# Spatial and temporal variability of personal environmental exposure to radio frequency electromagnetic fields in children in Europe

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## Abstract

**Background:** Exposure to radiofrequency electromagnetic fields (RF-EMF) has rapidly increased and little is known about exposure levels in children. This study describes personal RF-EMF environmental exposure levels from handheld devices and fixed site transmitters in European children, the determinants of this, and the day-to-day and year-to-year repeatability of these exposure levels.

**Methods:** Personal environmental RF-EMF exposure ($\mu W/m^2$, power flux density) was measured in 529 children (ages 8-18 years) in Denmark, the Netherlands, Slovenia, Switzerland, and Spain using personal portable exposure meters for a period of up to three days  between 2014-2016, and repeated in a subsample of 28 children one year later. The meters captured 16 frequency bands every four seconds and incorporated a GPS. Activity diaries and questionnaires were used to collect children's location, use of handheld devices, and presence of indoor RF-EMF sources. Six general frequency bands were defined: total, digital enhanced cordless telecommunications (DECT), television and radio antennas (broadcast), mobile phones (uplink), mobile phone base stations (downlink), and Wireless Fidelity (WiFi). We used adjusted mixed effects models with region random effects to estimate associations of handheld device use habits and indoor RF-EMF sources with personal RF-EMF exposure. Day-to-day and year-to-year repeatability of personal RF-EMF exposure were calculated through intraclass correlations (ICC).

**Results:** Median total personal RF-EMF exposure was 75.5$\mu W/m^2$. Downlink was the largest contributor to total exposure (median: 27.2$\mu W/m^2$) followed by broadcast (9.9$\mu W/m^2$). Exposure from uplink (4.7$\mu W/m^2$) was lower. WiFi and DECT contributed very little to exposure levels. Exposure was higher during day (94.2$\mu W/m^2$) than night (23.0$\mu W/m^2$), and slightly higher during weekends than weekdays, although varying across regions. Median exposures were highest while children were outside (157.0$\mu W/m^2$) or traveling (171.3μW/$m^2$), and much lower at home (33.0μW/$m^2$) or in school (35.1μW/$m^2$). Children living in urban environments had higher exposure than children in rural environments. Older children and users of mobile phones had higher uplink exposure but not total exposure, compared to younger children and those that did not use mobile phones. Day-to-day repeatability was moderate to high for most of the general frequency bands (ICCs between 0.43 and 0.85), as well as for total, broadcast, and downlink for the year-to-year repeatability (ICCs between 0.49 and 0.80) in a small subsample.

**Conclusion:** The largest contributors to total personal environmental RF-EMF exposure were downlink and broadcast, and these exposures showed high repeatability. Urbanicity was the most important determinant of total exposure and mobile phone use was the most important determinant of uplink exposure. It is important to continue evaluating RF-EMF exposure in children as device use habits, exposure levels, and main contributing sources may change.

**Keywords:** Cell Phones, Children's Health, Electromagnetic Fields, Radio Waves, Smart Phones, Wireless Technology

## 1. Introduction

Over the past thirty years, new mobile communication technologies such as mobile phones and their base stations, Wireless Fidelity (WiFi) access points, among others, have been developed and continue to rapidly evolve. These mobile technologies represent the main source of exposure to radio frequency electromagnetic fields (RF-EMF) in the general population (1). As these sources grow more numerous every day, researchers continue to evaluate the safety of human exposure to RF-EMF, encouraging caution and emphasizing the need for further research (2–6). Several European studies have attempted to characterize the quantity and variability of exposure to RF-EMF in the general population and found exposures to be consistently far below recommended limits (7–13). Nevertheless, the public and scientific communities remain concerned about exposure to RF-EMF, particularly in children (14–18). First of all, there is concern that children today are exposed to more RF-EMF than ever before and that this accumulated exposure over a lifetime could lead to adverse outcomes which have not yet been evaluated (17–20). Secondly, there is concern that exposure to RF-EMF at a young age, while organs and the brain are rapidly developing, could lead to adverse health effects in childhood or later in life (21). Therefore studies characterizing RF-EMF exposure in children have been identified as high priority by the World Health Organization (1).

Some studies have attempted to characterize RF-EMF exposure in children from fixed site transmitters (such as mobile phone base stations or broadcast antennas) through geospatial modeling (22–26). Other studies have used exposure meters and questionnaire data to characterize children's exposure from handheld devices (such as mobile phone or tablet) and indoor sources (cordless phone base stations or WiFi) (12,27–31). These studies have found that variations and quantity of exposure to RF-EMF can depend on many complex factors, and solely geospatial modeling or only extrapolating exposure from questionnaire data cannot accurately capture RF-EMF exposure (32,33). Personal exposure meters are considered one of the most accurate tools in assessing environmental personal exposure, allowing researchers to capture different sources of exposure, evaluate how this exposure varies over time, and validate exposure prediction models (32–35). While methods for assessing personal RF-EMF exposure continue to evolve, so do communication technologies and children's habits for using them; therefore it is necessary to continue evaluating this exposure with the newest technologies through personal measurement studies to better understand this exposure today and in the future in children. With the ever-increasing use of mobile communication devices in the general population, and with the age of first use dropping every year, it is critical to closely evaluate RF-EMF exposure in children.

In this study, we examined levels and sources of personal environmental RF-EMF exposure, as well as its determinants, including individual characteristics, handheld device use, and presence of residential indoor RF-EMF sources, over a period of up to three days in more than 500 children spanning ages 8-18 in five European countries using personal exposure meters between 2014 and 2016. We also assessed the day-to-day repeatability of these measurements in the whole sample and year-to-year repeatability in a smaller subsample whose measurements were collected twice in the same children, one year apart.

# 2. Methods

## 2.1 Study design and population

As part of three European projects to identify, describe, and assess health effects of exposure to RF-EMF in children (36–39), personal environmental RF-EMF exposure measurements were collected over a period of up to three days for 567 children, ages 8-18 years old, in Denmark, the Netherlands, Slovenia, Switzerland, and five regions of Spain (Gipuzkoa, Granada, Menorca, Sabadell, and Valencia). For 30 children that participated in the first round of measurements in Sabadell, Spain, measurements were repeated one year later in the same children. A standardized protocol was followed in all regions (32).

In Denmark, the Netherlands, and Spain, children were randomly recruited for participation during follow-up visits in the local population-based prospective birth cohort. These were: the Danish National Birth Cohort (DNBC) (40), the Amsterdam Born Children and their Development Study (ABCD) (41), and the Spanish Environment and Childhood Project (INMA) (42), respectively. In Slovenia, participants were recruited by direct invitation or public announcements (via website or advertisements in local media). In Switzerland, a little more than half of the participants were recruited from the Swiss prospective cohort study, Health Effects Related to Mobile phonE use in adolescentS (HERMES) (31,43,44). The rest of Switzerland's participants were recruited randomly from 10 communities of the canton Zurich within the framework of the ZuMe exposure study (45). Informed consent was obtained from all participants' parents or guardians, or the children themselves, in accordance with each center's institutional review board or ethics committee.

### 2.2 Personal environmental RF-EMF exposure measurements

Personal environmental exposure measurements to RF-EMF in the 87.5 MHz–6 GHz range (the frequency range of greatest concern for mobile communication technology) were collected using personal portable exposure meters, or "exposimeters" (ExpoM-RF, Fields At Work, Zurich, Switzerland) (46) between August 2014 and February 2016, depending on the region. The exposimeters weighed approximately 320 grams; dimensions were 16 x 8 x 4 cm. The exposimeters were calibrated in Switzerland in August 2014, then in February and August 2015. Exposimeters used in this study measured personal environmental exposure to 16 different frequency bands, corresponding to various sources of RF-EMF (Supplementary Table S1), with a measurement interval of four seconds. We defined six general frequency bands: total, digital enhanced cordless telecommunications (DECT), television and radio antennas (broadcast), mobile phones (uplink), mobile phone base stations (downlink), and WiFi (Supplementary Table S1). Total referred to all measured frequency bands except Mobile 3.5 GHz and ISM 5.8 GHz / U/NII 1/2e (both rarely used frequencies for mobile phones and WiFi, respectively) because of crosstalk concerns with other bands (where power emitted in one frequency band is measured and reported in another band (31)), as their inclusion would overestimate the total exposure. When the ExpoM was charging, the battery cable acted as an antenna, resulting in an overestimation of FM radio exposure. This was corrected by replacing these measurements with the median exposure values obtained under the same conditions, i.e. when the exposimeter was at home, but not charging. Crosstalk within the DECT frequency band was corrected using a self-developed algorithm (48). The correction algorithm identified crosstalk by searching for periods of increased correlations between Mobile 1800 MHz and downlink and DECT bands and between Mobile 2100 MHz uplink and DECT bands. Depending on the direction of cross-talk (Mobile -> DECT or DECT-> Mobile) the affected band's recorded values were replaced with the median value of exposure in said band while no crosstalk was found and while the same activity category was entered.

During the measurement period, children were instructed to behave as they normally would. Children wore the exposimeter for up to three consecutive days (up to 72 hours), with the device placed in a padded belt bag. Children were instructed to wear the bag around the waist when possible during the day, while some older children carried the device in a backpack. When situated somewhere for long periods (e.g. at home or school) or at night, children were instructed to place the exposimeter on a flat non-metallic surface (e.g. on a table) close by. The exposimeters had a global positioning system (GPS), which provided data on the location of the participant at all times. Parents of participants or in some cases children themselves also completed an activity diary using a smartphone operating in flight-mode. The diary asked parents or children to indicate detailed microenvironment information including presence in home (indoors or outdoors), school (the classroom, cafeteria, or playground) transport (via train, metro, tram, bus, or car), outdoor activity (stationary, walking, on bike, or on scooter), or other (theater, restaurant, shopping, gym, home of friend, or other). Questionnaires regarding individual characteristics as well as handheld device use and presence of residential indoor RF-EMF sources during the measurement period were also collected at the end of the measurements (variables and categories are listed in Table 1).

### 2.3 Statistical analysis

Diaries with implausible chronologies (e.g. changing locations from home to school without documented travel) were identified using R Statistical Software (49), then manually cleaned and corrected using the GPS coordinates and visualization of paths and measurements corresponding to diary entries. Briefly, inconsistencies between the GPS and diary information were automatically flagged by detecting violations of several "logical" rules. For example, inconsistencies were flagged if no travel activity was reported between "home" and "work", or between "home" and "school"; if the participant reported being at home while the GPS showed a geographical distance of more than 50m away from the home; if a participant travelled on foot or by bicycle/moped at speeds exceeding 70km/hour. If necessary, flagged violations of the logical rules were manually corrected by a study assistant tracing the GPS path on a map, and merged with the exposure measurement information. A participant was excluded if the diary had no information on activity, location, and microenvironment (n=21.4%). All calculations were performed in power flux density unit ($\mu W/m^2$). Statistical analyses were carried out using STATA version 14 (StataCorp, College Station, TX, USA).

The exposimeters reported values below or above the quantification limit (Table S1) specified by the developer. We censored values above the upper boundary (5 V/m or 3 V/m) and we replaced values below half of the lower quantification limit with half of the quantification limit.

We used time weighted average (TWA) calculations to estimate RF-EMF exposure in each general frequency band over the whole measurement period, by diurnal period, and by weekday and weekend day. This procedure was chosen in order to account for different durations of measurement periods and for interruptions in the measurements due to participants forgetting to charge the device or due to some device failures. We first created 8 time slots during daytime (every two hours between 6:00 and 22:00) and 1 time slot for nighttime (22:01-05:59). For each participant, we averaged the exposure of each timeslot. A time slot was considered incomplete and not taken into account if less than 30% of the data was available for that time slot. The cutoff of 30% was chosen to approximately reflect at least one full day of measurements. Mean exposure of the whole measurement period was calculated as TWA of all completed time slots. Mean exposure during the day was calculated as TWA of the 8 daytime slots and mean exposure during the night was the average exposure of the single nighttime slot. Mean exposure by weekday and by weekend day was calculated as TWA of all time slots of the corresponding days (i.e. from Monday to Friday and from Saturday to Sunday, respectively). Participants were excluded if less than 24 hours were recorded, the nighttime slot was incomplete, or 2 daytime slots were incomplete (n=17.3% of total sample). These participants were excluded because the short measurement period collected could possibly misrepresent the participant's personal environmental exposure. In addition, we used arithmetic mean values to estimate RF-EMF exposure to each general frequency band in each microenvironment.

To describe RF-EMF exposure from general frequency bands over the whole measurement period by region, by diurnal period, by day of the week, by microenvironment, and by types of travel we calculated median exposures, as well as other summary statistics. Our main descriptive analysis focused on the median of the TWA exposure distributions as a measure of central tendency due the approximately log-normal distribution of exposure levels in each region. We calculated the average contribution (%) of each general frequency band to the total exposure in each region and in the whole sample using median exposures. We also calculated the contribution (%) of total exposure in each microenvironment to the total exposure over the whole measurement period.

Associations of individual characteristics and device use habits with log-transformed individual RF-EMF exposures to each general frequency band were estimated using mixed models with random region effects. Geometric mean ratios and 95% confidence intervals were calculated. Models between individual characteristics and log-transformed exposures were unadjusted wanted to explore differences between individual characteristics, inherently representing differences in behavior and device use. Models between device use habits and log-transformed exposures were adjusted for individual characteristics as we hypothesized they could be potential confounding variables on the studied associations. Models were calculated without interactions. See supplementary materials for detailed descriptions of models (Tables S2 and S3).

To assess day-to-day repeatability, we calculated intraclass correlations (ICC) of log-transformed RF-EMF exposure to each general frequency band and of total exposure by diurnal period between two consecutive 24 hour period by weekdays and weekend days separately. To assess repeatability over a year, we calculated ICC of log-transformed RF-EMF exposure values to each general frequency band and of total exposure by diurnal period over two 24 hour periods one year apart taking the same type of day (weekday or weekend day). We also compared device use habits of these participants between both years using student's t-test or chi-square test, where applicable.

We performed two sensitivity analyses: i) to discern if exposure measurements differed among children that carried the exposimeter in a handbag or backpack instead of on the body, we repeated the analysis of total exposure in each region but stratified by where the child carried the exposimeter; and ii) to explore the regional exposure contributions of two frequencies that were excluded from the main analysis due to crosstalk concerns (Mobile 3.5 GHz and ISM 5.8 GHz), we compared the medians of TWA total exposure with and without these two frequency bands (separately by region).

## 3. Results

A total of 529 (n=93.3% of those recruited) child participants had valid measurements for the whole measurement period (between 24 and 72 hours). Children carried the exposimeter for an average of 62 hours each (SD 16.3 hours). The youngest children were in Gipuzkoa (8 years old), with the oldest children in Menorca (18 years old) (Table 1). Children were living mostly in urban environments, except in Denmark, Switzerland, Gipuzkoa, and Valencia where most children lived in suburban or rural environments. While device use habits varied by region, we summarize these habits for the whole sample (for region specific use habits, please see Table 1). Three-quarters of children reported using a mobile phone at least once a week, though this and all other handheld device use habits varied by region. Most children reported few phone calls (<2 calls per day) or short call duration (≤5 minutes per call) in all regions. Participants were generally more likely to use internet on phone than make calls, with overall 37% reporting internet use on mobile phone for more than 30 minutes a day. Only 10% of children overall reported SMS messaging more than 5 times a day. Children were more likely to send messages via messaging apps with overall 34% sending more than 10 messages a day.

Median total personal environmental RF-EMF exposure was 75.5 μW/m² (Table 2, Supplementary Table S4). Children in the Spanish regions of Granada and Sabadell had the highest median total exposure, and children in Switzerland had the lowest. Exposure from downlink contributed most to the total exposure (median of 27.2 $\mu$W/m$^2$) followed by broadcast (median of 9.9 $\mu$W/m$^2$) for most of the regions, except in Gipuzkoa and Granada where exposure was highest from broadcast, and in Switzerland where downlink, broadcast, and uplink contributed almost equally (Table 2, Figure 1). Overall, exposure from uplink contributed to only a median of 4.7 $\mu$W/m$^2$. WiFi and DECT contributed very little to exposure consistently across regions. Within exposure to general frequency bands, FM radio contributed most to broadcast, while Mobile 900 MHz frequency contributed most to uplink and downlink (Supplementary Table S4). This was consistent across regions (data not shown).

In all regions, the median total exposure was higher during the day (94.2 $\mu$W/m$^2$ versus 23.0 $\mu$W/m$^2$ during night) (Table 3). The median total exposure was slightly higher during weekdays compared to weekends in Denmark, Slovenia, Switzerland, Granada, and Menorca, but slightly higher overall during weekends for the whole sample (78.9 $\mu$W/m$^2$ during weekends versus 72.0 $\mu$W/m$^2$ during weekdays). Median exposures were highest while children were outside (157.0 $\mu$W/m$^2$) or traveling (171.3 $\mu$W/m$^2$), and much lower at home (33.0 $\mu$W/m$^2$) or in school (35.1 $\mu$W/m$^2$). This was consistent across regions except in Granada where median total exposure was higher at home and in school (125.5 $\mu$W/m$^2$ and 268 $\mu$W/m$^2$, respectively). Total exposure at home contributed most to the total exposure over the measurement period (Supplementary Figure S1). Within microenvironments, broadcast, uplink, and downlink exposures were higher while children were traveling (Supplementary Table S5).

Older children had higher uplink and WiFi exposures, but lower DECT and broadcast exposures (Table 4). Girls were more likely than boys to have higher uplink exposures. Children living in urban environments had higher total, DECT, and downlink exposures in comparison with children living in rural environments. Children whose parents had higher education were likely to have lower total and uplink exposures. Number of people living in home was not associated with exposure to any frequency band.

Handheld device use habits were not associated with total exposure (Table 5). Having a DECT phone in the home was associated with higher DECT and broadcast exposure. All handheld device use habits related to mobile phones (use of MP, use of smartphone, any MP call frequency and duration, any internet use on MP, SMS frequency of 1-5 messages per day, any app-based messaging, and MP turned on in the bedroom at night) were associated with higher uplink exposure. Use of a smartphone and intermediate levels of internet use (1-30 minutes/day) or app-based messaging (1-10 messages/day) were also associated with higher downlink exposure, while children that reported tablet use had lower downlink exposure. Highest levels of internet use (>30 minutes/day) or app-based messaging (>10 messages/day) on phone as well as having the phone turned on at night inside the bedroom were associated with higher WiFi exposure.

For day-to-day repeatability among weekdays, we observed an ICC of 0.57 for total exposure (Table 6, Supplementary Figure S2A). DECT and broadcast exposures showed a higher ICC (0.72 and 0.74, respectively). Uplink exposure had the most day-to-day variability (ICC 0.26). We also observed a higher ICC for total exposure at night (0.85) than during the day (0.42). Similar results were found for day-to-day variability among weekend days (Table 6, Supplementary Figure S2B).

Of the 30 children from Sabadell, Spain in the repeat subsample, 28 had valid repeated measurements one year later. Regarding year-to-year repeatability among weekdays, we observed an ICC of 0.49 for total exposure (Table 7). We plotted day-to-day and year-to-year total exposure on a log scale using scatterplots. (Supplementary Figure S2C). Broadcast exposure was the most stable over one year (ICC, 0.71), while uplink and WiFi had the most variation (ICC 0.11 and 0.12, respectively). We also observed a higher ICC of total exposure at night (0.76) than during the day (0.39). Similar results were found for year-to-year repeatability among weekend days (Table 7, Supplementary Figure S2D). Among the participants of this repeatability sub-study, handheld device use slightly increased over a year, mainly through internet use on mobile phone (Supplementary Table S6).

In sensitivity analyses, we found no important differences in exposure between children that carried the exposimeter in a handbag or backpack or those that carried it on the body (data not shown). Medians of TWA total exposure with two frequencies that were excluded from the main analysis due to crosstalk concerns (Mobile 3.5 GHz and ISM 5.8 GHz) did not differ significantly from the main analysis (data not shown).

## 4. Discussion

In this study, we closely examined the levels, sources, and individual determinants of personal environmental RF-EMF exposure over a period of up to three days in more than 500 children between 8 and 18 years old in five European countries. We also evaluated the day-to-day repeatability of this exposure in the whole sample and year-to-year repeatability in a smaller subsample. Main contributors to personal RF-EMF exposure were downlink followed by broadcast. Uplink contributed less to exposure, except in Switzerland where broadcast, uplink, and downlink contributed almost equally. DECT and WiFi contributed very little to exposure. Individual characteristics, such as age and sex of child, urbanicity of home, and highest level of parent education, were associated with exposure in general frequency bands. Handheld device use habits were associated with uplink exposures. Most personal environmental RF-EMF day-to-day exposures were consistent within weekdays as well as within weekend days. Total exposure, downlink, and broadcast for the year-to-year exposures were also consistent. Personal environmental RF-EMF exposures to uplink, DECT, and WiFi were less consistent one year later which might be due to changes in device use habits. Personal environmental RF-EMF exposures in our study were much lower than International Commission on Non-Ionizing Radiation Protection (ICINIRP) reference levels (between 4,500 and 10,000 μW/m² depending on the frequency band) (50).

Our study has some important strengths, including its sample size and wide age range across five countries, and the harmonized and detailed information regarding individual characteristics as well as handheld device use habits. To date, this is the first study to collect RF-EMF exposure data from children of different ages simultaneously in different countries. Furthermore, with the use of mobile communication devices on the rise in the general population and with the age of first use lowering each year, it is critical that RF-EMF exposure in children be closely evaluated. Also, RF-EMF exposimeters are one of the best current tools for environmental personal RF-EMF exposure (31). Additionally, participants wore the measurement devices for up to three days, allowing for a description of environmental RF-EMF exposure in different microenvironments and all hours of the day. Furthermore, collected information on individual characteristics was prone to little reporting error, considering their permanence (age, sex, parent education, urbanicity, etc). Handheld device use habits and indoor RF-EMF sources were reported at the end of the three-day data collection period, therefore there was little risk for recall bias. Finally, our study was the first of its kind to examine consistency of this type of measurements in a small subsample one year later.

Our study also has several limitations. While exposimeters are one of the best current tools for capturing environmental personal RF-EMF exposure, the device cannot control for several measurement uncertainties. For quantification of measurement uncertainties, please see supplemental materials (Supplemental Table S7). Other uncertainties include body shielding (interference of measurements by the body) or crosstalk between neighboring frequency bands, where power emitted in one frequency band is measured and reported in another band (31,47). Body shielding was mostly relevant when participants moved around but less so when they placed the device on a flat surface close to them. Thus, we may have underestimated the difference between exposure at home and public transport (47). We were able to correct measurements for some crosstalk errors using a DECT correction algorithm (48), but we could not control for crosstalk from two frequency bands (Mobile 3.5 GHz and ISM 5.8 GHz / U/NII 1/2e) and had to exclude them from analysis. Excluding these frequency bands means that we might have marginally underestimated total exposure in all regions, but in a sensitivity analysis, we showed that including these bands did not change our main results. Furthermore, much of our population was recruited from population-based birth cohort studies, which sometimes do not accurately represent the general population (51). This would limit the external validity of our results. Our study details various exposure levels occurring in Europe in various populations. While we observed RF-EMF differences between regions in our sample, these might not be fully generalizable, as the possibility remains that their exposure does not represent the exposure in the general population. Also, some studies argue that exposimeters are not useful for accurately estimating RF-EMF exposure from own mobile phone use (32,33). While our measurements indicate downlink from fixed site transmitters to be the largest contributor to environmental exposure, it is likely that highest doses were received from uplink via sources close to body (handheld devices), such as a child holding a mobile phone next to the head during a call (31). Thus, our uplink measurements are roughly representing far-field exposure from mobile phones in the child's environment, and not representative of dose received to the head. Finally, while we collected detailed information on mobile device use habits, we did not collect information on how these habits varied during different hours of the day.

For total RF-EMF exposure, we observed higher exposure than in previous studies carried out in children in Germany, Slovenia, and Switzerland (29,31,52). However, we need to take into consideration that none of the previous studies used the same exposimeter that we used, not all previous studies measured the same frequency bands that we measured, and handheld device use habits as well as telecommunication infrastructure have since evolved. Therefore, it is difficult to compare results with previous studies. We found lower exposure to uplink than in the recent analysis of children in Switzerland (the German and Slovenian analyses did not measure uplink), but higher levels of downlink than all previous personal exposure studies in children (22). In the previous Swiss study (31), it was observed that uplink contributed most to exposure, which does not align with our findings in Switzerland or elsewhere. Our sample in Switzerland is generally comparable in age and mobile phone use habits to the previous Swiss study's sample (95% of our Swiss sample reporting mobile phone use, while 100% of previous Swiss sample reported having a mobile phone), however the previous Swiss sample consisted of children living in exclusively rural areas, while only one-third of our Swiss sample lived in rural areas (22). Therefore, the higher downlink exposure could be due to a more urban sample, as higher people density has been correlated with more downlink exposure in our results and elsewhere (11). In fact, in our Swiss sample, median downlink levels in rural areas were 6.0 $\mu W/m^2$, versus 23.7 $\mu W/m^2$ in urban areas (data not shown). Furthermore, it is possible that changing handheld device use habits or telecommunication systems over time contributed to the discrepancies in results. However the previous Swiss study did not report frequency of mobile phone calls or app-based messaging (22).

In most regions, we found that broadcast was the second largest contributor to exposure, and this general frequency band was largely composed of FM Radio frequency band. In previous studies of exposure in children, FM Radio frequency band was not measured. As other studies have found (29,31,52), contributions from DECT and WiFi were very low. However, means of DECT and WiFi were slightly higher than means found in the previous Swiss study (31). This could be due to several factors such as a more urban sample or different measurement devices.

We found that age and sex of child, urbanicity of home, and parent education were significant determinants of increased environmental total RF-EMF exposure levels. While it is likely that older children and girls were using mobile phones more, it is also possible they were physically surrounded by a higher concentration of mobile phone users (compared to children that did not use or less frequently used mobile phones). Both situations might explain the increased environmental uplink exposure (uplink geometric mean increase of 85%) in females vs. males and in older children (with the uplink geometric mean ratio increasing 20% with each year of age). Children living in urban environments experienced almost double the total exposure levels and three times the downlink exposure levels compared to children living in rural environments. This could be due to signal compensation for the built environment and high people density, given that more base stations are needed to support more users in a highly populated area. Children of parents with higher education were less exposed (data not shown). All handheld device use habits regarding mobile phone use were associated with increased exposure to uplink, as expected; though there were not associated with total exposure. While the previous Swiss analysis illustrated mobile phone use habits, limited to having the phone turned on at night or using internet on the phone, were associated with higher total RF-EMF exposure, the authors did not assess the strength of this relationship (31). Smartphone use and intermediate categories of internet use on phone and app-based messaging were associated with higher downlink exposure, perhaps indicative of mobile communication traffic in the child's environment. Having the phone turned on in the bedroom at night was also associated with higher WiFi exposure, which makes sense, considering the WiFi router would continue communicating with the mobile phone throughout the night, regardless of use.

Between weekday to weekday and weekend day to weekend day, we found that most measurements were consistent, except for uplink and WiFi. Uplink and WiFi measurements were not expected to be consistent, as RF-EMF emissions from these bands can vary depending on use of devices. Though collected within a small sample, our study was the first of its kind to assess repeatability of RF-EMF measurements one year later. These measurements in Spain demonstrated that year over year, downlink followed by broadcast were still the largest contributors to total RF-EMF, with DECT and WiFi contributing very little. Since broadcast and downlink measurements were consistent the following year, total measurements were also consistent. Uplink, DECT, and WiFi measurements were not similar one year later, which again was likely due to variations in device use habits. With today's constant changes in mobile communication devices and device use habits, it was surprising that total exposure did not vary significantly over one year. However, we suspect that comparing measurements perhaps several years apart would illustrate more significant changes in environmental RF-EMF exposures.

# 5. Conclusion

In this population sample, the most common sources of personal environmental RF-EMF exposure were downlink and broadcast and these exposures were consistent between days and one year later. Urbanicity was associated with higher total exposure. More frequent mobile phone use of any kind and longer mobile phone calls were associated with higher uplink exposure. It is important to continue evaluating RF-EMF exposure in children as device use habits, mobile devices, and mobile communication infrastructure continue to evolve.

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