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Individual variation in temporal relationships between exposure to radiofrequency electromagnetic fields and non-specific physical symptoms: A new approach in studying 'electrosensitivity'

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ABSTRACT

Background: Everyday exposure to radiofrequency electromagnetic fields (RF-EMF) emitted from wireless devices such as mobile phones and base stations, radio and television transmitters is ubiquitous. Some people attribute non-specific physical symptoms (NSPS) such as headache and fatigue to exposure to RF-EMF. Most previous laboratory studies or studies that analyzed populations at a group level did not find evidence of an association between RF-EMF exposure and NSPS.
Objectives: We explored the association between exposure to RF-EMF in daily life and the occurrence of NSPS in individual self-declared electrohypersensitive persons using body worn exposimeters and electronic diaries.
Methods: We selected seven individuals who attributed their NSPS to RF-EMF exposure. The level of and variability in personal RF-EMF exposure and NSPS were determined during a three-week period. Data were analyzed using time series analysis in which exposure as measured and recorded in the diary was correlated with NSPS.
Results: We found statistically significant correlations between perceived and actual exposure to wireless internet (WiFi - rate of change and number of peaks above threshold) and base stations for mobile telecommunications (GSM + UMTS downlink, rate of change) and NSPS scores in four of the seven participants. In two persons a higher EMF exposure was associated with higher symptom scores, and in two other persons it was associated with lower scores. Remarkably, we found no significant correlations between NSPS and time-weighted average power density, the most commonly used exposure metric.
Conclusions: RF-EMF exposure was associated either positively or negatively with NSPS in some but not all of the selected self-declared electrohypersensitive persons.

1. Introduction

The term non-specific physical symptoms (NSPS) refers to symptoms such as headache, fatigue and dizziness that cannot be explained by a medical condition (Barsky and Borus, 1999; Henningsen et al., 2011; Korber et al., 2011; Kroenke and Price, 1993). NSPS are sometimes attributed to the exposure to radiofrequency electromagnetic fields (RF-EMF) emitted from wireless devices and mobile telecommunication transmitters, but there is no convincing evidence for an association between exposure to RF-EMF and NSPS in the population

Abbreviations: NSPS, non-specific physical symptoms; RF-EMF, radiofrequency electromagnetic fields; DECT, digital enhanced cordless telecommunications

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(Augner et al., 2012; Baliatsas et al., 2012a; Roosli et al., 2010; Rubin et al., 2011; Rubin et al., 2010). Because the origin of the symptoms is unclear, the WHO introduced the term Idiopathic Environmental Intolerance with attribution to EMF (IEI-EMF) (World Health Organization, 2005). IEI-EMF (also referred to as electro(hyper)sensitivity) remains a poorly defined condition (Baliatsas et al., 2012b) for which an internationally recognized case definition is missing (Baliatsas and Rubin, 2014; Baliatsas et al., 2012b). Estimated prevalence rates range mainly between 3.5% and 8% (Baliatsas et al., 2014; Röösli et al., 2010; Schreier et al., 2006; Schrottner and Leitgeb, 2008; van Dongen et al., 2014), and sometimes over 13% (Meg Tseng et al., 2011; Mohler et al., 2010). In the Netherlands, about one third of general practitioners, occupational physicians and occupational hygienists have ever been consulted by patients who attribute their symptoms to EMF (Slottje et al., 2017). No consistent symptom patterns among individuals reporting IEI-EMF were found, but neurological symptoms seem to be more pronounced (Baliatsas et al., 2014; Hillert et al., 2002). Belpomme et al. (2015) found that people with IEI-EMF showed enhanced blood histamine levels. Psychosomatic processes might be associated with NSPS in IEI-EMF (Johansson et al., 2010; Koteles et al., 2012; Landgrebe et al., 2008; Rubin et al., 2008; Rubin et al., 2010; Witthoft and Rubin, 2013), not necessarily as a cause, but rather as conditioned response from the onset of symptoms, and reinforcing the attribution to EMF (Dieudonne, 2016). The variability of symptoms reactions between and within individuals could explain the lack of a clear association (Tuengler and von Klitzing, 2013). However, the possibility of a causal effect of RF-EMF exposure cannot be completely dismissed yet, because of methodological and conceptual limitations in previous studies (Baliatsas and Rubin, 2014).

Most studies into exposure-response associations, in IEI-EMF were short-term laboratory studies, only suitable to detect symptoms that are elicited by relatively short, acute exposure. Further, it might be possible that only in some individuals an associations exist between NSPS and EMF; statistical analyses at group level would not pick that up. The few studies on IEI-EMF that did examine persons on an individual basis were laboratory studies that repeatedly tested individuals, mainly to check whether they could perceive EMF exposure vs. sham exposure (Rubin et al., 2010). An alternative approach would be to study exposure response relations at an individual level over time, the so called idiographic approach (Barlow and Nock, 2009). Idiographic studies facilitate the detection of clinically relevant differences between individuals without compromising ecological validity, since data are collected in daily life situations. Time series analysis (Brandt and Williams, 2007) can be used to assess causal heterogeneity (Rosmalen et al., 2012), with repeated measures of the variables of interest, aiming to explain variance within single individuals, allowing for the identification of people who develop symptoms following exposure to EMF. This study explored the association between exposure to RF-EMF and NSPS at individual level in self-declared IEI-EMF persons while using an ambulatory design adapted to individual characteristics. The study tested the feasibility of an idiographic approach. Individuals with IEI-EMF were selected using theory-based selection criteria. The level of and variability in personal RF-EMF exposure and NSPS were determined, and time series analysis was used as the primary statistical approach.

2. Materials and methods

2.1. Design and procedure

The study was an ecological momentary assessment study in which, for 21 consecutive days, participants carried a measurement set consisting of an RF-EMF personal exposure meter, also referred to as an exposimeter, a global positioning system (GPS) logger, and an electronic diary. The electronic diary had to be filled out every 6 h by the participants at alarm cues in the morning, afternoon, and evening, and was used to assess NSPS and perceived exposure over the last 6 h.

All study materials (diaries, exposimeters, and instructions) were delivered at the participants' homes. The participants were orally instructed about the study procedures by field workers and signed an informed consent form. During the study period, the participants were visited four times. Handling of personal data complied with the Personal Data Protection Act [in Dutch: Wet bescherming persoonsgegevens (Wbp)].

2.2. Selection of study population

In this exploratory study we selected seven self-declared hypersensitive people attributing their NSPS to a clearly defined source of radiofrequency electromagnetic fields. Further, to detect any possible correlation, both exposure pattern and severity of symptoms should vary over time. Because it proved difficult to find a sufficient number of participants from our databases of previous studies, they had to be recruited in various ways. Firstly, participants from an ongoing study (Bogers et al., 2013) were requested to also participate in the present study. Secondly, invitations to participate were placed on Twitter, Facebook, and the website of the Dutch National Institute for Public Health and the Environment (RIVM). Thirdly, participants were recruited via professional contacts (e.g. via the community health services) and via other participants. Fourthly, announcements were placed in local newspapers. Recruitment continued until seven participants completed the measurement protocol. From all applications, participants were initially selected on the basis of a short questionnaire during a telephone interview. Supplement A shows the questionnaire. Briefly, the questionnaire included questions on attribution of physical symptoms to EMF, EMF sources that caused or worsened the symptoms, variation in presence and intensity of symptoms during the day, time lag between exposure and the occurrence of symptoms, engagement in situations with potentially high EMF exposure, and willingness to minimize use of a mobile phone during the study period. Applicants were selected if they attributed their symptoms to RF EMF exposure, if they were expected to show sufficient variation in both RF EMF exposure and symptoms during the study period, and if they agreed to minimize use of a mobile phone. Applicants with knowledge on their personal EMF exposure, e.g. because of the use of a personal exposure meter or previous EMF measurements at home, were excluded. Although a question on knowledge of exposure was initially not asked at the first telephone interview, it was asked at a subsequent contact moment as it turned out that some participants of the abovementioned ongoing study had already received a personal exposure report. Also persons who were diagnosed with depression, anxiety disorder, burnout, psychosis, chronic fatigue syndrome or fibromyalgia were excluded.

2.3. Personal RF-EMF exposure assessment

Actual EMF exposure was measured using EME-SPY 121 exposimeters (Satimo, Cortaboeuf, France) worn at the hip in a camera bag. The exposimeters measure the RF electric field strength in 12 frequency bands used for communication and broadcasting (see Supplement B).

For each of the exposimeters the laboratory of the Dutch Air Force determined a multiplicative calibration correction factor for all 12 frequency bands. The calibration measurements were performed in an anechoic chamber by measuring the response of the exposimeter to a standard, vertically polarised input signal of 2.5 V/m, with a frequency at the mid of a specific frequency band.

The exposure to EMF over fixed time intervals of 6 h prior to filling out the diaries in the morning, afternoon and evening was characterised in several metrics for central tendency and variability. The metric for central tendency was the time-weighted average (TWA) (FM, downlink base stations for mobile telecommunications, DECT), and for variability

the rate of change metric (Kaune et al., 2001) (downlink base stations for mobile telecommunications, WiFi). The rate of change metric expresses the short term variability and is virtually unaffected by long term systematic trends. The rate of change metric (RCM) is the root-mean-square value of the first derivative in time:

$$RCM = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N-1}(S_{k+1} - S_k)^2}$$

S_k is the k-th sample of the power density in W/m^2, N is the total number of samples in a 6-hour block. Another metric for variability in exposure, especially with irregularly peaked signals or for sudden field changes in high exposure is the number of peaks above 0.1 mW/m^2 (WiFi) or 0.2 mW/m^2 (DECT). Based on the experience from earlier surveys in the Netherlands (Bolte et al., 2008; Bolte and Eikelboom, 2012), these thresholds were arbitrarily chosen at three times the TWA (WiFi and DECT) of that research project, such that they will provide a contrast between periods.

Because some participants indicated to be sensitive to base stations for mobile telecommunications rather than to specific frequency bands, and to reduce the number of exposure variables, the frequency bands for GSM (900 and 1800 MHz) and UMTS (2100 MHz) were summed into one GSM/UMTS band.

More detailed information about the RF exposure assessment is presented in Supplement B.

2.4. GPS logger

Participants wore a GPS device on their left shoulder. The GPS logger geo-located the personal RF EMF measurements. In case of doubts about the validity of EMF measurements or their interpretation, the GPS data was used to check whether the information provided in the diary on their whereabout, indoor/outdoor, travelling or at work in a block of 6 h, was correct.

2.5. Electronic diaries

For diary keeping *LG P-500 Optimus One* smartphones running on Android 2.3 were used. The phone operated in flight mode without a SIM card to preclude any RF EMF emittance. Indeed the exposimeter did not register any signal while it was placed against the diary while it was switched on, yielding that the CPU or GPU of the phone did not produce any signal above the detection threshold of 0.05 V/m. Information about software and operation of the diaries is shown in Supplement B.

2.6. Diary questionnaire

The diary questionnaire consisted of 26 items. In the morning and evening, 5 and 8 additional questions were included, respectively. The items were short, simply worded, and tried to mimic the participants' internal dialogue, e.g. 'I suffer from headache'.

2.6.1. Non-specific physical symptoms

On request by the field workers at the initial home visit, participants indicated one to three of their symptoms that they attributed to a source of RF EMF exposure. These symptoms were subsequently entered in the diary questionnaire software by the field workers. The symptoms were asked in the format 'In the time since the previous alarm cue, I suffered from …'. Response options were in a five-point Likert response format: 'not at all' (1), 'a little'(2), 'somewhat' (3), 'considerably' (4) and 'very much' (5).

2.6.2. Perceived exposure to (sources of) RF EMF

Perceived exposure to RF EMF was addressed with the question 'In the time since the previous alarm cue, I was exposed to radio frequency electromagnetic fields', with response options ranging from 'not at all' to 'very much' on a five-point scale with only the extreme answers labelled. Perceived exposure to specific sources of RF EMF was assessed by asking the participant to indicate which (if any; more than one source could be indicated) of the following sources mainly determined their exposure: mobile phone, DECT phone, WiFi, antennas for mobile telephony, radio or television masts, another source.

2.6.3. Location

In order to interpret the readings of the exposimeter, participants were asked to indicate the type of environment and type of area they were in (see Bolte and Eikelboom, 2012), during the time between alarm cues. The environments included: at home inside, at home outside, at work or educational institution, elsewhere inside, elsewhere outside, and travelling (on foot, by bike, car or public transport); the three types of area included: in the city centre or a shopping area, in a residential or built-up area but not the centre, outside the built-up area (e.g., in a rural area or in nature).

2.7. Background questionnaire

After the measurement period, all participants completed a questionnaire that contained questions about among others their electrosensitivity (including type of symptoms, devices or frequency bands that evoke symptoms, time lag between exposure and symptoms), general health status, and sensitivity to various other environmental factors. This information was used to describe the study population.

2.8. Statistical analysis

For each participant, one to three NSPS that the participants attributed to RF-EMF exposure were selected to be analyzed if the symptom scores varied over the study period; symptoms that were (almost) constant over time were not analyzed. In a similar way, actual and perceived exposures were only analyzed if the levels varied over the study period. For actual exposure, per frequency band metrics were chosen that displayed the most variation over the study period. The reason that not all NSPS, frequency bands and metrics were chosen was to reduce the number of statistical tests and thus reduce the chance of false-positive findings.

Table 1 shows which combinations of NSPS and EMF exposure were investigated. In order to use as much information as possible, the records with missing values in each individual data set were not deleted, but instead the missing values were imputed using the data that was observed, by the method of chained equations (Rubin, 1987; van Buuren, 2012). To account for the uncertainty due to incompleteness of some records, this procedure was repeated multiple times, yielding slightly different imputed data sets per participant, using the statistical software R 3.1.0 (R Core Team, 2015). Following recent recommendations, a number of 20 imputations were performed. All subsequent statistical procedures were performed using SPSS 22. The model for the associations between RF-EMF exposure and NSPS was developed using the first data set out of these 20 imputed data sets. It was assumed that the model selection procedure on one data set only is sufficient, as the procedure is robust to small deviations in the data set. Subsequently, the coefficients of the selected models were estimated on all of the 20 imputed data sets individually. Finally, the results were pooled according to Rubin's combination rules (Rubin, 1987; van Buuren, 2012). A two-tailed α level of 0.05 was used.

Scores of NSPS and perceived RF-EMF exposure, which were measured on a five-point scale, were treated in the analyses as continuous outcomes. To investigate the relationship between (perceived) RF-EMF exposure and NSPS within individuals, autoregressive integrated moving average (ARIMA) models were used (Box and Jenkins, 1976). For each participant, different types of RF-EMF exposure and NSPS were analyzed in separate models, where NSPS were used as an

Table 1
Overview of symptoms and types of exposure selected for statistical analysis.

Participant	Symptom 1	Symptom 2	Symptom 3	Frequency bands of actual exposure		Perceived exposure analyzed	
				Source A	Source B	Source A	Source B
3	Hearing specific sounds			FM	WiFi	No	No
4	Headache	Fatigue		GSM/UMTS (base station)	WiFi	No	No
5	Fatigue	Headache		WiFi	DECT	Yes	Yes
6	Headache	Muscle ache	'Electrically charged'[a]	GSM/UMTS (base station)	WiFi	No	No
8	Lightheadedness	Fatigue		GSM/UMTS (base station)	WiFi	Yes	Yes
9	Headache	Tinnitus		GSM/UMTS (base station)		No	
10	Fatigue	Unsettled feeling		GSM/UMTS (base station)	WiFi	Yes	Yes

[a] Participant described her symptom as a feeling of being electrically charged, but could not be more specific.

outcome, and RF-EMF exposures in the preceding 6 h as a predictor. More details on the ARIMA modelling can be found in Supplement B.

Because location and activities may be related to both RF EMF exposure and symptom scores, a potential association between NSPS and EMF exposure may be confounded by location and activities, in which case the statistical analysis should be adjusted for location and activities. However, since we did not have information on the duration of activities, we could not fully control for them in the statistical analyses. On the other hand, location and activities can also only determine EMF exposure without being a confounder, in which case adjustment would lead to overcorrection. Therefore, adjustments were not made, but to get an indication whether confounding might be present, in the case of significant associations between EMF exposure and NSPS differences in RF exposure and NSPS between periods that did or did not include travelling or being at work or school were tested with the Kruskal-Wallis test.

3. Results

3.1. Recruitment

Fig. 1 shows the recruitment process. Of 44 persons who previously participated in a study on EMF exposure and NSPS, seven persons were selected who fulfilled the inclusion criteria. Three persons who fulfilled the inclusion criteria were recruited via newspaper advertisement or via an acquaintance. This resulted in ten persons who fulfilled the inclusion criteria. The data of two persons had to be excluded due to technical problems with the electronic diaries, and one person could not participate because she got ill shortly before the measurement period.

3.2. Characteristics of study population

The characteristics of the individual participants are shown in Supplement C. Four were female, three male. There was a wide range in the participants' age, educational level, and self-rated health. Headache and fatigue were the symptoms most often attributed to RF-EMF. As EMF sources that triggered their symptoms, the participants mostly mentioned WiFi (six persons) and UMTS and/or GSM base stations (five persons). One person mentioned DECT as a triggering source, and one person FM. Five participants indicated to notice an effect of RF-EMF exposure on their symptoms within 1 h or shorter; one participant mentioned a variable time lag between exposure and symptoms, and one participant said symptoms aggravated with increasing exposure duration. According to the participants their symptoms usually lasted for 1–2 h to the whole day. The participants had been electrosensitive for approximately half a year to > 10 years.

All participants except participant #3 indicated that the study period was usual or very usual for them, i.e. there were no special circumstances that interfered with the study. Participant #3 reported an unusual study period because her housemate was admitted to hospital. The mean (SD) daily call times of mobile and DECT phones (combined, calls made and received) during the study period registered by the participants included in the statistical analyses were 31 (30), 16 (6), 19 (19), 9 (9) and 25 (27) minutes for participants #5, #6, #8, #9 and #10, respectively.

3.3. Compliance

Compliance to the study protocol was generally high. The percentage of diaries that the participants completed ranged from 91% to 95% except for participant #4 who completed 62% of the diary questionnaires. The percentage of valid exposimeter measurements (i.e. worn at the hip or placed close to the head while asleep) ranged between 89 and 97% but was much lower for participant #4.

3.4. EMF exposure and symptom scores

The measured electric field strengths were comparable with the earlier measured ones in the Netherlands (Bolte and Eikelboom, 2012), and never exceeded the ICNIRP levels (ICNIRP, 1998). Generally, the distribution of EMF exposure for the rate of change metric and the number of samples above the predefined thresholds was skewed to the left, meaning a relatively low exposure most of the time with infrequent peak exposures. The distributions of the time weighted average values were closer to a normal distribution. Regarding symptom scores, in general participants reported levels of symptoms that were mostly light to moderate, with fewer occurrences of the extreme scores. Participant #3 was an exception because she reported high symptom scores on almost all occasions.

3.5. Association between RF-EMF exposure and symptoms

For two participants, associations between EMF exposure and symptom scores were not analyzed. Participant #3 did not show any variation in symptom scores during the three measurement weeks (on all occasions except one the maximum symptom score was reported). For participant #4 there were too many missing diary questionnaires (> 25%) to be able to perform a valid statistical analysis. For the other five participants, Supplement C shows the associations between symptom scores and RF-EMF exposure. In participants #5 and #6, increases in WiFi exposure (the number of measurement samples above 0.1 mW/m^2) were associated with decreases in the severity of the experienced headache ($p = 0.032$ and 0.004, respectively). In participant #10, increases in the rate of change metric for WiFi exposure were associated with increases in the feeling of malaise ($p = 0.020$). In participant #8, increases in downlink exposure (rate of change metric, $p < 0.001$; perceived exposure, $p = 0.031$) and in perceived WiFi exposure ($p = 0.036$) were associated with increases in fatigue. In this participant, increases in the same exposure metrics were also associated with increases in lightheadedness ($p = 0.035$, 0.026 and 0.018 for rate of change metric, perceived downlink and perceived WiFi, respectively).

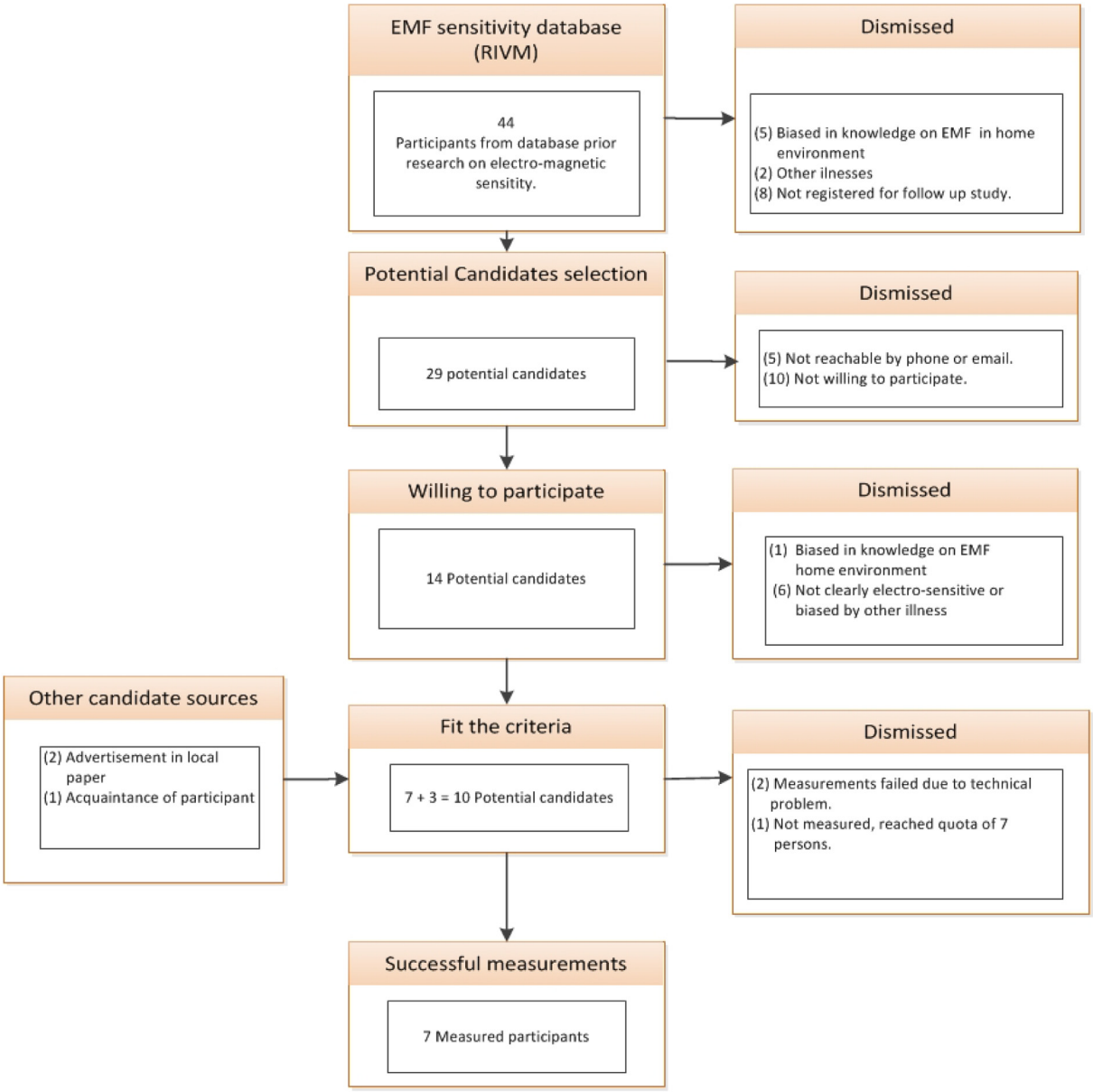

Fig. 1. Flow chart of recruitment process.

Figs. 2–5 show for the abovementioned statistically significant associations per participant, per frequency band, the graphs with the time (x-axis) sequences of the exposure metric (in blue, left y-axis), and the self-rated severity of the NSPS (in green, right y-axis) per block of 6 h.

For participant #5, Fig. 2 shows that the highest, but highly temporally variable, symptom scores were reported during roughly the first half of the measurement period, while WiFi exposure was relatively low. In the second half of the period, symptom scores were more constant, while there was more variation in WiFi exposure. WiFi exposure (the number of measurement samples above 0.1 mW/m^2) was (non-significantly) higher during six-hour periods that included travelling (Kruskal-Wallis test, $p = 0.13$) but the level of headache was not higher during periods that included travelling ($p = 0.32$). Headache scores were significantly higher ($p = 0.01$) during periods that included being at work, but WiFi exposure was not significantly different between these periods ($p = 0.63$).

For participant #6 (see Fig. 3), the highest headache scores were reported during approximately the second week, whereas in that week the number of measurement samples above 0.1 mW/m^2 for WiFi was relatively low. WiFi exposure and reported scores for headache did not differ between periods that did or did not include travelling or being at work (Kruskal-Wallis test, $p > 0.4$ for all four comparisons).

For participant #8 (Fig. 4a–d), in the downlink band the largest peaks for the RCM coincided with the peaks in the fatigue and lightheadedness. Also the peaks in both perceived downlink and perceived WiFi coincided with peaks in fatigue and lightheadedness. Perceived downlink and the RCM of downlink however were not correlated (Spearman's rho = −0.06, $p = 0.65$). The RCM in a six-hour period was higher when the participant had been travelling (Kruskal-Wallis test, $p < 0.001$) or at work ($p = 0.073$) in that period, but there was no difference in symptom scores between periods that did or did not include travelling or being at work ($p > 0.7$ for all comparisons).

For participant #10 (Fig. 5) in the WiFi band some of the largest peaks for RCM concurred with relatively high scores for malaise. The RCM in a six-hour period was significantly higher (Kruskal-Wallis test, $p = 0.011$) when the participant had been travelling in that period. The reported severity of malaise was also (non-significantly) higher during periods in which the participant had travelled ($p = 0.080$).

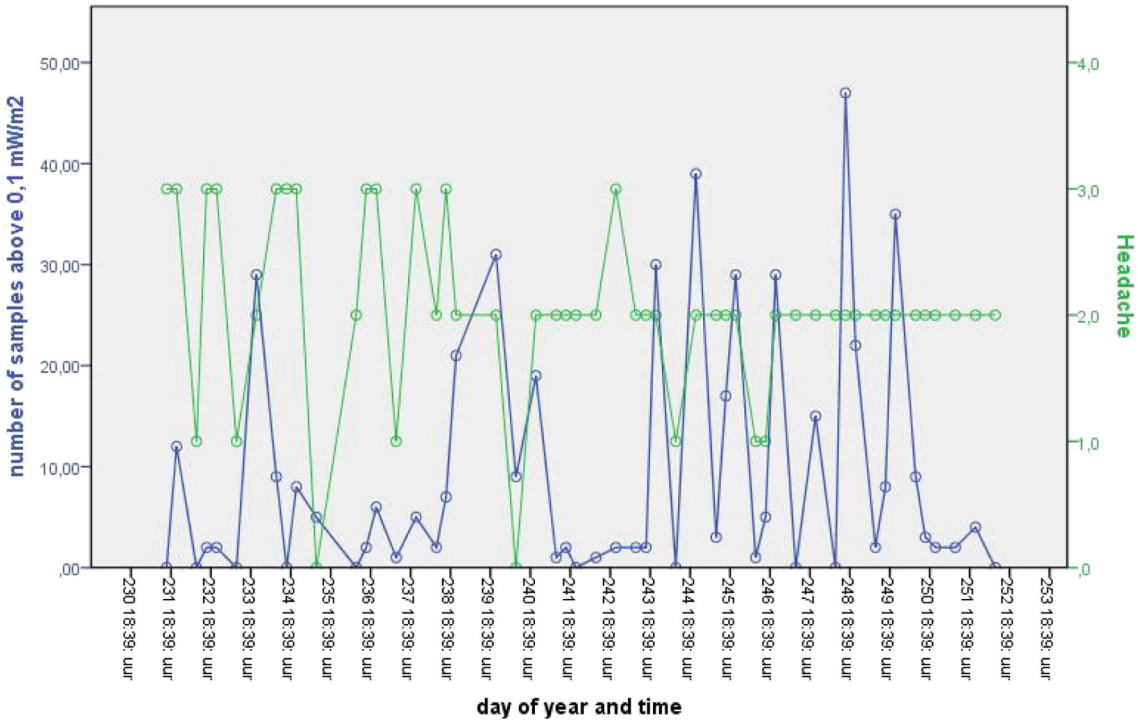

Fig. 2. Self-rated headache score and measured WiFi exposure (number of samples above 0.1 mW/m^2) in participant #5. Response options for headache are 'not at all' (0), 'a little' (1), 'somewhat' (2), 'considerably' (3) and 'very much' (4). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

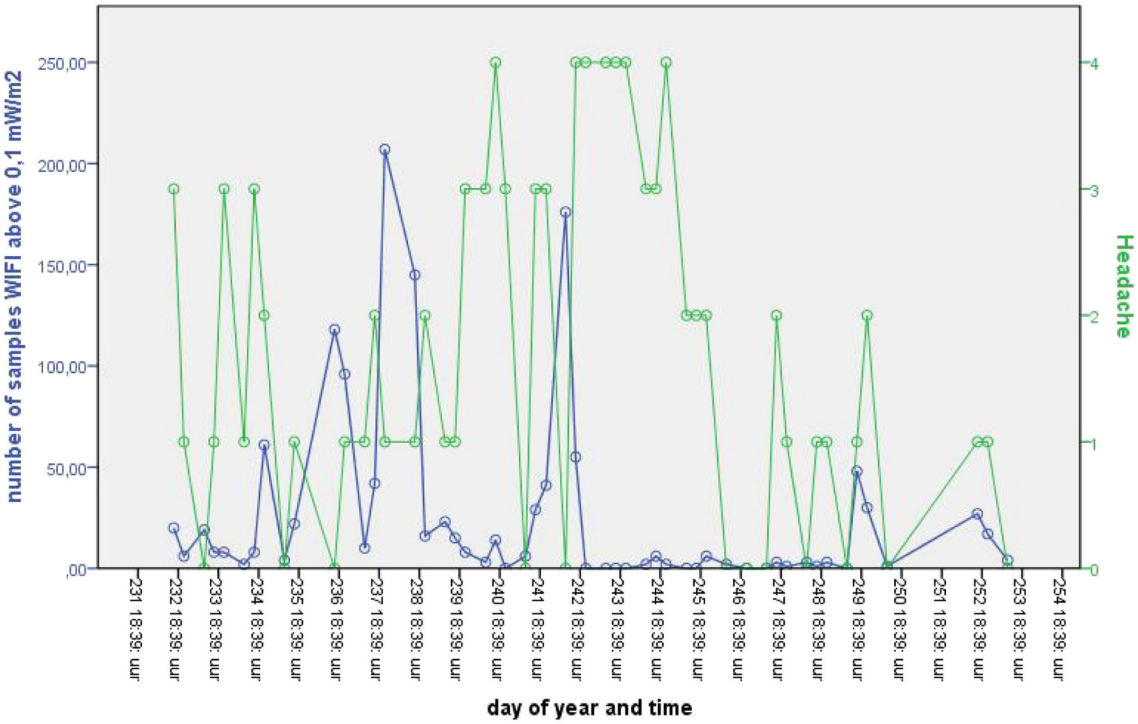

Fig. 3. Self-rated headache score and measured WiFi exposure (number of samples above 0.1 mW/m^2) in participant #6. Response options for headache are 'not at all' (0), 'a little' (1), 'somewhat' (2), 'considerably' (3) and 'very much' (4). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

4. Discussion

4.1. Summary of findings

This study explored the association between (actual and perceived) exposure to RF-EMF and the occurrence of NSPS on an individual level using an ambulatory design adapted to the individuals' characteristics. The study also tested the feasibility of such an idiographic approach. In four of the seven participants, significant weak positive and negative associations were found between NSPS and measured exposure to WiFi

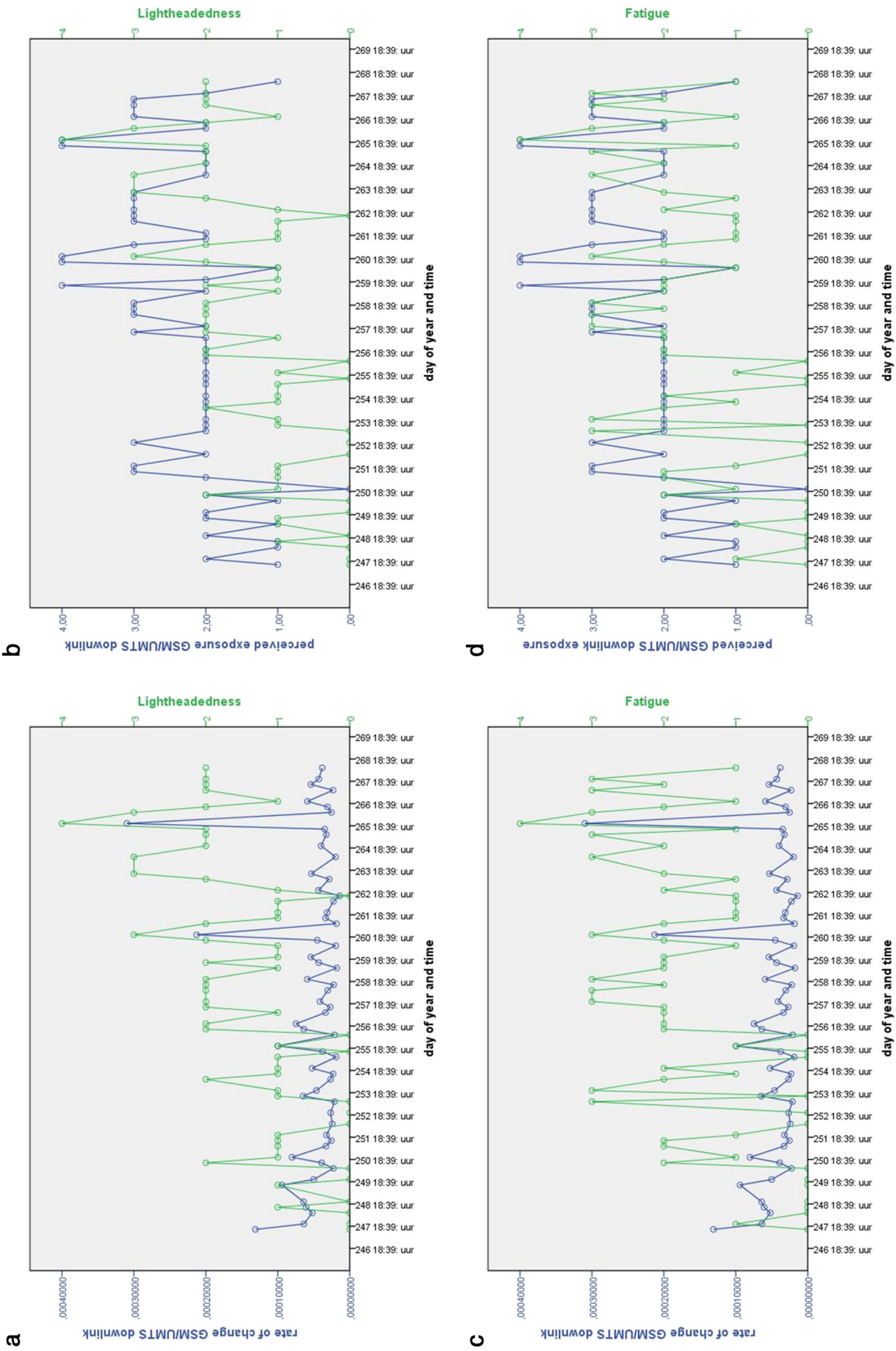

Fig. 4. a. Self-rated score for lightheadedness and measured downlink exposure (rate of change metric) in participant #8. Response options for lightheadedness are 'not at all' (0), 'a little' (1), 'somewhat' (2), 'considerably' (3) and 'very much' (4).
b. Self-rated score for lightheadedness and perceived downlink exposure in participant #8. Response options for lightheadedness are 'not at all' (0), 'a little' (1), 'somewhat' (2), 'considerably' (3) and 'very much' (4). Note that for this participant perceived downlink exposure concurred with perceived WiFi exposure, and thus the exposure–symptom associations was the same for perceived WiFi.
c. Self-rated score for fatigue and measured downlink exposure (rate of change metric) in participant #8. Response options for fatigue are 'not at all' (0), 'a little' (1), 'somewhat' (2), 'considerably' (3) and 'very much' (4).
d. Self-rated score for fatigue and perceived downlink exposure in participant #8. Response options for fatigue are 'not at all' (0), 'a little' (1), 'somewhat' (2), 'considerably' (3) and 'very much' (4). Note that for this participant perceived downlink exposure concurred with perceived WiFi exposure, and thus the exposure–symptom associations was the same for perceived WiFi. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

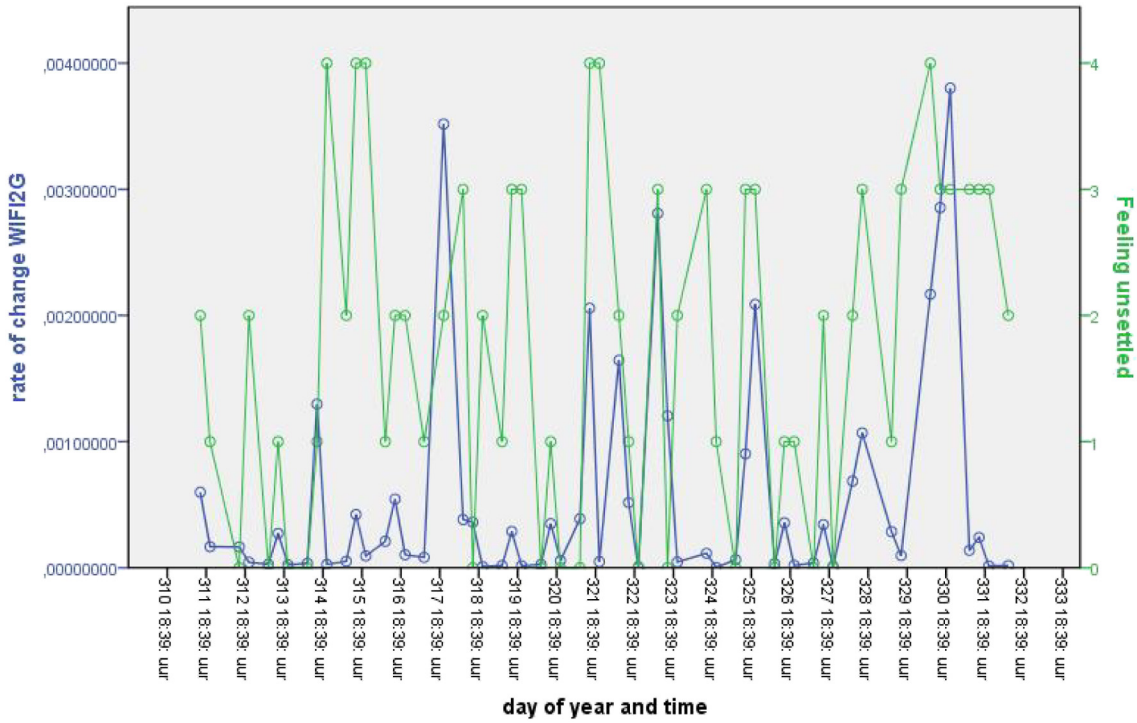

Fig. 5. Self-rated score for feeling unsettled and measured WiFi exposure (rate of change metric) in participant #10. Response options for feeling unsettled are 'not at all' (0), 'a little' (1), 'somewhat' (2), 'considerably' (3) and 'very much' (4). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

or GSM and UMTS downlink. In one participant increases in the perception of being exposed to downlink and WiFi were both related to increased symptom reporting, but perceived and actual exposure were not correlated. Expressing the regression coefficients relative to the within-individual variation in RF-EMF exposure shows that the strengths of the associations were in the order of a 0.4 to 0.9 change in symptom scores (on a five-point scale) for a change of 2 standard deviations in RF-EMF exposure.

4.2. Selection of participants

The selection of the study population was aimed at recruiting individuals who fulfilled criteria for IEI-EMF, i.e. who attributed their symptoms to (in this study RF) EMF, and who showed variation in RF-EMF exposure and symptom occurrence and/or severity during the day, a necessary condition to detect any exposure–outcome relationship. During the study period, six of the seven participants indeed displayed variations in RF-EMF exposure and symptoms. One of the participants (who was excluded from analysis) continuously reported high symptom scores; during the measurements, she told that her headache had initiated after a car crash.

Persons with conditions such as chronic fatigue syndrome were excluded. In these conditions other factors than EMF may trigger or maintain NSPS, which would have further complicated the analysis and interpretation of associations between EMF exposure and NSPS in this exploratory study. However, this may have led to exclusion of some potential persons with IEI-EMF.

4.3. Causality

Interpretation of the observed associations with respect to causality is difficult. Although participants were longitudinally followed, residual confounding may have affected the estimates of the associations. RF-EMF exposure, just as symptom scores, can depend on locations and activities (Bolte and Eikelboom, 2012; Durrenberger et al., 2014; Frei et al., 2009; Joseph et al., 2008; Viel et al., 2009). This may also be the case in our study, and may (partly) explain our findings, including the reverse associations between symptoms and exposure for two participants. Different scenarios are conceivable, for example, being at work may increase fatigue while at the same time exposure to WiFi may be relatively high, or being at home may decrease headache while WiFi exposure may be high. The questions in the diaries referred to the preceding 6 h, and in each block of 6 h often the same activities were undertaken, e.g. in almost each block participants had been at home. Further, because we had to confine to a limited number of questions, we only asked about activities known to be associated with relatively high RF EMF exposure levels. The activities travelling and working are known to cause a contrast in exposure (Bolte and Eikelboom, 2012). This was also reflected in the data. In some instances, symptoms such as fatigue and headache also contrasted between periods that did or did not include travelling and working. However, only in one participant (#10) activities may have confounded the relationship between exposure and symptoms because travelling was both associated with exposure (the RCM of WiFi) and (although not statistically significant) symptoms (malaise). Nevertheless, also other activities such as playing wireless videogames may be confounders, so we expect some residual confounding.

4.4. Methodological issues

4.4.1. Diaries

This study combined the advantages of electronic diary methods and measurement of personal RF-EMF exposure. Because the relatively long measurement period was a burden to the participants, the number of diaries per day was set at three, resulting in 6-hour periods between diaries. So as not to miss any relevant NSPS, participants were asked to report their symptoms over the previous six-hour periods instead of their symptom experience at the moment of filling out the diaries. This retrospective way of asking may have introduced some recall bias although we expect that participants remember most clinically relevant

symptoms over the previous 6 h. However, because six-hour periods were used, it was more difficult to detect co-fluctuations of symptoms and exposure within a shorter period. Because the diaries were filled out at fixed times, participants may (consciously or unconsciously) have anticipated the alarm cues. Random alarm cues as in Bogers et al. (2013) would therefore be preferable but as the statistical analysis required fixed time intervals this was not feasible.

91–95% of the diary questionnaires were completed except by one participant who completed 62% and was therefore excluded from subsequent analyses. Main reasons given for not completing a diary were not hearing the alarm or reacting too late. Reasons mentioned less often were being in a meeting or driving a car. Missing diary entries were statistically imputed and therefore missing values may have led to some attenuation, leading to conservative estimates of the associations.

4.4.2. RF measurements

The sampling time of the exposimeters determines the ability to detect the peaks in exposure and therefore the ability to optimally calculate the exposure metrics. The smaller the sampling interval, the better the metrics can be determined. For instance, it is known that the longer the interval between samples, the more peak exposures are missed, and subsequently the lower the TWA will be, and thus the less exposure contrast between the blocks. But there is a trade-off between the number of exposimeters available and the optimal sampling rate. We chose a sampling interval of 28 s. Firstly, because from an earlier survey (Bolte and Eikelboom, 2012) we know that it will allow at least one measurement during transitions by bike or on foot through the main beam of a downlink signal from a base station. Secondly, this sampling rate will allow for four days of measurements before the memory is filled and we had two exposimeters available per participant.

Bias or loss of precision in the RF-EMF measurements was introduced by the times that participants did not wear the exposimeter, e.g. during sports or showering. These periods were excluded, and exposure metrics were imputed based on measured intervals. The impact of such an exclusion is likely to be non-differential since the excluded periods may represent periods with either high or low RF-EMF exposure, and the effect on the observed associations can therefore be an overestimate or underestimate (Jurek et al., 2005). Also, since the excluded times represented maximally 11% of the total measured time, the influence of exclusion is expected to be modest.

Finally, the measurements may be biased and most certainly underestimate the actual exposure as a single exposimeter was worn on the right hip, therefore experiencing body shielding from all sources to the left of the body. This leads to a mitigation of the measured power density and possible missing of certain signal episodes, which has been minimized by following a strict measurement protocol (Bolte, 2016; Bolte et al., 2011). The past five years body distributed exposimeters have been developed in Belgium which have been tested and shown to lead to much smaller biases and underestimations (Bhatt et al., 2016).

4.4.3. Awareness of exposure

Although the exposimeters did not have a display that showed RF-EMF exposure, participants might have been aware of their exposure in some situations, for instance while sitting next to a WiFi router, in which case actual exposure and perceived exposure are correlated. However, in the one person (participant #8) in which NSPS was associated with perceived exposure, there was no association with measured exposure. This may indicate that psychosomatic processes can trigger NSPS (Rubin et al., 2010).

4.4.4. Statistical analyses

In the statistical analyses, for each participant associations were tested between two NSPS (three for one participant) and two frequency bands, with two metrics per band. For three participants also associations with perceived exposure were examined. A total of 52 statistical tests were performed. This increases the chance of false positive findings due to multiple testing. On the other hand, the analyses were performed on five independent data sets. Also, of all possible combinations of NSPS and frequency bands, only those were analyzed that the participants indicated themselves.

4.4.5. Metrics

The statistically significant relationships of symptom scores with exposure to WiFi concerned the RCM and number of measurements above 0.1 mW/m^2. As RCM is a measure for the irregularity, changes in WiFi exposure occur when environments with a low WiFi field strength are changed for environments with a high field strength or vice versa, e.g. when leaving or returning home for work, or with sudden increase or burst of usage, for instance, during the use of wireless internet. Exposure above a certain threshold occurs if large amounts of data are used by a wireless device such as working on a laptop, playing on a wireless game console or watching movies on a tablet. For GSM/UMTS exposure, changes (RCM) were related to symptom scores. Frequent changes in GSM/UMTS exposure mostly take place outside, e.g. when travelling. A high average GSM/UMTS exposure is dependent on someone's position relative to the location of a base station and the number of transmitters per base station, e.g. in the city centre more transmitters per base station are applied, leading to higher exposures. Indeed, the RCM in a six-hour period was higher when the participant had been travelling. Because symptom scores were not related to travelling (as shown by a Kruskal-Wallis test), travelling did not confound the observed association between downlink and symptoms. Remarkably, we found no significant correlations between NSPS and time-weighted average power density, the most commonly used exposure metric. This yields that in future research the RF EMF exposure signal should be expressed not only in TWA but in a set of metrics describing the main features of that signal, similar to earlier work on extremely low frequency magnetic field measurement by Yost (1999) and (Kaune et al., 2001) who looked at a set of metrics describing the exposure signal.

4.5. Previous studies

To our knowledge, this is the first study that used an idiographic approach to investigate associations between RF-EMF exposure and non-specific physical symptoms in self-reported electrohypersensitive individuals. Therefore, our results cannot be compared with previous studies. Nevertheless, the large majority of epidemiological and experimental studies conclude that, on a group level, NSPS are not related to EMF exposure, either in the general population (Baliatsas et al., 2012a) or in IEI-EMF (Rubin et al., 2010). Also double blind experiments on the individual level could not trigger physiological effects (Rubin et al., 2011). A feasibility study by van Wel et al. (2017) used an ecological momentary assessment (EMA) design to study associations between wellbeing, symptom scores and RF-EMF exposure in 34 non-IEI-EMF individuals during 48 h. Smartphone questionnaires were triggered by exposure conditions, e.g. a sudden increase in exposure or exposure exceeding an absolute threshold. There were no differences in mean wellbeing and symptom scores between trigger types.

4.6. Practical feasibility

The practical feasibility of an idiographic approach for studying IEI-EMF was high, although wearing the exposimeters was a considerable burden for the participants. This was one of the reasons it was difficult to recruit a sufficient number of participants. Compliance to the study protocol was high for the diaries and for the exposure assessment. The high compliance is in line with compliance reported in the EMA study by van Wel et al. (2017). As mentioned above, awareness of exposure could be a problem, and even potential manipulation of study results by placing the exposimeters close to RF-EMF sources cannot be ruled out.

However, visual inspection of the exposure plots and GPS location data did not show obvious signs of manipulating the measurements.

4.7. Recommendation for future research

The ecological momentary assessment approach we followed for EMF is also applicable for other environmental exposures. As wearable sensors for various kinds of exposure, such as particulate matter and volatile organic substances, but also for health effects, become smaller, lighter and cheaper, more simultaneous measurements can be performed on one person. Because persons are followed on an individual basis, the sensors do not even have to be precise in absolute measurements; as long as they are consistent and capable of ranking activities and detecting peaks, the measurements can be used to determine whether reported health or wellbeing related outcomes are associated with particular environmental exposures.

5. Conclusions

This study shows that an idiographic approach is feasible and can yield insights into exposure–outcome associations in single individuals that may not have been obtained if data were analyzed at a group level. Also, the choice for the metric to express the main feature of the exposure is clearly important, as a simple mean exposure intensity is not always describing the most important feature of a signal changing over time. In this exploratory longitudinal study we found weak associations between (perceived and actual) exposure to WiFi (rate of change and number of peaks above threshold) and GSM + UMTS downlink (rate of change and number) EMF and NSPS scores in some but not all of the included self-declared electrohypersensitive persons. In some persons a higher WiFi exposure was associated with higher symptom scores, but in other persons with lower scores. However, residual confounding may affect the estimates of the associations, because RF-EMF exposure, just as symptom scores, can depend on locations and activities for which we could not control in the analyses. In order to better control for potential confounders, we recommend replicating this study with more detailed diary questions on activities and shorter time between cues.

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Conflicts of interest

The authors declare no competing interests.

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