggest that IEL-EMF does not have a unitary aetiology. For certain individuals, a biophysical background cannot be excluded, whereas no such underlying factor appears to be at work for others. However, because of the small sample, these findings provides only limited evidence.

Declarations

Author contribution statement

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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