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Exposure to extremely low and intermediate-frequency magnetic and electric fields among children from the INMA-Gipuzkoa cohort

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ABSTRACT

Detailed assessment of exposure to extremely low frequency (ELF) and intermediate frequency (IF) fields is essential in order to conduct informative epidemiological studies of the health effects from exposure to these fields. There is limited information available regarding ELF electric fields and on both magnetic and electric field exposures of children in the IF range. The aim of this study was to characterize ELF and IF exposure of children in the Spanish INMA cohort. A combination of spot and fixed measurements was carried out in 104 homes, 26 schools and their playgrounds and 105 parks. Low levels of ELF magnetic fields (ELF-MF) were observed (with the highest 24-h time-weighted average (TWA) exposure being 0.15 μT in one home). The interquartile range (IQR) of ELF electric fields (ELF-EF) ranged from 1 to 15 V/m indoors and from 0.3 to 1.1 V/m outdoors and a maximum value observed was 55.5 V/m in one school playground. IQR ranges for IF magnetic and electric fields were between 0.02 and 0.23 μT and 0.2 and 0.5 V/m respectively and maximum values were 0.03 μT and 1.51 V/m in homes. Correlations between magnetic and electric fields were weak for ELF (Spearman 0.04–0.36 in different settings) and moderate for IF (between 0.28 and 0.75). Children of INMA-Gipuzkoa cohort were exposed to very low levels of ELF-MF in all settings and to similar levels of ELF-EF compared to the range of previously reported levels, although somewhat higher exposures occurred at home. Children enrolled to our study were similarly exposed to IF in all settings.

1. Introduction

Exposure to extremely low frequency (ELF) electromagnetic fields (EMFs) is ubiquitous in the general population. Since in 1979 Wertheimer and Leeper found a doubling of the risk of leukemia in children living near high current configurations, many researchers have made efforts to investigate this association (Greenland et al., 2000; Ahlbom et al., 2000). Due to the observed elevated risk of leukemia in children exposed to levels above 0.4 μT of ELF magnetic fields (ELF-MF), these EMFs were classified as possibly carcinogenic to humans by the International Agency for Research on Cancer (IARC) in 2002. Nevertheless, the association between exposure and other health effects remain unclear (Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), 2015; World Health Organization, 2007).

Great efforts have been made to characterize magnetic fields, but there is less data available regarding exposure to ELF electric fields (ELF-EF). Regarding interaction with the human body, electric fields also charge the body surface. If they are strong enough they can induce electric currents inside the body and stimulate nerve and muscle cells (Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), 2015), but this occurs only in the case of very high exposures above 5000 V/m (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 1998). Electric fields are

Abbreviations: ELF, extremely low frequency; ELF-MF, extremely low frequency magnetic field; ELF-EF, extremely low frequency electric field; IF, intermediate frequency; IF-MF, intermediate frequency magnetic field; IF-EF, intermediate frequency electric field; EMF, electromagnetic field; INMA, Environment and childhood (from INfancia y Medio Ambiente) cohort; THD, total harmonic distortion; IARC, International Agency for Research on Cancer; RF, radiofrequency; WHO, World Health Organization; SCENIHR, Scientific Committee on Emerging and Newly Identified Health Risks; TWA, time-weighted average

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attenuated by most common building materials and objects whereas magnetic fields are able to penetrate such materials (Kheifets and Oksuzyan, 2008; Kheifets et al., 2010). Hence, electric fields from outdoor sources are weaker in indoor settings and exposure to ELF-EF inside buildings is mainly due to indoor sources such as electrical wiring and home appliances. Notably, electric fields are more complicated to measure and characterize, mainly due to their higher spatial variability and the fact that they are perturbed easily by any conducting material, which is possibly one of the reasons behind the scarcity of studies in this field.

The World Health Organization (WHO) categorizes electromagnetic fields of non-ionizing radiation (EMF-NIR) into three major groups apart from static fields (i.e., 0 Hz): ELF fields from > 0 to 300 Hz, intermediate frequency (IF) fields from 300 Hz to 10 MHz and radiofrequency (RF) fields from 10 MHz to 300 GHz (WHO, 2017). In the scientific literature, ELF is often used to refer to the frequencies ranging from > 0 Hz to 100 kHz, that is, partially overlapping with the aforementioned IF range. IF-emitting sources are not very common, although the number of electric devices using these frequencies has been on the rise over recent years and include, for example, induction hobs, liquid-crystal displays (LCDs), fluorescent lightning and some types of microwave ovens (Aerts et al., 2017). Some studies have described exposure levels from these sources and observed that, in close proximity, IF magnetic fields (IF-MF) may exceed reference levels (Christ et al., 2012; Alanko et al., 2011). Such high exposure levels are likely not representative of the average population or children's exposure levels. To the best of our knowledge, however, no studies have assessed IF exposure levels in general population settings under conditions of daily life (Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), 2015). Comprehensive exposure assessments are essential both for acquiring knowledge on current levels of exposures and for conducting future epidemiological studies. For this reason, and given the lack of data, characterization of children's exposure to ELF-EF and to IF-MF and IF electric fields (IF-EF) was identified as a priority by the WHO (2005, 2007, 2010) and by the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (2015).

This study was conducted within the INMA-Gipuzkoa (*Infancia y Medio Ambiente*– Environment and childhood) birth cohort (www.proyectoinma.com) (Guxens et al., 2012). The aim of the study presented here was to characterize the exposure to ELF-MF, ELF-EF, IF-MF and IF-EF in the settings where the children tend to spend most of their time, i.e., in homes, schools and public open spaces, namely, parks and urban squares (hereon "parks").

2. Methods

2.1. Study population

INMA-Gipuzkoa is part of the Spanish INMA birth cohort and is located in the Basque Country. The INMA cohorts have been described in detail elsewhere (Guxens et al., 2012).

In brief, the recruitment of mother-child pairs took place during the first antenatal visit (10–13 weeks of gestation) to the physician in the public referral hospital (Zumarraga hospital) between April 2006 and January 2008.

In total, 638 out of 993 mother-child pairs invited to participate met the inclusion criteria and were enrolled in the study. Over the period 2014–2016, when the children reached 8 years of age, cohort members were contacted; at that time, 397 children (62.2 %) participated in the study.

2.2. Study procedure

We performed ELF-MF, ELF-EF, IF-MF and IF-EF measurements in places where children tend to spend most of their time, specifically, in homes, schools and parks. Due to time constraints, home measurements were performed in the living room and child's bedroom of a subsample of 104 households. Participants for these measurements were selected primarily based on their availability, as nearly all cohort members contacted agreed to have measurements performed in their homes (386 of 397 contacted, 97.2%). Families who gave consent were randomly contacted when the children were 8 years ± 3 months to determine the date and time for the measurements. If the families were available (and not e.g. on holidays) and it was possible to arrange an appointment with the study assistant to make the measurements in their homes, they were carried out. All primary schools in the study area (n = 26) were included in our measurement survey, given that our children are distributed within those schools. In each school, in order to have an overall idea of the levels on the areas of the schools where our participants use to be, measurements were taken in two classrooms of INMA children as well as the main school playground. Classrooms with greater number of INMA students were selected in each grade (second and third year of primary school). All cohort members filled in a questionnaire that inquired, among other items, about the parks and other public spaces where the children spent most time. For that purpose, we provided them with a list of parks that they had mentioned during previous follow-ups and they were allowed to add other relevant parks to the list. From this full list of parks (125), 105 (84%), including those most frequently named by families, were selected for the measurements, since we assumed that these parks represented those where children were most likely to spend most of their time.

2.2.1. Measurement devices

We used two EHP-50D electric field and magnetic flux density isotropic probe analyzers for frequencies between 5 Hz and 100 kHz together with a NBM-550 Broadband Field Meter Basic Unit, all from Narda Safety Test Solutions (Germany). The three axes are measured simultaneously, resulting in true root-mean-square measurements, but magnetic flux density (further referred to as magnetic fields) and electric fields are measured in sequence. The device also offers the possibility of narrowband spectrum analysis, to allow the user to estimate the contribution from a selected frequency band to the total broadband measurement. The EHP-50D allows relatively long-term measurements, up to 24 h, in stand-alone mode and it also allows spot measurements when connected to the Basic Unit. The highest resolution of the probes was selected, i.e., 1 nT and 1 mV/m when measuring in stand-alone mode and 0.1 nT and 1 mV/m with the Basic Unit for the magnetic and electric fields respectively. The measurement range was from 0.3 nT to 100 μT and from 5 mV/m to 1 kV/m, for magnetic and electric fields for all measurements. Total expanded uncertainty of the probes has been described to be up to 8% for magnetic field and up to 15% for electric field (Aerts et al., 2017). The devices were calibrated by the manufacturer prior to the measurement survey. Post-survey calibration showed very little deviation in accuracy; up to 3% for the magnetic field and up to 7% for the electric field.

2.2.2. Measurement procedure

Measurements were made following the methodology detailed in a previous publication (Gallastegi et al., 2016). In brief, short-term spot magnetic and electric field measurements (32 consecutive readings) were carried out in homes, schools and parks. Spot measurements were made at the center and in the four corners of rooms (homes and school classrooms), at 1.10 m above the floor (considering the age and heights of the participants) and at 1.40 m (diagonally) from the corners, in order to capture variability of exposure across the room. Similar procedures have been previously suggested for ELF-MF fields (Hareuveny et al., 2011), as well as for RF-EMF fields (European Committee for Electrotechnical Standardization (CENELEC) European Standard EN 50492, 2008). Outdoor measurements were only taken in the center of the corresponding space (geographical center or center of the children's play area in the case of parks with playground equipment). We selected measurement bandwidths (spans) in order to cover the total measurement range of the device. The minimum starting frequency of each span is 5 Hz or 1.2% of the selected span, specifically, 100 Hz, 1 kHz and 100 kHz. In line with this, the 100 Hz setting measures the band from 5 to 100 Hz, the 1 kHz setting from 12 Hz to 1 kHz and the 100 kHz setting from 1.2 kHz to 100 kHz. Note that the last of these bandwidths falls into the IF range.

In addition, we performed longer-term measurements of ELF-MF, which consisted of 24-h measurements in homes and classrooms but just 20-min measurements in school playgrounds and parks, since the devices needed to be supervised outdoors and longer periods of supervision were not feasible with the available resources. In schools, the probe was placed in the center of each classroom, while in homes, probes were placed in the center of the living room during the day and in the center of the child's bedroom when the child went to bed. Given variability of bedtimes across children, this timing was not identical across our study participants (Median/IQR of hours that the device was placed in the living room was 13.4/13–14 h). In playgrounds and parks, the probe was placed in the center (as for spot measurements, in the geographical center or in the center of play area). The frequency spans when measuring in 24-h and 20-min modes differ from those when measuring spots using the hand-held Basic Unit. For 24-h and 20-min measurements, we selected the lowest possible span, which is 500 Hz (corresponding to the frequency band from 6 Hz to 500 Hz). Measurements were taken at 30-s intervals (lowest selectable measurement interval for stand-alone mode).

All measurements were conducted from Monday to Friday, although 24-h measurements in homes could include some hours of Saturday. Time of spot measurements at homes was variable, depending on the availability of the families, with preference to afternoon hours, usually when children would be at home. Given that our aim was to assess the levels of exposure to which children are usually exposed to, all measurements were taken under the conditions in which they normally are. Thus, in indoor settings, i.e. in homes and classrooms, the appliances were set as they would be when the children are there. According to the manufacturer, operating relative humidity was up to 95% and operating temperature of the probes ranged from −20 to +55 °C. All of our measurements were conducted under these conditions. Characteristics of the measurements that were carried out are summarized in Supplementary Table 1.

2.2.3. Data collection

Previous studies have found that type of area, type of building, number of floors and building year are relevant factors in magnetic field exposure (Magne et al., 2016; Schuz et al., 2000; Brix et al., 2001). Therefore, we collected data on these factors together with others that we considered that might affect exposure levels. A questionnaire completed by the parents was used to gather data on: characteristics of the building where they lived (floor number of the property, total number of floors in the building, type of dwelling [detached/semi-detached house, building with 2–8 apartments or building with more than 8 apartments], period when the building was completed [up to 1990 or more recently] and type of area [rural or urban]); number of adults and children living in the household; parks and other public spaces most frequently visited by the children; and mean time spent in each setting. In schools, teachers were asked whether televisions, computers, projectors and/or electronic whiteboards were regularly used in classrooms. We also requested information regarding proximity of our measurement sites to outdoor sources of EMF, such as power lines and transformers, from the energy distribution and generation companies operating in the area. Details of the information requested are provided in Supplementary Table 2.

2.2.4. Data handling and statistical analysis

We evaluated if our participants differed from the whole study collective in terms of relevant characteristics but no statistically significant differences were observed (Supplementary Table 3).

We calculated descriptive statistics for both spot magnetic and electric field and time- weighted average (TWA) (24-h and 20-min) ELF-MF measurements. Variations in ELF-MF over the day were explored in the settings with 24-h data (homes and school classrooms). We also calculated Spearman's correlation coefficients of spot ELF-MF with ELF-EF and IF-MF with IF-EF levels for measurements made in the same location (and not considering a mean value for the room). For approximately one third of the homes (n = 37, 36%), we only performed spot measurements of magnetic fields in the center of the rooms, rather than in the center and all four corners. Data from homes with complete information and homes with partial information were treated separately.

In addition, we checked whether any frequency ranges made a dominant contribution to overall IF-MF exposure. Mann-Whitney *U* and Kruskal-Wallis tests were performed to check differences between settings in exposure to ELF-MF (comparing outdoor and indoor settings) and ELF-EF (comparing homes, schools and parks) respectively.

Total harmonic distortion (THD) for ELF-MF was calculated for the main contributing harmonics (up to the sixth harmonic), using the 1 kHz frequency measurement range that included these harmonics.

We also explored potential explanatory variables for observed TWA ELF-MF exposures (over 24 h indoors and 20 min outdoors). For homes, we calculated Spearman's correlation coefficients between exposure and the following: the number of adults and children per household; floor of the property; and total number of floors in the building; and we performed non-parametric Mann-Whitney *U* tests for age of the building (completed up to 1990 or more recently) and type of dwelling (detached or semi-detached house, multiple storey building with 2–8 apartments or multiple storey building with more than 8 apartments). For school classrooms, Mann-Whitney *U* tests were performed to investigate potential associations between magnetic field exposures and use of televisions, computers, projectors and/or electronic whiteboards. In all settings (homes, schools and parks), presence or absence of outdoor EMF sources like transformers, substations and power lines within certain distance (specified in Supplementary Table 2) was explored with non-parametric Mann-Whitney *U* tests (comparing groups that did or did not have each source within a previously established distance) and Kruskal-Wallis tests (comparing groups classified by the number of sources of each type). P values below 0.05 were considered as statistically significant.

Finally, we calculated and compared estimated TWA based on home exposure only and based on all settings (homes, schools and parks) for magnetic and electric fields respectively. The Cohen's kappa coefficient was used to assess agreement between both approaches.

Data were analyzed with Stata (version 12; StataCorp, College Station, TX, USA).

3. Results

Between November 2014 and February 2016, we performed measurements in 104 homes, 26 schools and 105 parks. Descriptive statistics of the TWA ELF-MF exposure levels over 24 h for indoor settings and 20 min for outdoor settings are provided in Table 1 and in Supplementary Figure 1. The highest ELF-MF exposure detected among all mean exposure levels captured with 24-h measurements values was 0.145 μT in one home.

Hourly patterns of ELF-MF exposures showed slightly higher exposure in the evening in homes and during the day in school classrooms (Supplementary Figure 1), although differences were not very pronounced (Table 1). The highest mean ELF-MF hourly exposure was 0.19 μT in one home.

Data from spot measurements of ELF and IF magnetic and electric fields are summarized in Table 2. For magnetic field, mean levels of ELF and IF exposure ranged from 0.013 to 0.028 μT across the different settings and frequency ranges. Levels of ELF-MF exposure were slightly

Table 1
Descriptive statistics of the ELF magnetic field (longer-term measurements)[a,b].

	Homes (24 h) (μT)	School classrooms (24 h) (μT)	School playground (20 min) (μT)	Parks (20 min) (μT)
N	103[c]	52	26	105
Mean (SD)	0.019 (0.015)	0.017 (0.015)	0.015 (0.008)	0.018 (0.019)
GM (GSD)	0.016 (1.615)	0.015 (1.694)	0.013 (1.540)	0.014 (1.807)
Median (IQR)	0.014 (0.012–0.019)	0.012 (0.010–0.017)	0.011 (0.010–0.013)	0.012 (0.010–0.016)
P95	0.043	0.050	0.035	0.064
Minimum- Maximum	0.010–0.145	0.009–0.100	0.009–0.035	0.009–0.117
Mean day			–	–
08:00–16:59	0.019 (0.020)			
09:00–16:59[d]		0.018 (0.016)		
Mean evening			–	–
17:00–22:59[e]	0.020 (0.018)	0.017 (0.015)		
Mean night (23:00–07:59)	0.017 (0.014)	0.017 (0.017)	–	–

ELF: extremely low frequency; SD: standard deviation; GM: geometric mean; GSD: geometric standard deviation; IQR: interquartile range; P95: 95th percentile; We provide magnetic flux density values; Measurement range of the probe: from 0.3 nT to 100 μT.
[a] Measured frequency range was between 6 and 500 Hz and the device was used in stand-alone mode.
[b] Calculations have been made using the mean values obtained for the whole measurement time in each setting.
[c] One reading from a home was lost during recording process.
[d] These are approximately equivalent to the usual school hours in primary schools.
[e] For the school classrooms, the time period from 8 to 9 am is also included in this row, in order that the mean provides an idea of the exposure levels when there are no formal classes but people may also be working in the building

lower outdoors than indoors (Mann–Whitney *U* test p values were < 0.01 for 100 Hz and 1 kHz spans). Average levels of ELF-EF exposure varied between 1.495 and 10.106 V/m across the different settings. Lower levels were obtained for IF-EF, with average exposures from 0.376 to 0.453 V/m. The highest and lowest ELF-EF levels were found in homes and parks respectively (Kruskal-Wallis test p values were < 0.01 for 100 Hz and 1 kHz spans).

The correlation between magnetic and electric ELF fields based on spot measurements (average of 32 consecutive samples) was low (correlation coefficients ranging from 0.044 to 0.357 across the different settings and frequency ranges) but higher correlations were observed for IF fields (from 0.285 to 0.752) (Table 3).

No frequencies made a dominant contribution to exposure in any of the separate spans in the IF frequency range (data not shown).

Median THD (calculated up to the sixth harmonic) for all the settings combined was 0.45 and 0.11 for magnetic and electric fields respectively (Supplementary Table 4).

Most of the participants lived in buildings built after 1990 (59.8%). Regarding school classrooms, in 40% of them teachers reported whiteboard use (detailed information is provided in Supplementary Tables 3 and 5). Of all the explanatory variables considered, only building year of the home, use of electronic whiteboards at school and overhead power lines (30–13.2 kV) within 200 m from parks were associated with the ELF-MF exposure levels encountered (Supplementary Table 5). Homes built before 1990 were associated with somewhat higher magnetic field exposure over 24 h (mean ± sd/median: 0.019 ± 0.011/0.015 μT) than those built after 1990 (mean ± sd/median: 0.018 ± 0.019/0.013 μT) (p = 0.037). School classrooms in which electronic whiteboards were used regularly were associated with slightly higher magnetic field exposure over 24 h (mean ± sd/median: 0.019 ± 0.013/0.015 for schools that use whiteboards and 0.017 ± 0.017/0.012 for schools that do not use whiteboard; p = 0.047). The proportion of measurement sites with power lines and transformers are specified in Supplementary Table 2. We did not observe any clear differences in average ELF-MF exposures (24 h indoors and 20 min outdoors) as a function of the presence or absence of any of these sources in the vicinity of our measurement sites in homes and schools but we encountered higher exposure levels in parks with overhead power lines (30–13.2 kV) at a distance of 200 m (p = 0.018).

In this study, based on data obtained from the questionnaires, the children spent a median of 16 h at home, 5.5 h in school buildings, 1 h in school playgrounds and 1.5 h in parks. Use of this time pattern for the calculation of TWAs yields mean, median and 90th percentile values for the magnetic (calculated from 24-h or 20-min measurements data) and electric (calculated from 1 kHz span spot measurement data) fields of: 0.018, 0.015 and 0.025 μT and 7.56, 6.93 and 13.30 V/m respectively. If the children enrolled in our study would be classified regarding exposure in three groups (below median, between median and 90th percentile, and greater than or equal to the 90th percentile), there would be moderate (Cohen κ = 0.58) and substantial (Cohen κ = 0.76) agreement between their classification based on home exposure only and calculated TWA estimates based on all settings (homes, schools and parks) for magnetic and electric fields respectively (Supplementary Figure 2).

4. Discussion

We performed measurements of ELF and IF electric and magnetic fields in multiple settings where children tend to spend most of their time. The ELF-MF levels encountered were low (with IQRs for the different settings in a range from 0.01 to 0.03 μT) and similarly low MF levels were found in the IF range. IQRs of ELF-EF levels were between 1 and 15 V/m for indoor settings and between 0.3 and 1 V/m for outdoor settings, while IQRs of IF-EF levels ranged from 0.2 to 0.5 V/m. All exposure levels were well below national and international regulations (Spanish Royal Decree 1066/2001; Council of the European Union, 1999). The correlation between magnetic and electric field strength was generally weak (though moderate for IF outdoors). The THD was higher for magnetic fields (median; 38–52% between settings) than for electric fields (median; 5–19% between settings).

Strengths of our study include the characterization of exposure in places where children tend to spend most of their time. While several studies have investigated children's exposure to ELF-MF (Schuz et al., 2000; Struchen et al., 2015; Calvente et al., 2014; Liorni et al., 2016; Li et al., 2007; Lin et al., 2008; Deadman et al., 1999; Forssen et al., 2002; Valic et al., 2015), studies focused on electric field exposures, or exposures in the IF range are scarce.

Our measurement device (EHP-50D, Narda) (https://www.narda-sts.com/en/) was calibrated prior to the study, and it has lower quantification limit and a higher resolution than other devices frequently used in ELF-MF exposure surveys (quantification limits for magnetic field: 0.3 nT for EHP-50D and between 10 nT and 100 nT for other devices; quantification limits for electric fields: 0.005 V/m for EHP-50D and between 0.3 and 10 V/m for other devices (http://www.enertech.net/html/EMFMeasurements.html; http://www.wes-

Table 2
Spot measurements of magnetic and electric fields.

	N			Mean (SD)			GM (GSD)			Median (IQR)			P95		
	5–100 Hz	12 Hz-1 kHz	1.2–100 kHz	5–100 Hz	12 Hz-1 kHz	1.2–100 kHz	5–100 Hz	12 Hz-1 kHz	1.2–100 kHz	5–100 Hz	12 Hz–1 kHz	1.2–100 kHz	5–100 Hz	12 Hz-1 kHz	1.2–100 kHz
Magnetic field (μT)															
Homes															
Living room	99[a]	104	104	0.018 (0.018)	0.027 (0.202)	0.023 (0.000)	0.015 (1.731)	0.024 (1.494)	0.023 (1.018)	0.012 (0.010–0.017)	0.021 (0.020–0.025)	0.023 (0.022–0.023)	0.053	0.050	0.023
Only center	99	104	104	0.018 (0.018)	0.025 (0.019)	0.023 (0.001)	0.015 (1.731)	0.022 (1.484)	0.023 (1.039)	0.012 (0.010–0.017)	0.020 (0.018–0.023)	0.023 (0.022–0.023)	0.053	0.050	0.023
Corners		67	67		0.027 (0.019)	0.023 (0.000)		0.024 (1.464)	0.023 (1.016)		0.022 (0.019–0.025)	0.023 (0.022–0.023)		0.054	0.023
Child's bedroom	99[a]	104	104	0.017 (0.017)	0.025 (0.024)	0.023 (0.000)	0.014 (1.659)	0.022 (1.453)	0.023 (1.014)	0.011 (0.010–0.017)	0.020 (0.019–0.0229)	0.023 (0.022–0.023)	0.042	0.044	0.023
Only center	99	104	104	0.017 (0.017)	0.023 (0.015)	0.023 (0.000)	0.014 (1.659)	0.022 (1.372)	0.023 (1.017)	0.011 (0.010–0.017)	0.020 (0.018–0.023)	0.023 (0.022–0.023)	0.042	0.033	0.023
Corners		67	67		0.027 (0.032)	0.023 (0.000)		0.023 (1.542)	0.023 (1.013)		0.020 (0.019 −0.023)	0.023 (0.022–0.023)		0.058	0.023
School															
Rooms[b]	52	52	52	0.018 (0.018)	0.028 (0.020)	0.023 (0.000)	0.014 (1.707)	0.025 (1.556)	0.023 (1.012)	0.012 (0.010–0.017)	0.021 (0.019–0.026)	0.023 (0.023–0.023)	0.047	0.069	0.023
Playgrounds	26	26	26	0.013 (0.008)	0.021 (0.007)	0.023 (0.000)	0.012 (1.519)	0.021 (1.278)	0.023 (1.011)	0.011 (0.009–0.011)	0.019 (0.018–0.020)	0.023 (0.022–0.023)	0.032	0.041	0.023
Parks	104	67	103	0.017 (0.018)	0.023 (0.017)	0.022 (0.001)	0.013 (1.790)	0.020 (1.502)	0.022 (1.024)	0.010 (0.009–0.014)	0.018 (0.016–0.020)	0.022 (0.022–0.022)	0.051	0.057	0.023
Electric fields (V/m)[c]															
Homes															
Living room	65	104	104	6.901 (8.955)	8.891 (6.312)	0.376 (0.151)	3.758 (2.971)	6.762 (2.215)	0.353 (1.411)	3.196 (1.630–7.223)	7.646 (4.012–11.957)	0.360 (0.262–0.429)	30.256	22.125	0.585
Child's bedroom	65	104	104	8.643 (8.594)	10.106 (7.887)	0.385 (0.164)	4.881 (3.249)	7.179 (2.457)	0.361 (1.422)	5.942 (2.103–13.035)	7.886 (3.820–14.809)	0.371 (0.263–0.457)	27.285	25.030	0.593
School															
Rooms[b]	45	52	52	3.208 (3.251)	3.720 (3.102)	0.453 (0.287)	2.340 (2.166)	2.906 (1.964)	0.407 (11.515)	2.469 (1.154–3.746)	2.619 (1.939–4.398)	0.371 (0.354–0.447)	9.597	10.956	1.007
Playgrounds	26	26	26	3.682 (10.899)	3.781 (10.781)	0.389 (0.130)	1.194 (2.999)	1.376 (2.780)	0.373 (1.322)	0.867 (0.721–1.074)	0.999 (0.929–1.120)	0.388 (0.366–0.402)	11.156	11.210	0.428
Parks	68	67	68	1.495 (5.934)	1.656 (5.948)	0.282 (0.098)	0.610 (2.433)	0.815 (2.121)	0.268 (1.363)	0.584 (0.344–0.757)	0.709 (0.543–0.975)	0.216 (0.211–0.368)	3.722	3.769	0.419

SD: standard deviation; GM: geometric mean; GSD: geometric standard deviation; IQR: interquartile range; P95: 95th percentile; We provide magnetic flux density values; Measurement range of the probe: from 0.3 nT to 100 μT and from 5 mV/m to 1 kV/m, for magnetic and electric fields respectively.

[a] Five readings were missed.

[b] Calculations have been made based on rooms and not as a mean of school.

[c] There were some missing readings for the 100 Hz span of electric fields, mainly due to human errors.

Table 3
Correlation between electric and magnetic fields based on spot measurements.

	50 Hz	5–100 Hz	12 Hz-1 kHz		1.2–100 kHz	
	N[a] rho	rho	N[a]	rho	N[a]	rho
Homes	129 −0.059	−0.107	742	0.086	742	**0.724****
Living room	64 −0.044	−0.103	369	0.127	369	**0.743****
Child's bedroom	65 −0.074	−0.103	372	0.037	372	**0.705****
Schools						
Classrooms	45 −0.189	−0.229	260	0.077	259	**0.647****
Playgrounds	26 0.283	0.136	26	0.232	26	0.285
Parks	67 **0.268***	**0.288***	67	**0.357***	67	**0.752****

rho: Spearman's rank correlation coefficient.
All significant values are in bold.
[a] Calculations were based on individual spot measurements, which consisted of the average of 32 consecutive readings.
* p value < 0.05;
** p value < 0.001

tek.com.au/wp-content/uploads/2012/08/TAOMA-Brochure.pdf). Although we found very low exposure levels, we were always able to obtain readings above the quantification limit in all settings. In addition, since the device allows either broadband or narrowband measurements, it enabled us to check the contribution of specific frequencies in relation to other specific frequency bands, as we did for the THD calculation. Some studies researching ELF-MF have paid more attention to the fundamental frequency (50 Hz in Europe, 60 Hz in North America and Brazil)(Bowman, 2014) than to the harmonics and few studies have reported data on this matter (Bowman and Methner, 2000; Fiocchi et al., 2015; Khan and Silva, 2010; Preece et al., 1997). Nowadays, most modern electrical equipment use electronics for power regulation instead of transformers. As a consequence, the frequency content of the daily magnetic field exposure has changed mainly by adding odd harmonics (Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), 2015). Single-frequency emissions have become rare and simultaneous emissions of series of harmonics common, increasing the importance of spectrally-weighted measurements (Leitgeb et al., 2008). In the present study, IQRs of THD for magnetic and electric fields were 26–75% and 3–34% respectively, quite high compared to values reported by Bowman and Methner (2000) and Khan and Silva (2010), particularly given that the latter authors consider fields up to 400 kHz. For IF fields, we did not identify any dominant frequencies which is probably due to different sources that contribute different dominant frequencies (Aerts et al., 2017). Correlation between ELF-MF and ELF-EF was very low in our study, especially indoors, in line with previous assessments (Armstrong et al., 1990). This result emphasizes the relevance of measuring both types of fields separately, since it is not possible to predict one from the other.

Limitations of our study relate to the lack of longer-term measurements of outdoor magnetic fields (limited to 20-min measurements), and indoor and outdoor electric fields. Regarding 24-h measurements of ELF-MF, the ARIMMORA project found that a 24-h period was sufficient to validly characterize longer-term average exposure (Struchen et al., 2015). We measured ELF-MF for 24 h in each indoor location, but due to time and financial constraints, it was not feasible to make such measurements for ELF-EF or IF fields, and hence, we are unable to explore possible patterns in exposure to these fields over time. Nevertheless, in contrast to ELF-MF, ELF-EF do not arise from current flow, so should not depend on usage of appliances. In line with this, ELF-EF have previously been shown to vary little over 24 h (Skinner et al., 2002). We have no knowledge of the temporal variability of IF fields, given the lack of previous assessments accounting temporal variability of these fields in general population settings.

In addition, although we only conducted measurements on homes of a subsample of the cohort, no differences were observed between participants with measurements and the rest of the cohort members.

Concerning shielding elements, these can be relevant when assessing electric field strength. Although we did not collect information on those elements during the field work, measurements were not taken in close proximity to any element that could disturb the readings.

With regards to short-term spot measurements of MFs in homes, we only performed all measurements (in the center and four corners) in around two-thirds (64%) of cases, while in the other third (36%), we just took measurements in the center of each room. Based on homes with full measurements, however, Spearman's correlation coefficients between center and corner readings were high: 0.78 for the 1 kHz magnetic fields and 0.84 for the 100 kHz magnetic fields, and hence, center-only spot measurements can be considered a good proxy for average exposure in rooms (Table 2).

Unfortunately, data regarding exact location and characteristics of power lines or substations are not publicly available for our measurement area. While the local utility company kindly provided us with information regarding sources within a certain distance from our measurement sites, this information had relatively low spatial resolution and, in general, we were unable to assess whether the observed variation in exposure levels was associated with distance to these sources. In any case, there is already evidence that environmental sources only result in distinct differences in exposure when a strong source such as a high voltage power line or transformer is located very nearby (Struchen et al., 2015; Huss et al., 2013). We collected information on type of area, type of building, number of floors and building year based on the influence of these variables on magnetic field exposures in other studies (Magne et al., 2016; Schuz et al., 2000; Brix et al., 2001), but, among them, in this study we only detected significant differences by building year. Data on in-house presence and usage of appliances can be collected with questionnaires (Behrens et al., 2004), but exposure patterns display a very high spatial variability and therefore contributions of individual devices to exposure levels are difficult to capture. In addition, exposure from electric and household appliances may contribute less to children's exposure than environmental sources, given that exposure from household appliances is very localized, strongly depends on the distance (Thuróczy et al., 2011) and children usually do occasional use of these devices.

Overall, although there are a few ELF-MF exposure assessment studies, there is no standardized methodology for assessing ELF exposure and this hinders comparisons between studies. Even in our study, we conducted a combination of different types of measurements seeking to adequately characterize the exposure. Nevertheless, some general comparisons can be made, to facilitate the interpretation of our results.

The 24-h ELF-MF exposure levels we observed in homes and classrooms were low (Schuz et al., 2000; Struchen et al., 2015; Huang et al., 2013) or very low (Calvente et al., 2014) compared to those found in other studies. Tomitsch et al. (2010) also reported very low exposures (a mean value of 0.06 μT at night, with bedroom measurements from 10 pm to 6 am), though they found exposures exceeding 0.1 μT in 2.3% of homes. Low exposures have also been found in France (24-h personal measurements, 40–800 Hz) and Germany (fixed 24-h measurements in homes, 50 Hz), similar to ours (mean and median 0.09 and 0.02 μT in France and 0.046 and 0.031 μT in Germany) (Magne et al., 2016; Schuz et al., 2000). In addition, in the French and German studies with samples of 977 children and 1314 homes respectively, 86.4% and 91.4% of measurements were below 0.1 μT. With regard to ELF-EFs, we found higher exposure levels and higher spatial variability in homes than parks. ELF-EF median values in our spans were higher than those reported by Calvente et al. (2014) in homes (median value 3.7 V m^{-1} for 15 Hz–100 kHz bandwidth) and Huang et al. (2013) in schools (median value 0.15 V m-1 for 50 Hz frequency). Our EF levels are close to those of Huang et al. for IFs, but, on the other hand, they provide results combined for indoors and outdoors. Higher indoor ELF-EF were observed in a study performed in Austria (Tomitsch and

Dechant, 2015).

Overall, we are aware of only few studies that have performed spot measurements or longer-term exposure measurements outdoors (Paniagua et al., 2004; Lindgren et al., 2001; d'Amore et al., 2001; Straume et al., 2008) or in schools (Lin et al., 2008; Huang et al., 2013; Tardon et al., 2002; Farag et al., 2003; Alonso et al., 2012), and among them only three included measurements in school playgrounds. Previous studies providing outdoor data found higher ELF-MF levels than we did with average exposures ranging from 0.11 µT in Spain (40–400 Hz bandwidth) to 0.90 µT in Sweden during winter (40–800 Hz bandwidth), both one order of magnitude larger than our results, and we do not have a clear explanation for this observed difference. In contrast, our exposures were similar to those reported from school playgrounds in Oviedo (mean of 0.016 µT and median of 0.012 µT at 50 Hz) and Valladolid (5 Hz-100 kHz bandwidth, mean of 0.280 µT) but lower than exposures observed in Barcelona (mean of 0.034 µT and median of 0.007 µT at 50 Hz), all in Spain (Tardon et al., 2002; Alonso et al., 2012).

There is limited knowledge regarding typical levels of exposure to electric fields, especially in the IF range (Gajsek et al., 2016; Litvak et al., 2002). In general, our measured IF-MF and IF-EF field levels were very similar across the different settings, including playgrounds and parks, which would be expected to be further away from any potential sources like induction hobs, antitheft alarms, computer screens or compact fluorescent lighting. Our parks were in relatively close proximity to buildings, as parks were usually in squares located in residential areas, and this could possibly explain why we found some low-level and similar exposures in these settings to those found indoors. Nevertheless, it is worth noting that the selected frequency band (1.2–100 kHz) covers only a part of the total IF bandwidth. In addition, when conducting the measurements, we set all the appliances to "normal use" and measurements were not taken close to them. A recent study assessed IF exposure in homes of volunteers (in the 1.2–100 kHz frequency band) and reported higher magnetic field levels (geometric mean: 0.063 µT) and similar electric field levels when the devices were switched off (geometric mean: 0.4 V/m when the devices were switched off) than us (Aerts et al., 2017). They performed measurements under two scenarios: with all the appliances switched off and with all of them switched on. They found differences (170%) for IF-EF exposure levels between both scenarios, while the emissions of IF-MF were similarly low under both conditions and considered as background. Based on their results, we would not expect to detect much more emissions of IF-MF indoors if we would have all appliances switched on and the differences between indoor and outdoor exposure would remain similar.

Overall, great efforts have been put into evaluating the contribution of various sources to magnetic field exposures to personal exposure levels. This is more complicated to perform for electric field exposures: since the human body perturbs electric fields, unperturbed personal measurements are not possible (WHO, 2007). We attempted to overcome this problem by performing spot measurements in many different settings, to allow the estimation of TWA exposures depending on location and time spent in each location by the children in our cohort. Based on our results, while assessing ELF-MF exposure from home measurements only without incorporating exposure received in other environments would lead to misclassification (Cohen $\kappa = 0.58$), performing just home measurements of ELF-EFs could be considered a reasonable proxy for children's overall exposure to ELF-EF (Cohen $\kappa = 0.76$).

All ELF-MF data presented in this study are considered background exposure, and the level is well below the threshold of 0.3–0.4 µT that has been associated with increased risks of childhood leukemia (Bailey and Wagner, 2008). We consider further research on ELF-EF and IF exposures necessary for future epidemiological studies. WHO has specifically called for further research on IF, given the lack of data on this frequency range (WHO, 2005, 2007, 2010).

5. Conclusions

We performed extensive measurements to characterize exposure to ELF and IF magnetic and electric fields in environments where children spend most of the day (homes, schools and parks). Children of INMA-Gipuzkoa cohort are exposed to very low levels of ELF-MFs, but similar ELF-EF levels to those reported in most published studies. Very low ELF-MF levels were observed in all settings, although slightly lower exposures were found in parks and playgrounds than homes and classrooms. Somewhat higher exposures occurred at home and during the evening. ELF-EF levels were higher in homes and lower in parks. We also present data on IF exposure levels, but the lack of previous assessments of this frequency range means that there is barely equivalent data with which to compare our results. Interestingly, exposure levels of IF were similar in all settings. With the introduction of further appliances using IF, it may be relevant to explore the contribution of IF to overall EMF exposure in the future and to assess potential health effects of that exposure.

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Ethical declaration

Prior to children's inclusion in the study, their legal guardians provided written informed consent. The research has been performed in accordance with the Spanish Law 14/2007 on Biomedical Research and the ethical principles of the Declaration of Helsinki. This work has been approved by the ethical committee of the Basque Country (CEIC-E).

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http://www.proyectoinma.org/cohorts/gipuzkoa/en_membres-gipuzkoa.html

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2017.05.027.

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