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Time course of health complaints attributed to RF-EMF exposure and predictors of electromagnetic hypersensitivity over 10 years in a prospective cohort of Dutch adults

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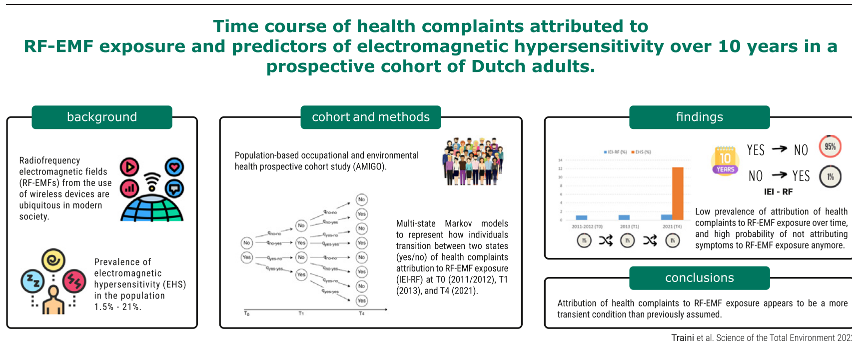
HIGHLIGHTS

- Time course of attribution of health complaints to RF-EMF exposure.
- Predictors of electromagnetic hypersensitivity.
- Multi-state Markov models to represent how individuals in the cohort transition between states of IEI-RF.
- Attribution of health complaints to RF-EMF exposure appears to be a more transient condition than previously assumed.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Some individuals attribute health complaints to radiofrequency electromagnetic field (RF-EMF) exposure. This condition, known as idiopathic environmental intolerance attributed to RF-EMFs (IEI-RF) or electromagnetic hypersensitivity (EHS), can be disabling for those who are affected. In this study we assessed factors related to developing, maintaining, or discarding IEI-RF over the course of 10 years, and predictors of developing EHS at follow-up using a targeted question without the condition of reporting health complaints attributed to RF-EMF exposure.
Methods: Participants ($n = 892$, mean age 50 at baseline, 52 % women) from the Dutch Occupational and Environmental Health Cohort Study AMIGO filled in questionnaires in 2011/2012 (T_0), 2013 (T_1), and 2021 (T_4) where information pertaining to perceived RF-EMF exposure and risk, non-specific symptoms, sleep problems, IEI-RF, and EHS was collected. We fitted multi-state Markov models to represent how individuals transitioned between states ("yes", "no") of IEI-RF.
Results: At each time point, about 1 % of study participants reported health complaints that they attributed to RF-EMF exposure. While this percentage remained stable, the individuals who reported such complaints changed over time: of nine persons reporting health complaints at T_0, only one reported IEI-RF at both T_1 and T_4, and two newly reported health complaints at T_4. Overall, participants had a 95 % chance of transitioning from "yes" to "no" over a time course of 10 years, and a chance of 1 % of transitioning from "no" to "yes". Participants with high perceived RF-EMF exposure and risk had a general tendency to move more frequently between states.
Conclusions: We observed a low prevalence of IEI-RF in our population. Prevalence did not vary strongly over time but there was a strong aspect of change: over 10 years, there was a high probability of not attributing symptoms to RF-EMF exposure anymore. IEI-RF appears to be a more transient condition than previously assumed.

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1. Introduction

Over the past few decades, the rapid advancement of wireless technologies and electronic devices has led to a considerable increase in exposure to radiofrequency electromagnetic fields (RF-EMFs) and RF signals are now part of everyday life. The condition known as idiopathic environmental intolerance attributed to electromagnetic fields (IEI-EMF) is used to describe individuals who attribute health complaints such as headaches, sleep disturbances, or problems in concentrating, to EMF exposure (Baliatsas et al., 2012; Martens et al., 2017; Röösli et al., 2004), and in severe cases it can be disabling or result in a lower quality of life (Kjellqvist et al., 2016). Similarly, the term electromagnetic hypersensitivity (EHS) refers to someone who claims to be hypersensitive to EMFs, but does not necessarily report health complaints attributed to such exposure (Röösli et al., 2010). In particular, IEI-EMF and EHS have been hypothesized to correspond to different levels of involvement in the EMF topic (Röösli et al., 2010). Nevertheless, diagnostic criteria for these conditions are not fully established and research has yet to produce clear evidence on the mechanisms causing people to attribute health complaints to EMF exposure or to define themselves as hypersensitive to EMFs (Baliatsas et al., 2009; Dieudonné, 2019, 2020; Stein and Udasin, 2020), although psychosocial factors are thought to play a role (Augner and Hacker, 2009; Baliatsas et al., 2015; Frick et al., 2002; Martens et al., 2018; Ramirez-Vazquez et al., 2019; Rubin et al., 2010; Watrin et al., 2022). As a consequence, the terms IEI-EMF and EHS are frequently used interchangeably in epidemiological studies, and this is likely to affect the range in estimated prevalence, which in industrialized countries varies between 1.5 % and 21 % (Eltiti et al., 2007; Hillert et al., 2002; Karvala et al., 2018; Levallois et al., 2002; Schreier et al., 2006).

Little is understood in how far IEI-EMF changes over time: intriguingly, some studies observed a similar percentage of IEI-EMF at baseline and at follow-up one or two years later (Kowall et al., 2012; Martens et al., 2018; Röösli et al., 2010), despite a high turnover rate in the population reporting IEI-EMF at follow-up. This implies that attribution of health complaints to EMF exposure is temporary for many but not all people. Therefore, it would be informative to study not only predictors of developing IEI-EMF, but also predictors of maintaining or discarding IEI-EMF. This requires a longitudinal design with repeat surveys on both symptom experience and attribution to EMF exposure, to understand what comes first. To the best of our knowledge, while several studies have addressed risk factors for developing IEI-EMF, few research efforts have targeted the question for whom IEI-EMF is a transient phenomenon.

In this study we aim to evaluate the time course of attribution of health complaints specifically to RF-EMF exposure (IEI-RF) in a Dutch population assessed at three time points over the course of 10 years by examining factors that are related to developing, maintaining, or discarding IEI-RF, defined as reporting any health complaint attributed to RF-EMF exposure sources. Second, we aim to assess predictors of developing EHS at follow-up using a question targeting the notion of being electromagnetic hypersensitive, without the condition of self-reporting health complaints attributed to RF-EMF exposure.

2. Material and methods

2.1. Study participants

We used data from the population-based occupational and environmental health prospective cohort study (AMIGO) established in 2011/2012 to investigate environmental and occupational determinants of diseases and symptoms in the Dutch adult population. The rationale, study design and participant recruitment in AMIGO were described in detail previously (Slottje et al., 2014). In short, AMIGO participants were recruited from the general population in the Netherlands through the Primary Care Database of the Netherlands Institute for Health Services Research (NIVEL), which consists of routinely recorded data from health care providers to monitor health and utilization of health services in the Dutch population (Nivel Primary Care Database|Nivel, 2022). The sample includes 14,829 adults (16 % of those invited), aged 31–65 years at the time of data collection (2011/2012), who were randomly selected within households based on their address. The AMIGO cohort study includes dedicated questionnaires to assess relationships between exposure, risk perception, symptom reporting and symptom attribution to environmental factors including RF-EMFs. Participants filled in an online questionnaire at baseline (2011/2012; T_0) and in 2015 ($n = 7905$; T_3; response rate 54 %), and a targeted subset of participants sampled based on contrast in perceived and estimated RF-EMF exposure at baseline filled in two additional follow-up questionnaires in 2013 ($n = 2228$; T_1; response rate 56 %) and 2014 ($n = 1740$; T_2; response rate 78 %) to answer questions about perceived RF-EMF and other environmental factor exposure and risk, health concerns, symptom attribution to RF-EMF exposure, non-specific symptoms and sleep disturbances (Martens et al., 2017, 2018). We performed an update in 2021 (T_4) in which individuals who had participated at T_1 completed a questionnaire where information pertaining to RF-EMF perceptions (perceived exposure, risk and concern, including pertaining to 5G technology), symptoms, and attribution to RF-EMF exposure were assessed again ($n = 892$; response rate 40 %). In the 2021 (T_4) questionnaire additional items were added related to EHS. We included in the current analyses participants who filled in questionnaires at time points T_0, T_1, and T_4 in order to achieve the largest possible sample size (Fig. 1).

2.2. Health complaints attributed to RF-EMF exposure – IEI-RF

Self-reported health complaints attributed to RF-EMF exposure (IEI-RF) were assessed at time points T_0 and T_1 with the subsequent questions: "Do you currently have health complaints that you attribute to the environment" and "if so, to what environmental factors/sources, select from the following or describe another factor/source". From this list of sources we selected: (1) electromagnetic fields from mobile phone base stations, radio or TV; (2) electromagnetic fields from mobile phones; (3) electromagnetic fields from cordless phones; (possible answers "yes" or "no")?, and at time point T_4 with the subsequent questions: "Do you currently have health complaints that you attribute to the environment" and "if so, to what environmental factors/sources, select from the following or describe another factor/source". From this list of sources we selected: (1) electromagnetic

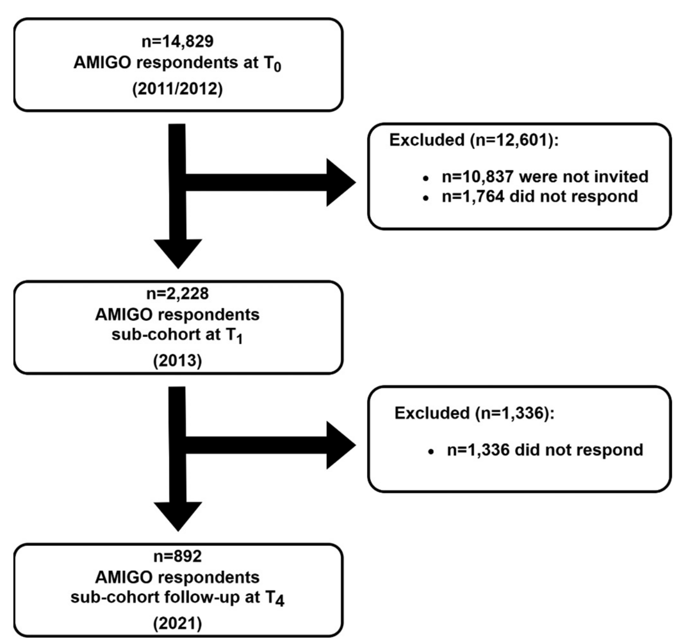

Fig. 1. Flow of participants. We included in the analyses participants who filled in questionnaires at time points T_0, T_1, and T_4 ($n = 892$ of 2228 invited participants).

fields from mobile phone base stations, radio or TV; (2) electromagnetic fields from mobile phones, cordless phones and other wireless devices, (e.g. laptop, tablet); (3) electromagnetic fields from 5G technology; (possible answers "yes" or "no")?. Participants were considered as IEI-RF at any time point if at least one RF-EMF category was marked in the respective questionnaires.

2.3. Self-reported notion of being electromagnetic hypersensitive – EHS

At T_4 we asked participants to indicate to which extent they considered themselves as electromagnetic hypersensitive by asking the following question: "Do you think you are electromagnetic hypersensitive (on a scale of 0–6, where 0 = not at all and 6 = very much)?".

In the analyses we classified as electromagnetic hypersensitive participants whose score ranged between 4 and 6.

2.4. Perceived RF-EMF exposure and risk

Perceived exposure to RF-EMFs (among other environmental exposures) was assessed at T_0 and T_1 with the question: "To what extent do you think you are exposed to: (1) electromagnetic fields from mobile phone base stations, radio or TV; (2) electromagnetic fields from mobile phones; (3) electromagnetic fields from cordless phones; (on a scale of 0–6, where 0 = not at all and 6 = very much)?", and at time point T_4 with the question: "To what extent do you think you are exposed to: (1) electromagnetic fields from mobile phone base stations, radio or TV; (2) electromagnetic fields from mobile phones, cordless phones and other wireless devices, (e.g. laptop, tablet); (3) electromagnetic fields from 5G technology; (on a scale of 0–6, where 0 = not at all and 6 = very much)?"

Perceived risk with respect to RF-EMFs (among other specified environmental factors) was assessed at T_0 and T_1 with the question: "To what extent do you think that ((1) electromagnetic fields from mobile phone base stations, radio or TV; (2) electromagnetic fields from mobile phones; (3) electromagnetic fields from cordless phones) pose a risk to the health in everyday circumstances? (on a scale of 0–6, where 0 = not at all and 6 = very much)", and at time point T_4 with the question: "To what extent do you think that ((1) electromagnetic fields from mobile phone base stations, radio or TV; (2) electromagnetic fields from mobile phones, cordless phones and other wireless devices, (e.g. laptop, tablet); (3) electromagnetic fields from 5G technology) pose a risk to the health in everyday circumstances? (on a scale of 0–6, where 0 = not at all and 6 = very much)".

The cut-offs to define low/high exposure and risk perception categories were calculated based on the distribution of perceived RF-EMF exposure and risk at T_0 (low: 0th–90th percentile, high: 90th–100th percentile, cut-off point $_{\text{perceived RF-EMF exposure}} = 12$; cut-off point $_{\text{perceived RF-EMF risk}} = 12$).

2.5. Self-reported non-specific symptoms and sleep disturbances

We assessed non-specific symptoms and sleep disturbances at time points T_0, T_1, and T_4. For the first, we used the Four-Dimensional Symptom Questionnaire (4DSQ) (Terluin et al., 2006), a self-report questionnaire developed in the Dutch language and validated to discriminate in clinical practice between four dimensions (distress, somatization, anxiety, depression). We calculated the total symptom score (range 0–32) from the somatization scale (4DSQ-S) which consists of 16 nonspecific somatic symptoms (e.g. headache, palpitations, low back pain) commonly reported by patients with somatization (disorder). Participants self-reported on a 5-point scale ranging from "no" to "constantly" whether they had experienced any of these symptoms during the previous week. To obtain a total score, we trichotomized and then summed over the symptoms (no = 0; sometimes = 1; regularly/often/constantly = 2) (Martens et al., 2017). Sleep disturbances were assessed using the 6-item medical outcomes study (MOS) scale, a sleep problem index which ranges from 0 to 100, with higher scores indicating more sleep disturbances or lower sleep quality (Spritzer and Hays, 2003).

2.6. Socio-demographic characteristics

Socio-demographic characteristics collected at baseline included sex, age, the highest level of education attained (low: primary school, lower vocational training or lower secondary education; intermediate: intermediate vocational education or intermediate/higher secondary education; high: higher vocational education or university degree), and self-reported mobile phone use (user; nonuser). In addition, urbanicity level was determined for each participants home address based on the density of addresses (very highly urban: ≥ 2500 addresses per km^2; highly urban: 1500–2500 addresses per km^2; moderately urban: 1000–1500 addresses per km^2; little urban: 500–1000 addresses per km^2; non-urban: <500 addresses per km^2) (Statistiek, 2011).

2.7. Statistical analysis

We calculated descriptive statistics for age, sex, the highest level of education attained, urbanicity level, and self-reported mobile phone use at baseline, and at each time point for perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, and MOS sleep index. We used one-way repeated measures ANOVA to compare group means of 4DSQ-S score and MOS sleep index, respectively, across all time points. The proportion of participants reporting IEI-RF was calculated at each time point T_0, T_1, and T_4, whereas the proportion of those defining themselves as EHS was only available at T_4.

We used the R package *msm* to calculate the observed transitions and transition probabilities of IEI-RF over different time intervals, and fit multi-state Markov models to our data (Jackson, 2011). In short, the multi-state Markov model is a flexible way of describing a process in which an individual moves through a discrete set of states, assuming that there is a continuous process underlying the data (i.e. the event varies continuously through time, but is only observed at the same times as the state of the Markov process). It relies on the Markov assumption that future evolution only depends on the current state (Kalbfleisch and Lawless, 1985). We fitted multi-state Markov models to represent how individuals in our cohort transitioned between two states defined by the presence ("yes") or absence ("no") of IEI-RF. More specifically, we estimated four multi-state Markov models including perceived RF-EMF exposure (Model 1), perceived RF-EMF risk (Model 2), 4DSQ-S score (Model 3), MOS sleep index (Model 4) as time-dependent risk factors to investigate potential time-variant effects on transition rates, adjusted for sex and age. To fit a multi-state model to our data, we estimated a transition intensity matrix in which each individual may transition from one state to another at each time point T_0, T_1, and T_4, and the next state to which the individual moves, and the time of the change, are governed by a set of transition intensities for each pair of states. The defined multi-state model is illustrated in Supplementary Fig. 1. The intensities represent the instantaneous risk of moving from one state to another. It may depend on the time of the process, or more generally a set of individual-specific or time-varying explanatory variables, assuming that they are constant in between the observation times of the Markov process. We performed Pearson-type goodness-of-fit tests to assess the overall fit of the models (Titman and Sharples, 2008). This method, available in the *msm* package, compares observed and expected numbers of transitions between pairs of states for a series of transition starting times, transition time intervals and covariate categories, and it is intended for data which represent observations of the process at arbitrary times. In cases where there are several low expected counts in the resulting contingency tables, the number of observation time, time interval, or covariate categories may be reduced to improve the χ^2 approximation (Aguirre-Hernández and Farewell, 2002; Jackson, 2011).

We explored the association between EHS at T_4 and perceived RF-EMF exposure and risk, 4DSQ-S score, MOS sleep index assessed at T_0. We estimated four logistic regression models including perceived RF-EMF exposure (Model 5), perceived RF-EMF risk (Model 6), 4DSQ-S score (Model 7), MOS sleep index (Model 8) as independent variables, adjusted for sex and age. We fitted two mutually adjusted logistic regression models

Table 1
Characteristics of the participants at T_0 (2011/2012) in the sub-cohort of AMIGO ($n = 892$).

	Cohort at T_0 (2011/2012)	
	n (%)	Mean (SD)
Sex		
Male	424 (47.5)	
Female	468 (52.5)	
Age (in years)		50.4 (9.0)
Highest level of education attained[a]		
Low	157 (17.6)	
Intermediate	266 (29.8)	
High	469 (52.6)	
Urbanicity level[b]		
Very highly urban	117 (13.1)	
Highly urban	282 (31.6)	
Moderately urban	238 (26.7)	
Little urban	177 (19.8)	
Non-urban	78 (8.8)	
Mobile phone use		
Nonuser	234 (26.2)	
User	658 (73.8)	

Characteristics of the participants at baseline (T_0: 2011/2012) in the sub-cohort of AMIGO ($n = 892$).

[a] Low: primary school, lower vocational training or lower secondary education; intermediate: intermediate vocational education or intermediate/higher secondary education; high: higher vocational education or university degree.

[b] Very highly urban: ≥2500 addresses per km^2; highly urban: 1500–2500 addresses per km^2; moderately urban: 1000–1500 addresses per km^2; little urban: 500–1000 addresses per km^2; non-urban: <500 addresses per km^2.

where perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, and MOS sleep index were considered simultaneously, adjusted for sex and age (Model 9), and sex, age, the highest level of education attained, urbanicity level, and self-reported mobile phone use (Model 10) as sensitivity analysis, respectively.

In addition, we conducted the following secondary analyses to explore the association between EHS at T_4 and perceived RF-EMF exposure and risk, 4DSQ-S score, MOS sleep index assessed at T_1: we estimated four logistic regression models including perceived RF-EMF exposure (Model 11), perceived RF-EMF risk (Model 12), 4DSQ-S score (Model 13), MOS sleep index (Model 14) as independent variables, adjusted for sex and age. We fitted two mutually adjusted logistic regression models where perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, and MOS sleep index were considered simultaneously, adjusted for sex and age (Model 15), and sex, age, the highest level of education attained, urbanicity level, and self-reported mobile phone use (Model 16) as sensitivity analysis, respectively.

This population-based cohort study was conducted according to an analysis plan developed a priori and defining in detail the planned statistical analysis (Supplementary Analysis Plan). Missing values (<1.0 %) were replaced with the most common category (categorical variables) or with the mean value (continuous variables). All analyses were conducted with the R statistical software, version 4.0.4. Computing code related to all analyses presented is publicly available at https://github.com/eugeniotraini/multistate_RF_EMF.

3. Results

3.1. Descriptive statistics

Baseline characteristics of the study population are presented in Table 1. The AMIGO sub-cohort for this analysis consisted of 892 adults, half of whom were male, with a mean age of 50 years. More than half of the respondents attained a high level of education and most of the participants lived in urban areas. Three-quarters of the cohort were mobile phone users.

Participant characteristics in the full cohort at baseline were similar to those of the respondents included in the sub-cohort, although highly educated participants and those living in urban areas were slightly overrepresented in the sub-cohort compared to the full cohort (Supplementary Table 1).

Median perception of RF-EMF exposure ($T_0 = 5$; $T_1 = 6$; $T_4 = 9$) and risk ($T_0 = 4$; $T_1 = 6$; $T_4 = 9$) showed a rising trend over time (Supplementary Fig. 2), with around 5 % and 7 % of participants classified in the high perception group at T_0, values that increased up to 20 % and 14 % at T_4 (Table 2). The distribution of scores of perceived RF-EMF exposure and risk grouped by exposure source are presented in Supplementary Fig. 3 and showed that participants at T_4 indicated they perceived themselves to be stronger exposed to and more at risk from RF-EMFs compared to T_0 and T_1. Additionally, around 28 % of respondents self-reported they were exposed to RF-EMFs from 5G at T_4, and the same percentage also applied to those who indicated that 5G may pose risks to their health.

The 4DSQ-S score ($F(2,24) = 1.39$, $p = 0.3$) and MOS sleep index ($F(2,46) = 1.62$, $p = 0.2$) were not statistically significantly different at T_0, T_1, and T_4, respectively (Table 2).

Table 3 lists the proportion of participants reporting IEI-RF at each time point, and those self-declaring as EHS at T_4. Results showed that 12 % of the respondents claimed to be EHS at T_4, whereas the percentage of individuals reporting IEI-RF was limited in our population and did not vary substantially over time (ranging from 1.0 % at T_0 to 1.2 % at T_4) (Table 3).

3.2. Observed transitions, estimated transition probabilities, and multi-state Markov models

The observed transitions, that is the number of times each pair of states were observed in successive observation times between T_0 and T_1, T_1 and T_4, and any consecutive time points T_0, T_1, T_4, are shown in Supplementary

Table 2
Perceived RF-EMF exposure, perceived RF-EMF risk, and symptom characteristics at T_0 (2011/2012), T_1 (2013), and T_4 (2021) in the sub-cohort of AMIGO (n = 892).

	Cohort at T_0 (2011/2012)		Cohort at T_1 (2013)		Cohort at T_4 (2021)	
	n (%)	Mean (SD)	n (%)	Mean (SD)	n (%)	Mean (SD)
Perceived RF-EMF exposure[a]						
Low perception	847 (94.9)		826 (92.6)		718 (80.5)	
High perception	45 (5.1)		66 (7.4)		174 (19.5)	
Perceived RF-EMF risk[b]						
Low perception	828 (92.8)		805 (90.2)		767 (86.0)	
High perception	64 (7.2)		87 (9.8)		125 (14.0)	
4DSQ-S score		5.9 (5.3)		5.7 (4.9)		7.0 (5.1)
MOS sleep index		26.7 (14.3)		27.0 (14.1)		26.4 (14.8)

Abbreviations: 4DSQ-S, somatization scale of the Four-Dimensional Symptom Questionnaire; MOS, Medical Outcomes Study; n, number of participants; SD, standard deviation. Distribution of perceived RF-EMF exposure and perceived RF-EMF risk at T_0 (2011/2012), T_1 (2013), and T_4 (2021) and mean (standard deviation) of non-specific symptoms (4DSQ-S score) and sleep disturbances (MOS sleep index) at T_0 (2011/2012), T_1 (2013), and T_4 (2021) in the sub-cohort of AMIGO (n = 892).

[a] The cut-off point for low/high perception was based on the distribution of perceived RF-EMF exposure at T_0 (low: 0th-90th percentile, high: 90th-100th percentile, cut-off point = 12).

[b] The cut-off point for low/high perception was based on the distribution of perceived RF-EMF risk at T_0 (low: 0th-90th percentile, high: 90th-100th percentile, cut-off point = 12).

Table 3
Prevalence of self-reported health complaints attributed to RF-EMF exposure (IEI-RF) at T_0 (2011/2012), T_1 (2013), and T_4 (2021), and self-reported notion of being electromagnetic hypersensitive (EHS) at T_4 (2021), in the sub-cohort of AMIGO (n = 892).

	Cohort at T_0 (2011/2012)		Cohort at T_1 (2013)		Cohort at T_4 (2021)	
	n	%	n	%	n	%
Health complaints attributed to RF-EMF exposure (IEI-RF)						
No	883	99.0	882	98.9	881	98.8
Yes	9	1.0	10	1.1	11	1.2
Self-reported notion of being electromagnetic hypersensitive (EHS)						
No	–		–		784	87.9
Yes	–		–		108	12.1

Distribution of health complaints attributed to RF-EMF exposure (IEI-RF) at T_0 (2011/2012), T_1 (2013), and T_4 (2021) and self-reported notion of being electromagnetic hypersensitive (EHS) at T_4 (2021) in the sub-cohort of AMIGO (n = 892).

Table 2. Results indicated that the number of participants transitioning between the two states of IEI-RF (from "no" to "yes", or "yes" to "no") between T_0 and T_1 (A) and T_1 and T_4 (B) was stable over time, however, the transition did not always involve the same participants. Of nine respondents reporting IEI-RF at T_0, three still reported the same at T_4, but only one of them also reported the same at both T_1 and T_4 (Supplementary Fig. 4). Based on the results from the fitted transition probability matrix, we observed that participants had a 95 % chance of transitioning from "yes" to "no" over a time course of 10 years (46 % in 2 years' time), and a 1 % chance of transitioning from "no" to "yes" (0.6 % in 2 years' time) (Supplementary Table 3).

The results of the multi-state Markov models are presented in Table 4 and suggested that participants with a high perception of both RF-EMF exposure (Model 1) and risk (Model 2) at any time point had an increased tendency to switch state by attributing health complaints to RF-EMF exposure (HR = 4.11, 95 % CI:0.87, 19.53; HR = 3.81, 95 % CI:0.76, 19.18). On the other hand, participants had a reduced tendency of no longer attributing health complaints to RF-EMF exposure (HR = 0.56, 95 % CI:0.11, 2.82; HR = 0.46, 95 % CI:0.10, 2.16) compared to those in the low exposure perception group. 4DSQ-S score (Model 3), and MOS sleep index (Model 4) were not associated with transitioning between states.

Table 4
Associations of self-reported health complaints attributed to RF-EMF exposure (IEI-RF) with perceived RF-EMF exposure (Model 1), perceived RF-EMF risk (Model 2), 4DSQ-S score (Model 3), MOS sleep index (Model 4), evaluated with multi-state models with transitions at T_0, T_1, and T_4 in the sub-cohort of AMIGO (n = 892).

	Transition	HR 95 % CI
Model 1[a]		
Perceived RF-EMF exposure		
Low perception	No-Yes	1
	Yes-No	1
High perception	No-Yes	4.11 (0.87;19.53)
	Yes-No	0.56 (0.11;2.82)
Model 2[a]		
Perceived RF-EMF risk		
Low perception	No-Yes	1
	Yes-No	1
High perception	No-Yes	3.81 (0.76;19.18)
	Yes-No	0.46 (0.10;2.16)
Model 3[a]		
4DSQ-S score		
No-Yes		1.07 (0.95;1.20)
Yes-No		0.96 (0.85;1.08)
Model 4[a]		
MOS Sleep Index		
No-Yes		0.98 (0.91;1.05)
Yes-No		0.93 (0.87;1.01)

Abbreviations: 4DSQ-S, somatization scale of the Four-Dimensional Symptom Questionnaire; MOS, Medical Outcomes Study; HR, Hazard Ratios; CI, Confidence Interval.
Results from four multi-state Markov models representing how individuals in the sub-cohort transitioned between two states defined by the presence ("yes") or absence ("no") of IEI-RF. We included perceived RF-EMF exposure (Model 1), perceived RF-EMF risk (Model 2), 4DSQ-S score (Model 3), and MOS sleep index (Model 4) as time-dependent risk factors to investigate potential time-variant effects on transition rates, adjusted for sex and age.
[a] Adjusted for sex and age at T_0.

3.3. Factors associated with the self-reported notion of being EHS

In Table 5 we present results from logistic regression on the association between the self-reported notion of being EHS at T_4 and independent variables assessed at T_0. In the models evaluating each independent variable separately, perceived RF-EMF exposure and risk, 4DSQ-S score, and MOS sleep index were significantly associated with increased odds of being EHS at T_4. More specifically, participants who showed a high perception of RF-EMF exposure at T_0 had an increased odds of being EHS at T_4 (OR = 4.17, 95 % CI:2.10, 8.00). Similarly, participants with a high perception of RF-EMF risk at T_0 had an increased odds of being EHS at T_4 (OR = 4.08, 95 % CI:2.26, 7.17). Finally, both the 4DSQ-S score and the MOS sleep index at T_0 were associated with an increase in the odds of being EHS at T_4 (OR = 1.07, 95 % CI:1.03, 1.10; OR = 1.02, 95 % CI:1.00, 1.03). Results from the mutually adjusted model with minimal adjustment (Model 9) and full adjustment (Model 10) were consistent with those from the models evaluating each independent variable separately, although the estimates were generally attenuated (Table 5). Results from secondary analyses exploring the association between EHS at T_4 and perceived RF-EMF exposure and risk, 4DSQ-S score, MOS sleep index assessed at T_1 showed no discrepancies from the main results (Table 6).

4. Discussion

In our study we observed a low prevalence (~1 %) of adults reporting IEI-RF over the 10-year follow-up. While this 1 % of persons remained stable at all time points in our study, the individuals who reported IEI-RF changed over time: of nine persons reporting symptoms attributed to RF-EMF at T_0, only one still reported the same at T_1 and T_4, and two newly reported health complaints at T_4. In addition, about 12 % of the participants reported the notion of being EHS (without the condition of health complaints attributed to RF-EMF exposure) at T_4, and we observed that high RF-EMF risk and exposure perception, as well as self-reported symptoms and sleep disturbances at T_0 and T_1, were statistically significant risk factors for this condition.

To the best of our knowledge, this is the first epidemiological study investigating the time course of IEI-RF in a well-established general population cohort of adult individuals assessed at multiple time points over a long time period of follow-up, which enabled us to investigate the dynamic process of IEI-RF with 2 and 10 years of latency. Furthermore, by collecting data on perceived RF-EMF exposure and risk, and non-specific symptoms (i.e. symptom reporting and sleep disturbances) over the 10-year follow-up, we were well positioned to investigate the dynamics of several individual factors possibly related to IEI-RF.

Weakness of our study includes that it was not feasible to measure true exposure in our study participants and we were therefore not able to follow the time course of actual RF-EMF exposure. Because we asked for the "most important health complaint" attributed to RF-EMF exposure, we were also not able to reliably follow which exact symptoms were included into the attribution over time. Furthermore, given the sparseness of consistent "yes" data of IEI-RF over time, we did not estimate mutually adjusted multi-state Markov models. Finally, we could not assess the time course of EHS in the study population due to the lack of EHS data at T_0 and T_1.

A previous longitudinal study conducted in Switzerland in 2008 and 2009 showed that only a minority of the participants who attributed health complaints to RF-EMF exposure (27 %) made the same declaration after one year (Röösli et al., 2010), and a longitudinal study conducted in

Table 5
Associations of self-reported notion of being electromagnetic hypersensitive (EHS) at T_4 with perceived RF-EMF exposure (Model 5), perceived RF-EMF risk (Model 6), 4DSQ-S score (Model 7), MOS sleep index (Model 8), and perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, MOS sleep index mutually adjusted (Model 9 with minimal adjustment; Model 10 with full adjustment) assessed at T_0.

	Model 5[a]	Model 6[a]	Model 7[a]	Model 8[a]	Model 9[a]	Model 10[b]
	OR 95 % CI	OR 95 % CI	OR 95 % CI	OR 95 % CI	OR 95 % CI	OR 95 % CI
Perceived RF-EMF exposure						
Low perception	1	-	-	-	1	1
High perception	4.17 (2.10;8.00)				2.39 (1.09;4.97)	2.38 (1.08;5.01)
Perceived RF-EMF risk						
Low perception	-	1	-	-	1	1
High perception		4.08 (2.26;7.17)			2.92 (1.50;5.49)	3.07 (1.57;5.83)
4DSQ-S Score	-	-	1.07 (1.03;1.10)	-	1.05 (1.01;1.09)	1.05 (1.00;1.09)
MOS sleep index	-	-	-	1.02 (1.00;1.03)	1.01 (0.99;1.02)	1.01 (0.99;1.02)

Results from logistic regression on the association between EHS at T_4 and perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, MOS sleep index, assessed at T_0. We estimated four logistic regression models including each independent variable separately, and two mutually adjusted logistic regression models (with minimal and full adjustment) where perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, MOS sleep index were considered simultaneously.
[a] Adjusted for sex and age at T_0.
[b] Adjusted for sex, age, the highest level of education attained, urbanicity level, and self-reported mobile phone use at T_0.

Germany between 2004 and 2006 found a slightly larger proportion of participants (31 %) who did the same after two years of follow-up (Kowall et al., 2012). These results are consistent with what we found in our study, with a strong change in the population reporting symptoms attributed to RF-EMF exposure. Over the course of 10 years this translated to a 95 % probability of not attributing health complaints to RF-EMF exposure any more in persons who did so at baseline, and to a 1 % probability of acquiring such an attribution in those who did not attribute at baseline.

The estimated prevalence of EHS as well as of IEI-RF and IEI-EMF in the general population is uncertain (Eltiti et al., 2007; Hillert et al., 2002; Karvala et al., 2018; Levallois et al., 2002; Schreier et al., 2006). In our cohort we observed a lower prevalence of IEI-RF compared to previous studies. Kowall et al. estimated the prevalence of IEI-RF to be 8.7 % (2004) and 7.2 % (2006) based on attribution of health complaints to RF-EMF exposure (Kowall et al., 2012). However, this study was limited to only focusing on RF-EMF exposure from mobile phone base stations. Röösli et al. reported an IEI-RF prevalence of 13.0 % and 14.3 % in 2008 and 2009, respectively, when evaluating health complaints generally attributed to electromagnetic pollution in everyday life. In that same study, EHS prevalence was also assessed based on a question targeting the notion of being EHS. Based on that question, the EHS prevalence was lower (8.6 % and 7.7 % in 2008 and 2009, respectively), and lower than what we found in our general population cohort in 2021 (12.1 %) using a similar question to define EHS (Röösli et al., 2010). We provided data about prevalence of IEI-RF and EHS by year, in our and in the named other studies, in Supplementary Table 4.

The following factors could contribute to the disagreement between the estimated prevalence of IEI-RF and EHS: first, the term "electromagnetic hypersensitivity" may not be familiar to all individuals in our Dutch cohort. Interestingly, of the 11 participants reporting IEI-RF in 2021, only 6 defined themselves as EHS when answering the question targeting the notion of being electromagnetic hypersensitive in the same year. In contrast, only 6 out of 108 participants defining themselves as EHS also attributed own health complaints to RF-EMF exposure in the same year. These results indicated that our participants provided a different interpretation of IEI-RF and the notion of being EHS, thus suggesting that future studies should carefully design their survey and questionnaire in order to obtain the most comprehensive and accurate estimates of IEI-RF and EHS prevalence in the study population. Due to the considerable heterogeneity in the criteria used by researchers to define EHS, reports of EHS as well as of IEI-RF prevalence in different populations may be difficult to align (Baliatsas et al., 2012).

Second, people who self-describe as electromagnetic hypersensitive may avoid exposure and thus not be attributing symptoms. As a consequence, one could expect a higher prevalence for being sensitive than for experiencing symptoms that can be attributed. At the same time, the exact wording of the question in the questionnaire can play a role. It might be easier for participants who generally consider themselves sensitive to any (environmental) stressors to perceive themselves also electromagnetic hypersensitive. On the other hand, by asking for health complaints attributed to specific RF-EMF sources, it might be less likely for those who generally consider themselves sensitive to say "yes".

Third, we did not consider in our analyses health complaints attributed to extremely low frequency electric and magnetic fields (ELF-EMF), such as from powerlines or electric appliances. Therefore, we cannot exclude that these additional EMF sources may have influenced the proportion of

Table 6
Associations of self-reported notion of being electromagnetic hypersensitive (EHS) at T_4 with perceived RF-EMF exposure (Model 11), perceived RF-EMF risk (Model 12), 4DSQ-S score (Model 13), MOS sleep index (Model 14), and perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, MOS sleep index mutually adjusted (Model 15 with minimal adjustment; Model 16 with full adjustment) assessed at T_1.

	Model 11[a]	Model 12[a]	Model 13[a]	Model 14[a]	Model 15[a]	Model 16[b]
	OR 95 % CI	OR 95 % CI	OR 95 % CI	OR 95 % CI	OR 95 % CI	OR 95 % CI
Perceived RF-EMF exposure						
Low perception	1	-	-	-	1	1
High perception	2.85 (1.53;5.10)				1.64 (0.79;3.28)	1.84 (0.87;3.72)
Perceived RF-EMF risk						
Low perception	-	1	-	-	1	1
High perception		3.02 (1.74;5.09)			2.36 (1.24;4.36)	2.41 (1.25;4.51)
4DSQ-S Score	-	-	1.06 (1.02;1.10)	-	1.04 (0.99;1.09)	1.03 (0.99;1.08)
MOS sleep index	-	-	-	1.02 (1.00;1.03)	1.01 (0.99;1.03)	1.01 (0.99;1.03)

Results from logistic regression on the association between EHS at T_4 and perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, MOS sleep index, assessed at T_1. We estimated four logistic regression models including each independent variable separately, and two mutually adjusted logistic regression models (with minimal and full adjustment) where perceived RF-EMF exposure, perceived RF-EMF risk, 4DSQ-S score, MOS sleep index were considered simultaneously.
[a] Adjusted for sex and age at T_0.
[b] Adjusted for sex, age, the highest level of education attained, urbanicity level, and self-reported mobile phone use at T_0.

participants defining themselves as sensitive to RF-EMF exposure at T_4. However, information on health complaints attributed to ELF-EMF was available at T_0 and T_1 and showed that only 2 out of 892 participants reported at least one symptom that they attributed to ELF-EMF exposure. This result suggested that an underestimation of EHS prevalence due to missing information on ELF-EMF at T_4 was unlikely to have been large in our study.

Finally, given the sample size of the AMIGO sub-cohort, the difference in estimated prevalence of EHS and IEI-RF should be interpreted cautiously.

Three main pathways have been hypothesized to explain what underlies EHS or IEI-RF: first, the biological pathway outlines that participants' RF-EMF exposure causes symptoms (Dieudonné, 2020). Presumably, for symptoms to go away, exposure would need to be attenuated. Given that we did not measure true RF-EMF exposure of our participants over time, we are limited in our ability to explore this exposure attenuation hypothesis in detail. However, it has been shown that one's own exposure is primarily driven by the own use of devices, in particular when calling with mobile phones (van Wel et al., 2021). Exposure reduction over time thus should entail that participants are aware of their own behavior changes and thus one would expect that their perceived exposure would be reduced as well. However, persons who attributed symptoms to RF-EMF exposure at T_0 or T_1, but not at T_4, tended to report higher exposure perception at T_4 than at the two previous time points, which does not fit this hypothesized pattern. Of note, current evidence is limited regarding a biological pathway in causing symptoms (French Agency for Food, Environmental and Occupational Health & Safety (ANSES), 2013; SSM's Scientific Council on Electromagnetic Fields, 2021). Second, the cognitive pathway hypothesizes that perceived exposure and risk promote a nocebo response that generates symptoms (Dieudonné, 2020). Ample experimental evidence supports nocebo effects (Martens et al., 2017; Szemerszky et al., 2010), although duration of such induced health problems have rarely been assessed. In our study, participants with higher risk and exposure perception were somewhat more likely to transition towards attributing symptoms, indicating that nocebo effects may be relevant. Contrasting this, the observation that study participants reporting IEI-RF at T_0 and T_1, but not at T_4, overall increased (and not decreased) exposure and risk perception over time, does not support the cognitive hypothesis. Alternatively, symptoms triggered by nocebo effects may not be persistent. A recent qualitative study on IEI-EMF subjects suggested symptom reports preceded EMF risk perception which also contradicts the cognitive pathway (Dieudonné, 2016). As a third hypothesized pathway, symptoms may be attributed to RF-EMF exposure to help explain a health problem and reduce uncertainty regarding the underlying cause (attributive hypothesis) (Dieudonné, 2020). Prevalence of non-specific symptom reporting based on the 4DSQ-S score was 91, 91, and 95 % of the participants reporting at least one non-specific symptom at T_0, T_1, and T_4, respectively. Given that we cannot explore whether symptom reporting or risk perception came first, we are not able to prove or disprove this pathway. Nevertheless, the high prevalence of symptom reports means that this pathway was possible in our population.

5. Conclusion

In our study we found that IEI-RF appears to be a more transient phenomenon than previously assumed. At each time point, about 1 % of study participants reported health complaints that they attributed to RF-EMF exposure and, overall, participants had a 95 % chance of transitioning from "yes" to "no" over a time course of 10 years, and a chance of 1 % of transitioning from "no" to "yes". Participants with a high perception of both RF-EMF exposure and health risk had a general tendency to transition more frequently between states.

RF-EMF perceptions as well as non-specific symptom reporting and sleep disturbances at baseline were predictive for the notion of being EHS at 10 years follow-up, regardless of whether reporting health complaints attributed to RF-EMF exposure. The knowledge regarding predictors of these dynamics may provide opportunities for future risk communication and prevention, particularly targeting those individuals in the population who consistently attribute health complaints to RF-EMF exposure over time.

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CRediT authorship contribution statement

Eugenio Traini: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Astrid L. Martens:** Writing – review & editing. **Pauline Slottje:** Writing – review & editing. **Roel C.H. Vermeulen:** Conceptualization, Supervision, Writing – review & editing. **Anke Huss:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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