Personal exposure to radio-frequency electromagnetic fields in Europe: is there a generation gap?

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Abbreviations:

RF-EMF: radio-frequency electromagnetic fields

DECT: Digital Enhanced Cordless Telecommunications

GSM: Global System for Mobile Communications

ICNIRP: International Commission on Non-Ionizing Radiation Protection

UMTS: Universal Mobile Telecommunication System

ABSTRACT

Background:

Exposure to radiofrequency electromagnetic fields (RF-EMF) from mobile communication technologies is changing rapidly. To characterize sources and associated variability, we studied the differences and correlations in exposure patterns between children aged 8 to 18 and their parents, over the course of the day, by age, by activity pattern, and for different metrics of exposure.

Methods:

Using portable RF-EMF measurement devices, we collected simultaneous real-time personal measurements of RF-EMF over 24 to 72 hours in 294 parent-child pairs from Denmark, the Netherlands, Slovenia, Switzerland, and Spain. The devices measured the power flux density (mW/m^2) in 16 different frequency bands every 4 seconds, and activity diary Apps kept by the participants were used to collect time-activity information in real-time. We analyzed their exposures by activity, for the different source constituents of exposure: downlink (radiation emitted from mobile phone base stations), uplink (transmission from phone to base station), broadcast, DECT (digital enhanced cordless telecommunications) and Wi-Fi. We looked at the correlations between parents and children overall, during day (06:00-22.00) and night (22:00-06:00) and while spending time at home.

Results

The mean of time-weighted average personal exposures was 0.16 mW/m^2 for children and 0.15 mW/m^2 for parents, on average predominantly originating from downlink sources (47% for children and 45% for parents), followed by uplink (18% and 27% respectively) and broadcast (25% and 19%). On average, exposure for downlink and uplink were highest during the day, and for Wi-Fi and DECT during the evening. Exposure during activities where most of the time is spent (home, school and work) was relatively low whereas exposure during travel and outside activities was higher. Exposure to uplink increased with age among young people, while DECT decreased slightly. Exposure to downlink, broadcast, and Wi-Fi showed no obvious trend with age. We found that exposure to total RF-EMF is correlated among children and their parents ($R_{spearman}$ = 0.45), especially while at home (0.62) and during the night (0.60). Correlations were higher for environmental sources such as downlink (0.57) and broadcast (0.62) than for usage-related exposures such as uplink (0.29).

Conclusion

The generation gap between children and their parents is mostly evident in uplink exposure, due to more and longer uplink and cordless phone calls among parents, and their tendency to spend slightly more time in activities with higher environmental RF-EMF exposure, such as travel. Despite these differences in personal behavior, exposure to RF-EMF is moderately correlated between children and their parents, especially exposures resulting from environmental RF-EMF sources.

Introduction

On a global scale, the ownership of mobile phones has rapidly increased, with most adults and adolescents in Europe now owning a smartphone(International Telecommunication Union 2017). Many people are concerned about exposure to radiofrequency electromagnetic fields (RF-EMF) from their environment and the possible implications for public health (Eurobarometer ; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans 2013). Concern is especially targeted at children and adolescents, because of their rapid early-life adoption and increased use of mobile technologies (Kheifetset al. 2005). In addition, it has been suggested that children typically suffer higher exposures to their brain regions than adults. (Christet al. 2010) Possible effects on cognitive ability, cancer incidence, non-specific symptoms and other outcomes have been suggested and challenged (Baanet al. ; Group 2010; Röösli and Hug 2011; van Deventeret al. 2011).

The World Health Organization puts high priority on the characterization of real-life exposure to electromagnetic fields (EMF) and its determinants (van Deventeret al. 2011). Personal measurements using exposimeters are considered to be a feasible and accurate method to gain a comprehensive picture of the complex mixture of real-life RF-EMF exposure (Röösliet al. 2010). Neither questionnaires nor propagation modelling are able to quantify objectively the band-specific level of exposures resulting from both environmental sources (mobile phone base stations, Wi-Fi access points, broadcast towers) as well as personal use (e.g. use of mobile and cordless phones). Several personal exposure surveys have been carried out in recent years, mostly in Europe(Bolte and Eikelboom 2012; Freiet al. 2009; Josephet al. 2010; Röösliet al. 2016; Roseret al. 2017; Thomaset al. 2008a; Thomaset al. 2008b; Vielet al. 2009) but also in other parts of the world(Choiet al. 2018), showing that exposure levels generally comply with recommended standards, but that they differ greatly between different microenvironments and activity patterns. This stresses the importance of taking into account time-activity to derive representative exposure estimates for the population.

Conclusions from previous personal surveys about exposure patterns are quickly outdated because of rapidly evolving mobile technologies (GSM; Global System for Mobile communications, UMTS; Universal Mobile Telecommunications System, LTE; Long-Term Evolution) and functionalities (video streaming, gaming, WhatsApp). Contemporary children grew up surrounded by these new technologies, readily adopting new functionalities. Meanwhile, their parents have typically attempted to enhance traditional functionality such as phone calls and text messages, with typically slower adoption of new functionalities (Prensky 2001). The combination of differences in time-activity patterns, age and early-age exposure to mobile technologies results in different user patterns of mobile technologies, and -hence- a different RF-EMF exposure pattern (Foerster and Röösli 2017; Sudanet al. 2016). Besides personal use of mobile technologies, other personal measurement campaigns have found that environmental RF-EFM exposure varies with the level of urbanicity (Bolte and Eikelboom 2012; Röösliet al. 2016; Thomaset al. 2008a; Thomaset al. 2008b; Vielet al. 2009), activity pattern or microenvironment (Bolte and Eikelboom 2012; Freiet al. 2009; Josephet al. 2010; Röösliet al. 2016; Roseret al. 2017; Sagaret al. 2017; Vielet al. 2009), time of day (Bolte and Eikelboom 2012; Freiet al. 2009; Roseret al. 2017; Thomaset al. 2008b; Vielet al. 2009), between males/females (Röösliet al. 2016) and with age (group) of the study participants (Bolte and Eikelboom 2012; Röösliet al. 2016; Thomaset al. 2008b; Vielet al. 2009). This has not previously been studied simultaneously in members of the same family.

As part of the GERoNiMO project (Generalized EMF Research using Novel Methods), we carried out a personal exposure survey among child-parent couples in five European countries (Switzerland, Slovenia, Spain, Denmark, and the Netherlands). We present some results by country, but emphasize that our main focus is on those exposure patterns which can be generalized to the whole sample. Exposure variability among children measured for the study in relation to personal characteristics and usage, was published separately (Birkset al. 2018). To better understand the determinants of the differences and similarities in exposure between children and their parents, this paper describes and compares the RF-EMF exposure levels and variability in children and their parents, in relation to their behavioural patterns and environments.

Methods

Study design

Exposure to RF-EMF was measured in five European countries: Switzerland, Slovenia, Spain, Denmark and the Netherlands. Dutch, Spanish and Danish children were recruited from the Amsterdam Born Children and Development study (ABCD) (Van Eijsdenet al. 2010), the Sabadell branch of the Spanish Environment and Childhood project (INMA) (Guxenset al. 2011) and the Danish National Birth Cohort in Copenhagen (Olsenet al. 2001). Slovenian children were recruited from the general population in Ljubljana through public announcements and direct invitation. Half of the Swiss children were recruited from the Health Effects Related to Mobile phonE use in adolescentS (HERMES) cohort in central, rural Switzerland (Roseret al. 2017; Schoeniet al. 2016; Schoeniet al. 2015) and the other half from cohort from 10 communities within the canton of Zurich(Röösliet al. 2016). Each country targeted recruitment of 50 child-parent pairs (Online Supplement 1), who were asked to carry an exposimeter for at least 24 hours, keep track of their activities over the same period and fill out a questionnaire on their use of mobile technologies. Sampling campaigns were conducted over six month periods in each region between September 2014 and February 2016. Participating regions used the same sampling protocols, equipment and procedures for calculating the exposure metrics. After each measuring campaign, the exposimeters were sent for calibration to ETH Zurich (Switzerland).

Exposure measurements

We used the ExpoM-RF personal radiofrequency exposimeter (Fields At Work, Zurich, Switzerland, http://www.fieldsatwork.ch/). The ExpoM-RF samples 16 different frequency bands in the range of FM radio (87.5-108 MHz) to ISM 5.8 GHz / U-NII 1-2e (5150-5875 MHz), allowing a detailed specification of the exposure from all major wireless communication and broadcasting services, see Online Supplement 2A. In addition, the ExpoM-RF has an integrated GPS logger. ExpoM-RFs were set to sampling continuously at an interval of 4 seconds.

When moving around, participants carried the ExpoM-RF in a padded pouch on their waist or inside their (school/work) bag to increase acceptance of wearing a personal exposimeter among children. When sitting down (in school, office or at home), the participants were asked to take the pouch out of their bag and put it near them in the room on a table to limit body shielding. During the night, the ExpoM-RF was charged and placed near the bed of the participant. All participants were instructed to place the exposimeter away from the own mobile phone and any metal objects, such as keys at all times, to limit reflection and shielding (Bolte 2016).

Time-activity diary

All participants entered their activities in real time on a provided study smartphone with a time-activity diary App, developed by Fields at Work. The App was available in all local languages of the study. The study phone was locked into flight mode for the entire duration of the measurements, so that it did not affect the exposure measurements. The activities were divided into six main categories, and several subcategories:

1) Travelling (subcategories: *on foot/by bicycle*, *train*, *metro*, *tram*, *bus*, *car*)
2) At home (subcategories: *house/apartment* or *garden/balcony/terrace*)
3) Outside
4) At school (subcategories: *classroom* or *canteen/elsewhere*)
5) At work (subcategories: *own office*, *other office/meeting room* or *canteen/elsewhere*)
6) Miscellaneous (subcategories: *cinema/theatre/concert*, *restaurant/café*, *sports centre/fitness room*, *at friends/relatives/acquaintances*, *shopping* or *other*)

Questionnaire

All participants were asked to fill out a short questionnaire about the frequency and intensity of their use of mobile technologies such as phones, laptops and tablets. In addition, the parents were asked about the building characteristics (e.g. number of floors, size of the household, number of rooms etc).

Recruitment

We aimed for an approximate 1:1 ratio between boys and girls and between fathers and mothers. However, the Danish birth cohort was restricted to include only mothers by design. To cover the full exposure range within each cohort, we selected study subjects from different geographical areas (e.g. from urban and rural areas, i.e. relatively high and low population and building density) and from different schools. Ethical approval was granted for all study areas prior to the start of the research, and informed consent was obtained from all participants.

Local field workers scheduled an instructional home visit at a time when both participating child and parent were at home. The measurements took place during regular school weeks (rather than holidays) and included at least one full weekday (Monday to Friday). During the instruction visit, questionnaires, exposure meters, and study smartphones were distributed, after which the child and parent simultaneously carried the ExpoM-RF for at least 24 hours. All materials were typically collected three days later by the study assistant. For the duration of the measurement period, all participants were asked to carry the exposimeters as instructed, and behave as they would normally.

Corrections and data cleaning

ExpoM-RF measurements which had a total duration of less than 24 hours on a weekday (Monday to Friday) were excluded from the analysis (four parents and three children). Only complete child-parent pairs were considered for the analysis, excluding a further 5 unpaired parents and five unpaired children. All measurements were converted from V/m to power density (mW/m^2) before further calculations. We also applied several corrections prior to analysing the data in the following order:

Diary correction

GPS data recorded by the ExpoM-RF were used to identify entries in the time-activity diary which were incomplete (e.g. participant forgot to log an activity), incorrect (e.g. the wrong activity was logged), or imprecise (e.g. the activity happened earlier or later than logged). This process is described in more detail elsewhere (Röösliet al. 2016). 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.

Correction of values above and below the dynamic range

The ExpoM-RF is calibrated for a wide range of exposure levels, which depends slightly on the frequency band (Online Supplement 2, TableS2A). However, very low and very high signal strengths are not well-quantifiable. Therefore, values below the lower quantitation limit of the dynamic range were set to half of this value (on the V/m scale) for all bands (reporting limit) in order to account for the slightly different detection limits (e.g. lowest registered number) between devices. Values above the upper quantitation limit of the dynamic range are set to this upper limit, following Roser et al.,2017.(Roseret al. 2017)

FM correction during charging of the device

When the ExpoM-RF is charging, the charging cord acts as an antenna, making the device more sensitive to the FM Radio band. The strength of the FM signal is therefore higher, and -if left uncorrected- would constitute a large part of total exposure. Since the strength of broadcast signals is rather constant in time and follows a (relatively) uniform spatial distribution within close distances, such as a home, the FM-value when charging (as registered by the device itself) was replaced by the median FM-value experienced at home while the device was not charging.

Cross-talk correction

Cross-talk – also called out-of-band-response – occurs when a signal in a specific frequency band is also unintentionally registered by another band. Bands which are close to each other on the frequency band spectrum, such as DECT, 1800MHz downlink and 2100MHz uplink, are prone to cross-talk. In order to correct for this “double counting” measurements, we developed a function which identifies periods of crosstalk in the time series, correcting the affected frequency band by assigning the median exposure level experienced during that same activity, thereby reducing DECT by around half (on average), and with minimal impact on 1800MHz downlink and 2100MHz uplink. Further details are provided in a separate publication (Eeftens Accepted, 2018) and the correction method is available as the R function “correct_crosstalk” within the free R package “EMFtools” (Eeftens 2017).

Data analyses

Frequency bands were grouped by source into downlink (Mobile downlink 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz, the signal from the base station to the mobile device), uplink (Mobile uplink 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz, the signal from the mobile device to the base station), broadcast (FM Radio and DVB-T), DECT (cordless phones), Wi-Fi (ISM 2.4 GHz) and total (all). WiMax and Wi-Fi5 (ISM 5.8 GHz) frequencies were excluded from the analysis because the bands are hardly used and are heavily affected by harmonic cross-talk from bands whose multiple frequency range is in this range, following earlier studies (Roseret al. 2017).

Exposure was calculated as a mean per diary activity, for day (06:00-22:00) and night (22:00-06:00), and per time slot for each participant, distinguishing nine slots (06:00-08:00, 08:00-10:00, 10:00-12:00, 12:00-14:00, 14:00-16:00, 16:00-18:00, 18:00-20:00, 20:00-22:00, and 22:00-06:00). Activities which were reported by fewer than 5 subjects, or which relied on less than 5 hours of data (for all participants combined) are not shown, because they show a high amount of noise and may not accurately represent the typical exposure during this activity (Röösliet al. 2010).

To summarize the entire exposure period for each participant, we calculated time weighted average (TWA) exposures by calculating the time-weighted average over each of these time slots. This was done to account for possible missing not-at-random data because of participants forgetting to charge the device in the evening (typically causing it to stop measuring during the night). Correlations were calculated between children's and parents' time-weighted average exposure over the whole day, and between mean day, night and while-at-home exposure.

All database compilations, corrections, and data management tasks were done in R (R Core Team). The R package ggplot2 was used to obtain the graphics. Correlations between children and parents were determined by frequency band, activity, and for the time at home, day (06:00-22:00), night (22:00-06:00), and total. We did not assume any shape for the dependence of exposure on age; instead trends were obtained by locally weighted regression (LOESS).

Supplementary analyses

Our main study population included children and their parents, with a "generational gap" in the age range measured. During the same study period (September 2014 - February 2016), we additionally recruited 31 young adults aged 20-35 from Switzerland (Röösliet al. 2016) and 221 children (with no adult counterpart) from different regions of Spain (Birkset al. 2018) who took measurements and kept a time-activity diary following the same protocol. In one additional analysis, we "bridged" the age gap by combining the 31 young adults with the 97 Swiss child/parent pairs from the main population in order to look at the full age range within Switzerland. In a second additional analysis, we combined the 294 children from the main study population with the additional 221 children from Spain to look at exposure by age among children.

Results

A total of 294 child-parent pairs (Switzerland, 97; Denmark, 45; Spain, 49; The Netherlands, 54; Slovenia, 49) completed the exposure survey, the time-activity diary, and the questionnaire, see Online Supplement 1 for details. The mean age of the children ranged between 9.5 years (standard deviation (SD) 0.6 years) in Spain to 15.4 years (SD = 1.3 years) in Denmark (Online Supplement 1). Among the children, boys and girls were roughly equally represented, but among the parents, fewer fathers participated than mothers in Spain, and the Netherlands, and only mothers were included in Denmark. Generally, the families taking part in the survey were well-educated, with few parents unemployed. Almost all parents owned mobile phones (98% on average for all countries), most of them owned a smartphone (89%). Mobile phone ownership among children was on average 83%, but was substantially lower in Spain (45%) and Slovenia (73%)which included younger children than in Switzerland (95%), Denmark (96%) and the Netherlands (94%). Among those who owned phones, most children owned smartphones (79%). Ownership of cordless phones differed considerably between countries: the vast majority of Swiss (91%) and Spanish (86%) families owned at least one, slightly fewer Dutch (76%) and Slovenian (69%) families, and only very few Danish families (27%).

The impact of the corrections on the measured values resulted in a less than 1% reduction for downlink, uplink and Wi-Fi (Online Supplement 2B). The corrections reduced broadcast and DECT bands by a median of 61% and 46% (respectively), consistent with previous studies (Eeftens Accepted, 2018). The charging correction affected the total, but the impact of the DECT correction on the total was very small. The broadcast bands were most impacted due to the charging correction, Time weighted average exposure was 0.15 mW/m² for parents and 0.16 mW/m² for children (Figure 1). Downlink exposure constituted the majority of these time-weighted average exposures (47% for children and 45% for parents), followed by uplink and broadcast. Wi-Fi and DECT only contributed marginally to time-weighted average exposures (Figure 1), these patterns were similar in all five countries which took part in the study (Online Supplement 3). Parents reported making more mobile phone calls and spending more time calling on their mobile phones and on cordless phones, and sending more SMS messages than children (Online Supplement 4). Patterns for WhatsApp, Viber, and iMessage messages and for surfing the Internet were less different between children and parents (Online Supplement 4). Children more frequently reported never using Internet messaging or surfing than parents, but they also more frequently reported the highest use categories: 25% of children reported sending over 20 WhatsApp/Viber/iMessage messages per day (against 11% for parents), and 30% of children spent more than 60 minutes per day surfing the Internet (against 18% for parents) (Online Supplement 4).

Exposure by activity in children and parents

Besides obvious differences in time activity patterns between parents and children (spending time at work versus school), we found that the average parent spent more time (4.6 hours) travelling, during which exposures are typically high, compared to 2.9 hours for children. The means of the subject-specific activity means are plotted in Figure 2A. Country-specific results are presented in Online Supplement 5. Exposure is typically low in the indoor environments where the participants spend most of their time: in schools, at work, at home and at friends'/relatives' homes, with downlink as the largest source contributor (Figure 2A). Other activities such as "travel", "outside" and "miscellaneous" were highest in total and downlink exposure. The same pattern (relatively low exposure during indoor activities and higher exposures during travel and outdoor activities) was measured in all five countries (Online Supplement 5). Uplink exposure was highest during travel activities, especially in public transport (tram, train, metro, bus), where many participants as well as others around them interact with their phones. Similarly, in public places such as fitness centers, shops, restaurants and cinemas/theaters/concert halls, the high uplink probably also results from a combination of the participants' own use and from the phone use of people around them. Several Spanish children had increased exposure to broadcast bands, which was not prevalent for parents and occurred mostly at school, outside, and in sport/fitness centers (Figure 2). This affects the mean, but involves only few individuals and therefore is not apparent for the median exposure level during these same activities (Figure 2B).

Total RF-EMF exposure is typically lower during the night than during the day (Figure 3). Broadcast exposure was very stable over the course of the day for both parents and children (Figure 3), whereas uplink frequency bands show a clear diurnal pattern, peaking during the daytime and decreasing in the late evening (Figure 3). DECT exposure is generally very low, but similar between children and their parents and slightly lower at night than during the day. Downlink exposure is clearly higher during the day than at night, peaking between 14:00 and 16:00. Exposure to Wi-Fi is steady for most of the day, but appears to show a slight peak in the evening between 18:00 and

22:00 for parents and children, then drops substantially between 22:00 and 06:00. Diurnal patterns differed slightly by country depending on different typical lunch and dinner times (Online Supplement 6).

Exposure correlation between members of the same family

There was a Spearman correlation of 0.45 between the child's and parent's exposures for total exposure over the course of the entire day (Figure 4, Online Supplement 7). Moderate to high correlations exist between children and their parents for downlink (0.57) and broadcast (0.62), while we found moderate correlations between children and their parents for exposure to Wi-Fi (0.45) and DECT (0.40) bands. We found a weak, but still substantial correlation for uplink (0.29). All exposure correlations between children and their parents were higher if we focused on time spent at home (0.62 for total exposure) than if we took all observations together (0.45), and this pattern can also be seen in the different exposure bands. Exposure correlations between children and their parents were also higher during the night (0.60 for total exposure) than during the day (0.37). For activities where children and parents from the same family engaged in the same activity, the highest correlations between their exposures were found for activities at home (0.62, as previously noted), at home outside (0.60), at the restaurant/café (0.50), shopping (0.50), or in the sport/fitness center (0.52) (Figure 5).

Exposure and age

Total exposure to RF-EMF did not show a very clear age-related trend among the 294 children (Figure 6). Similarly, the high broadcast exposures measured in some Spanish children were also visible in Figure 6, but otherwise neither broadcast nor Wi-Fi show much of a trend with age. Uplink exposure increased slightly with age in our children's study population, and seemed to be accompanied by a drop in DECT exposure (Figure 6). This trend became clearer when we add the measurement data on the 221 additional unpaired children from Spain (Online Supplement 8, Figure S8a). Interestingly, exposure to uplink appeared to be similar for children up to age 11, after which it increased with age (Online Supplement 8, Figure S8a). DECT showed a different pattern, increasing until age 11 and then dropping as uplink increases. Adding the measurement data on the 31 additional young adults from Switzerland to the Swiss subset of the main sample, we were able to analyze the age-dependency of exposure over the entire age range (Online Supplement 8, figure S8b). This showed a clear age-related increase of uplink, downlink, and Wi-Fi exposure, peaking at ages 20 to 30 (Online Supplement 8, figure S8c).

Discussion

Our study is one of the largest personal exposure measurement surveys done for RF-EMF so far, measuring 294 child-parent pairs (588 participants) in five different European countries. Our data show that in terms of RF-EMF exposure, the generation gap between children and their parents is mostly evident in uplink exposure, which is higher for parents because of their personal preferences to make more and longer uplink and cordless phone calls, and their tendency to spend slightly more time in activities with higher environmental RF-EMF exposure, such as travel. Exposure during activities where most of the time is spent (home, school, and work) is relatively low, with downlink as the main contributing source on average, whereas exposure during travel and outside activities is higher, and the contribution of uplink becomes more substantial. Exposure to frequency bands which are behavior-related (such as uplink, DECT, and to some extent Wi-Fi and downlink) clearly show the diurnal exposure pattern. Whereas exposure to downlink, broadcast and Wi-Fi show no obvious trend with age, exposure to uplink increases with age among the children's study population around age 11, while DECT decreases slightly. Exposure was correlated between members of the same family, especially for exposure resulting from environmental sources (e.g. broadcast and downlink). Correlations between family members are also higher during the night and for the time spent at home. The different activity patterns and personal exposure behavior explains the observed differences between the generations.

Contributions of uplink, downlink and other sources

We found that exposure to RF-EMF is slightly higher for parents than for children, especially for uplink and DECT, which is in agreement with other studies(Choiet al. 2018; Vielet al. 2009) and with a higher self-reported frequency and duration of mobile phone and cordless phone calls (Figure 1). Previous personal surveys (Bolte and Eikelboom 2012; Freiet al. 2009; Röösliet al. 2016; Roseret al. 2017) from Europe mostly reported a higher percentage contribution of uplink to the total (29-67%) than the 18% for children and 27% for adults found in this study (Figure 1, Online Supplement 3). This could be due to a combination of the following: 1) the selection of a more urban study population than previous studies, 2) a different (younger) children's age range resulting in a general shift from using uplink voice calls to using mobile data while in public transport, 3) temporal changes in the telecommunication infrastructure (e.g. more UMTS than GSM) and 4) the use of a different exposimeter in some of the earlier studies. A Korean personal measurement study in children of similar age and their parents found much lower relative contributions of uplink, against much higher total exposures which was mostly from downlink (Choiet al. 2018), which may be due to a very different network architecture.

Diurnal patterns and exposure differences by activity

We found differences in exposure between different activities (Figure 2), and diurnal trends in exposure (Figure 3), but only weak signs for an age-related trend in exposure, again mostly for uplink (Figure 6). Relatively high exposures during transport related activities (Figure 2) were also previously reported by other personal monitoring studies (Choiet al. 2018; Freiet al. 2009; Röösliet al. 2016; Roseret al. 2017; Vielet al. 2009). Several previous studies from the Netherlands (Bolte and Eikelboom 2012) and Switzerland (Freiet al. 2009; Röösliet al. 2016; Roseret al. 2017) also found that RF-EMF was typically lower during the night than during the day (Figure 2), but this was not clearly visible in an earlier French study (Vielet al. 2009). Previous studies found higher exposures in the afternoon than in the morning (Thomaset al. 2008b) and higher levels in the evening than during the day (Bolte and Eikelboom 2012). Only two of these earlier studies broke the day down into more precise time slots, so the diurnal pattern can be studied in more detail, revealing similar, but stronger diurnal contrasts than were found in the current study (Röösliet al. 2016; Roseret al. 2017). The constant level of broadcast over the course of the day was expected because of the relatively low spatial and temporal contrast of broadcast exposure. In contrast, frequency bands which are heavily dependent on personal behavior, such as uplink exposure, show a more distinct diurnal pattern: people rarely make many phone calls in the early morning, or very late at night, resulting in lower uplink exposures between 06:00 and 08:00, a decrease during the evening hours between 20:00 and 22:00 and the lowest exposures after 22:00 (Figure 2). Here, we can also clearly see that uplink exposure is generally higher in parents than in children, and that the elevated exposures of uplink and DECT persisted between 20:00 and 22:00 for adults, but decreased for children, suggesting earlier bedtimes. The diurnal pattern in downlink exposure, showing higher exposures during the daytime, is likely related to the times when people spend time outside, within direct line of sight from a base station, as was also reported by the Dutch (Bolte and Eikelboom 2012) and one of the Swiss studies (Roseret al. 2017). The Wi-Fi peak in the evening was previously reported in the Dutch study, of which the majority is likely due to increased surfing in the evening along with a smaller contribution of stray radiation from microwave oven use (Bolte and Eikelboom 2012). The age-related increase in uplink and DECT exposures may be caused by increasing use of personal (rather than communal) devices after the age of 11 (Figure 3, Online Supplement 8, Figure S8b). A limitation of this analysis is that many of the cohorts were recruited within a very specific age range, and that trends within countries are therefore limited to these limited ranges. Our finding that young adults as an age group, have a higher exposure to uplink, downlink, and Wi-Fi than children and parents was also previously reported for Switzerland in an earlier publication (Röösliet al. 2016). A similar decrease in exposure with age during adulthood was reported in a study from the Netherlands (Bolte and Eikelboom 2012). This is likely due to young adults being more independent and more outgoing than children and parents, resulting in more time spent in transport, outdoor and miscellaneous activities.

Exposure correlations between children and parents

We also found substantial correlations between child - parent pairs who lived in the same household and experienced many environmental exposures jointly (Figure 4). Sources of downlink and broadcast bands produce a continuous environmental exposure which is jointly experienced by both children and their parents, and therefore highly correlated within families (Figure 4). Wi-Fi and DECT, which are typically specific to the home, but are also affected by the person’s behavior, were somewhat less correlated between children and their parents, while uplink, whose exposure is highly related to personal behavior, only showed a low correlation between children and their parents (Figure 4). Furthermore, exposure between children and their parents were more correlated during the night time than during the daytime, when families typically spend time together, and if we restricted to only measurements taken at home. Similarly, levels experienced by parents and children while engaged in the same activities were correlated (Figure 5). We are only aware of one other study which looked at the comparability of RF-EMF exposures between members of the same family.(Röösliet al. 2016) This study found moderate correlation for broadcast, and low correlations for Wi-Fi and DECT, but -in contrast to this study- no correlations for downlink, uplink or total exposure.(Röösliet al. 2016) Moreover, when we studied within-subject variability from day to day, we found a similar order of magnitude in the correlation of 0.57 between exposures measure on subsequent days by the same person (Birkset al. 2018).As for between-subject variability, the repeatability correlation was also higher during the night while subjects were at home, and for those exposures resulting from environmental sources (downlink, broadcast) (Birkset al. 2018). This suggests that the variability between members of the same family is not substantially larger than the variability of a person on different days.

Strengths and limitations

The current study is one of the largest personal measurement surveys on RF-EMF so far. The simultaneous measurement in children and their parents allowed for a direct comparison between members of the same family. Since the majority of our study population was recruited from existing cohort studies, and from specific geographical regions within each country, our samples may not generalize to the entirety of each country’s population. We have therefore limited any comparison between countries, and instead focus primarily on the group as a whole. Personal exposimeters also have several technical limitations, which were previously discussed in several earlier publications (Bolte 2016; Iskraet al. 2010; Thielenset al. 2015):

1) Personal exposimeters do not enable the measurement of peak exposures to the head and brain, resulting from phone calls. The exposures in this study therefore reflect more closely the whole-body exposure (Bolte 2016). If the peak exposures to the head were considered, the percentage contribution from uplink to the total RF-EMF would likely increase substantially, and the contributions from downlink, broadcast, Wi-Fi, and DECT would decrease (Roseret al. 2017).
2) While we tried to minimize body shielding by design (see methods), we cannot completely prevent all shielding, which would have resulted in an underestimation of exposure (Iskraet al. 2010; Thielenset al. 2015). The amount of shielding may depend on where the ExpoM-RF is worn on the body, the environment in which the participant is, their body morphology and the frequency of the signal. Studies have limited the effects of body shielding by calibrating the monitoring devices on the body of the wearer (Bhattet al. 2016; Thielenset al. 2015), which is unfeasible in a volunteer study. Another approach is a post-measurement correction (Choiet al. 2018), but accurately correcting for shielding requires this input information and corresponding correction factors, for which the estimates differ a lot between different studies, reportedly ranging between 1 and 1.6 (Bolte 2016; Choiet al. 2018; Thielenset al. 2015).
3) Cross-talk occurrences have been reported to result in partial double counting of exposures measured with devices which include broadband antennas and band pass filters (Thielenset al. 2015). We corrected for cross-talk using an algorithm used in several previous studies (Röösliet al. 2016; Roseret al. 2017), which uses participants' activities to find and remove signals resulting from crosstalk, yet prevent the erroneous removal of actual signals. However, cross-talk cannot always be determined accurately, and some over or under correction is inevitable. As shown in Online Supplement 2B, the impact of this correction on the DECT band is substantial, but the impact on the overall measurement is almost negligible.

The personal measurement study design also has practical limitations: Firstly, the measurements relied on the study participants entering their activities correctly. We minimized diary errors through extensive semi-automated checking and correction. Secondly, it is unfeasible for researchers to verify that the volunteers followed all protocols. Despite these limitations, personal exposimeters provide important quantitative insights into the totality of RF-EMF exposures as they occur in real life settings, which neither questionnaires, measurements by trained technicians nor propagation modelling can provide (Röösliet al. 2010). The studies' large sample size and paired simultaneous measurements in a child and parent of the same family allowed us to study the contributions of environmental (jointly experienced) and behavior related (individually experienced) exposures.

Conclusion

The generation gap between children and their parents is mostly evident in uplink exposure, due to more and longer uplink and cordless phone calls among parents, and their tendency to spend slightly more time in activities with higher environmental RF-EMF exposure, such as travel. Despite these differences in personal behavior, time-weighted average exposures from children and their parents show a moderate spearman correlation of 0.45 for total exposure, with higher correlations for environmental exposures like downlink (0.57) and broadcast (0.62) and lower correlations for behavior-related exposures such as uplink (0.29). Mean exposures experienced by parents and children while engaged in the same activity mostly showed low to moderate correlations.

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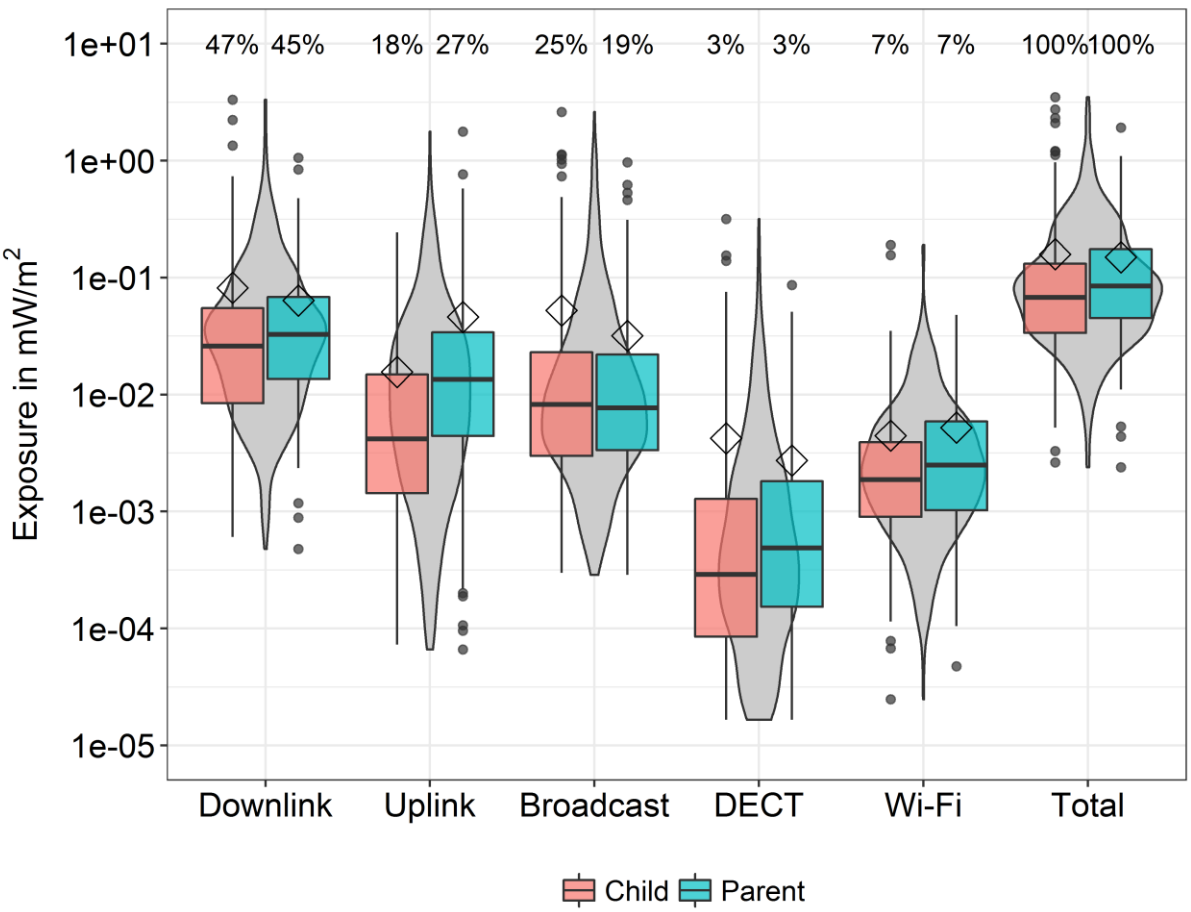
Figure 1: Distribution of personal time-weighted average exposures as calculated for the 294 children and 294 parents. The percentile distribution (boxplot) and mean (diamond) of the personal time-weighted averages are shown for downlink [a], uplink, broadcast, DECT, Wi-Fi and total RF-EMF for children and parents. The box shows the 25th, 50th and 75th percentiles, whiskers extend to the smallest observation ≥ the 25th percentile - 1.5 * IQR (Interquartile Range) and the largest observation ≤ the 75th percentile + 1.5 * IQR. Participants whose time-weighted average exposure fell outside of the whiskers' range are represented by points. The percentage indicates the average contribution of each specific band to the total exposure. The gray violins portray the overall distribution for all participants [b].



[a] Downlink is the sum of the mobile downlink 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz bands: the signal from the base station to the mobile device. Uplink is the sum of the mobile uplink 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz bands: the signal from the mobile device to the base station. Broadcast is the sum of FM Radio and DVB-T, DECT is from cordless phones, Wi-Fi is from the ISM 2.4 GHz band and total is the sum of all 14 bands previously mentioned.

[b] Gray violins (mirrored density plots) were obtained with the geometric object geom_violin available from the ggplot2 library in R using default settings. They are occasionally flat on the bottom because a number of participants had a time-weighted average exposure equal or close to the lower detection limit (e.g. 0.000017 mW/m² for DECT and 0.000246 mW/m² for uplink, which is the calculated as the sum the lower detection limits of all five uplink bands).

Figure 2: Means of personal mean (above) and medians of personal mean (below) exposure to broadcast, DECT, downlink, uplink, and Wi-Fi per activity and for children and parents. The total number of participants whose measurements contributed to each summary is shown, as well as the total number of measurement hours. Bars are not shown where fewer than 5 participants provided data or where the total number of hours measured was lower than 5.

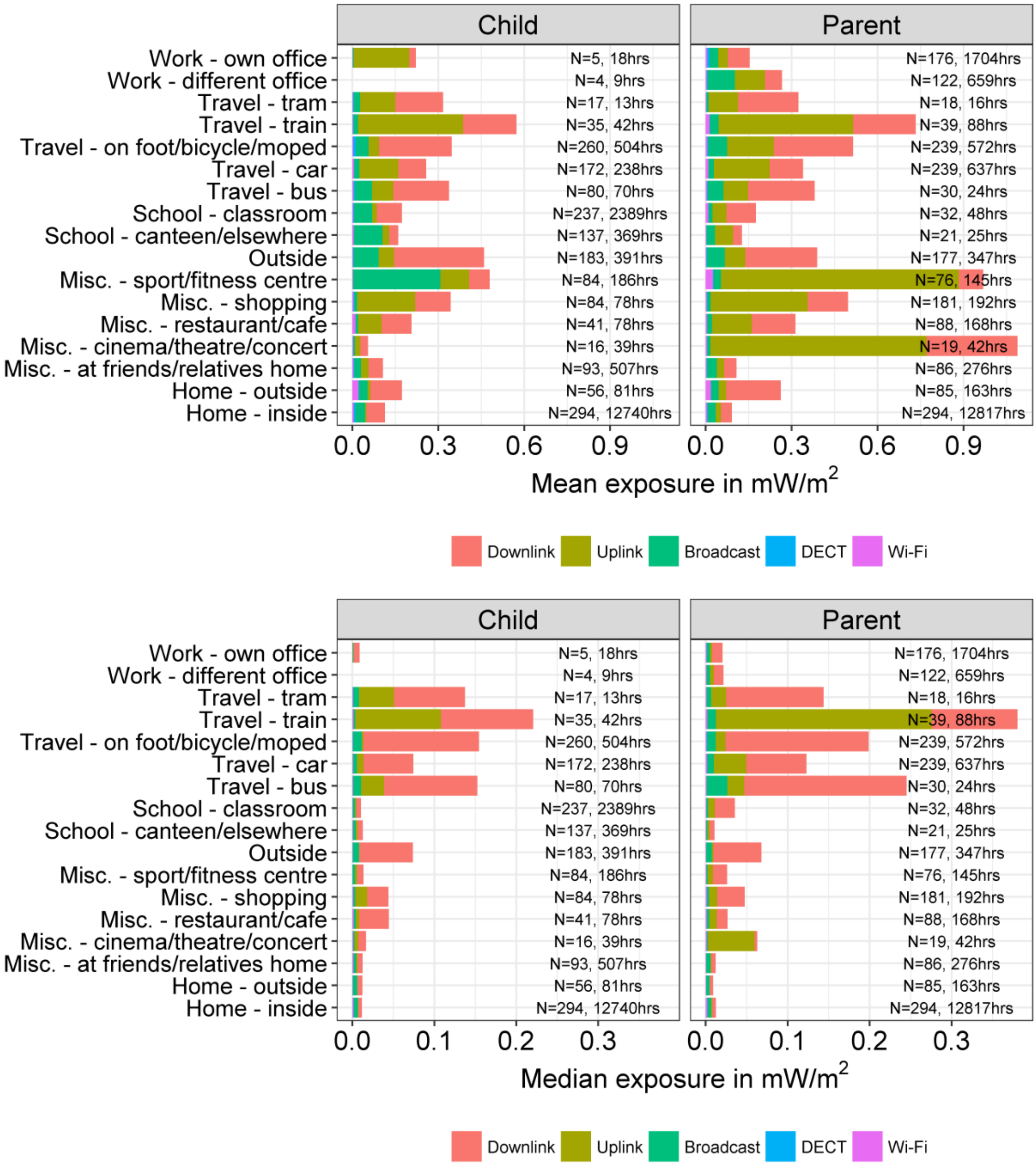
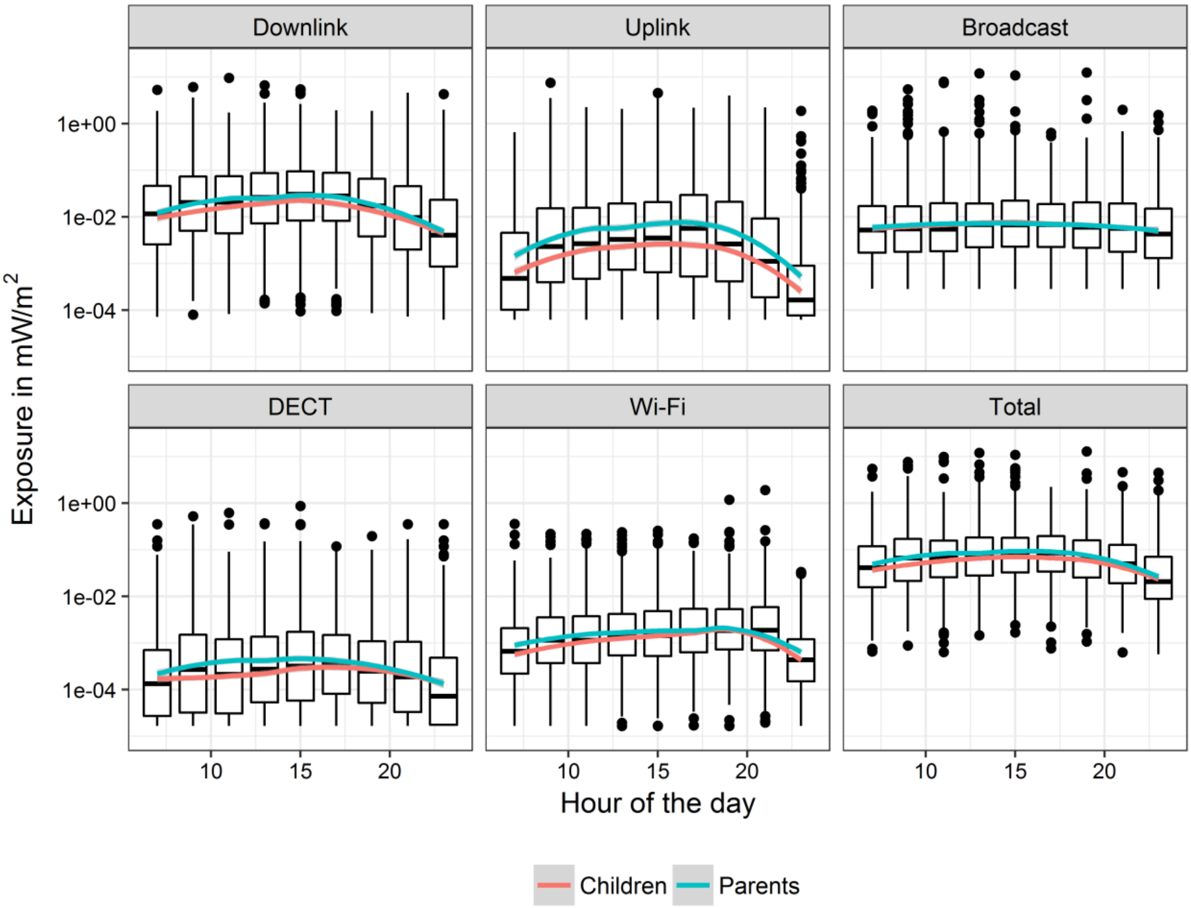


Figure 3: Diurnal patterns of exposure for children and their parents for broadcast, downlink, uplink, DECT, Wi-Fi, and total RF-EMF exposure.



Exposures are shown for the following time slots: 06:00-08:00, 08:00-10:00, 10:00-12:00, 12:00-14:00, 14:00-16:00, 16:00-18:00, 18:00-20:00, 20:00-22:00 (all 2 hours) and 22:00-06:00 (8 hours).

Figure 4: Spearman (r[s]) correlations between exposures of children and their parents for sources broadcast, downlink, uplink, DECT, Wi-Fi, and total RF-EMF. Personal exposures were calculated as mean exposure during the daytime, night time, and time spent at home, and as time-weighted average exposure overall. The country is indicated by different color points.

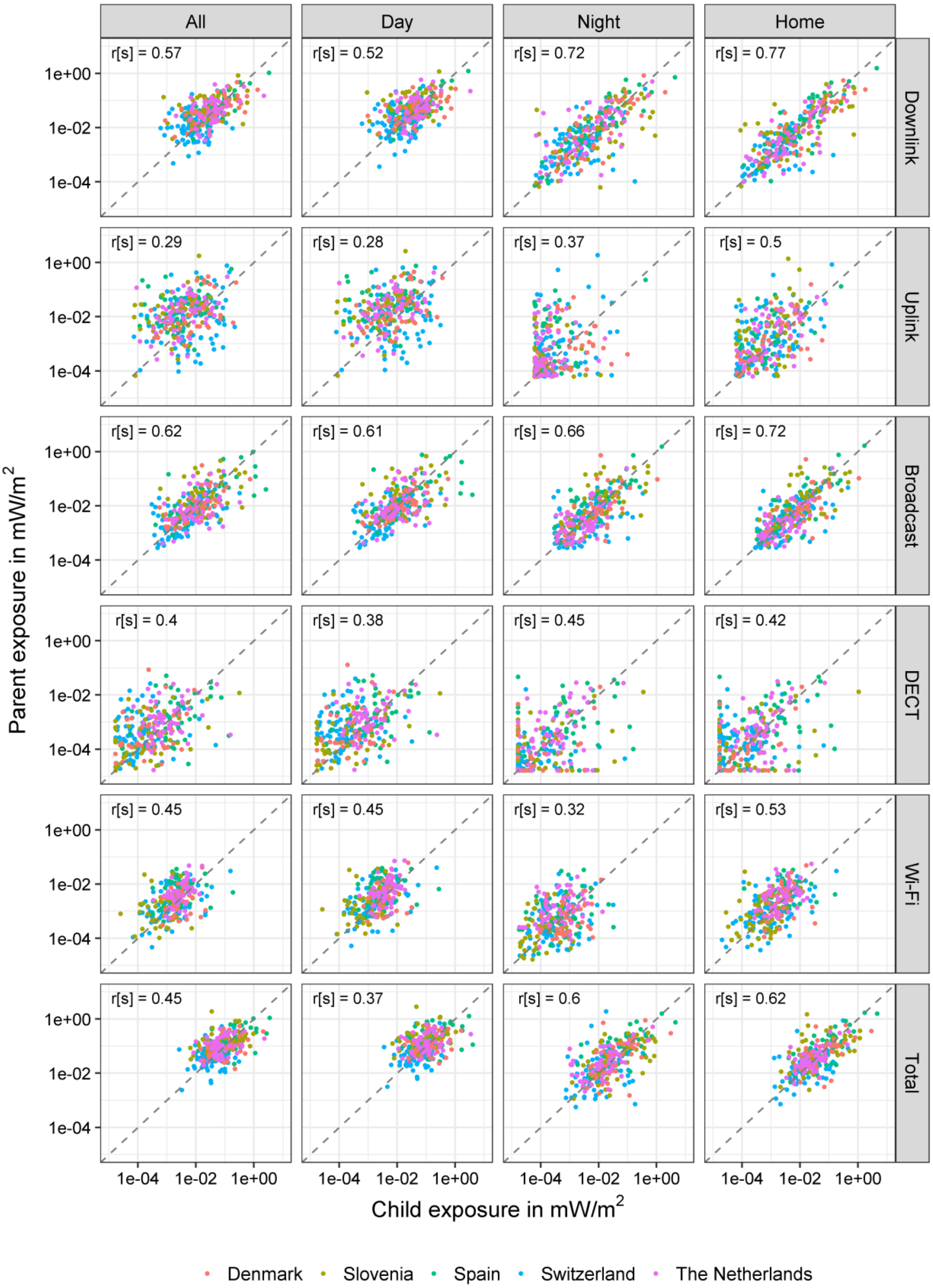


Figure 5: Spearman (r[s]) correlations between total RF-EMF exposure between children and parents of the same families during the same activities. The size of the dots reflects the cumulative activity duration in hours (by child and parent), values for activity "Home - inside" were divided by 20 for better visibility. Please note that the number of dots in the graph varies according to the number of families where both a child and a parent engaged in a certain activity.

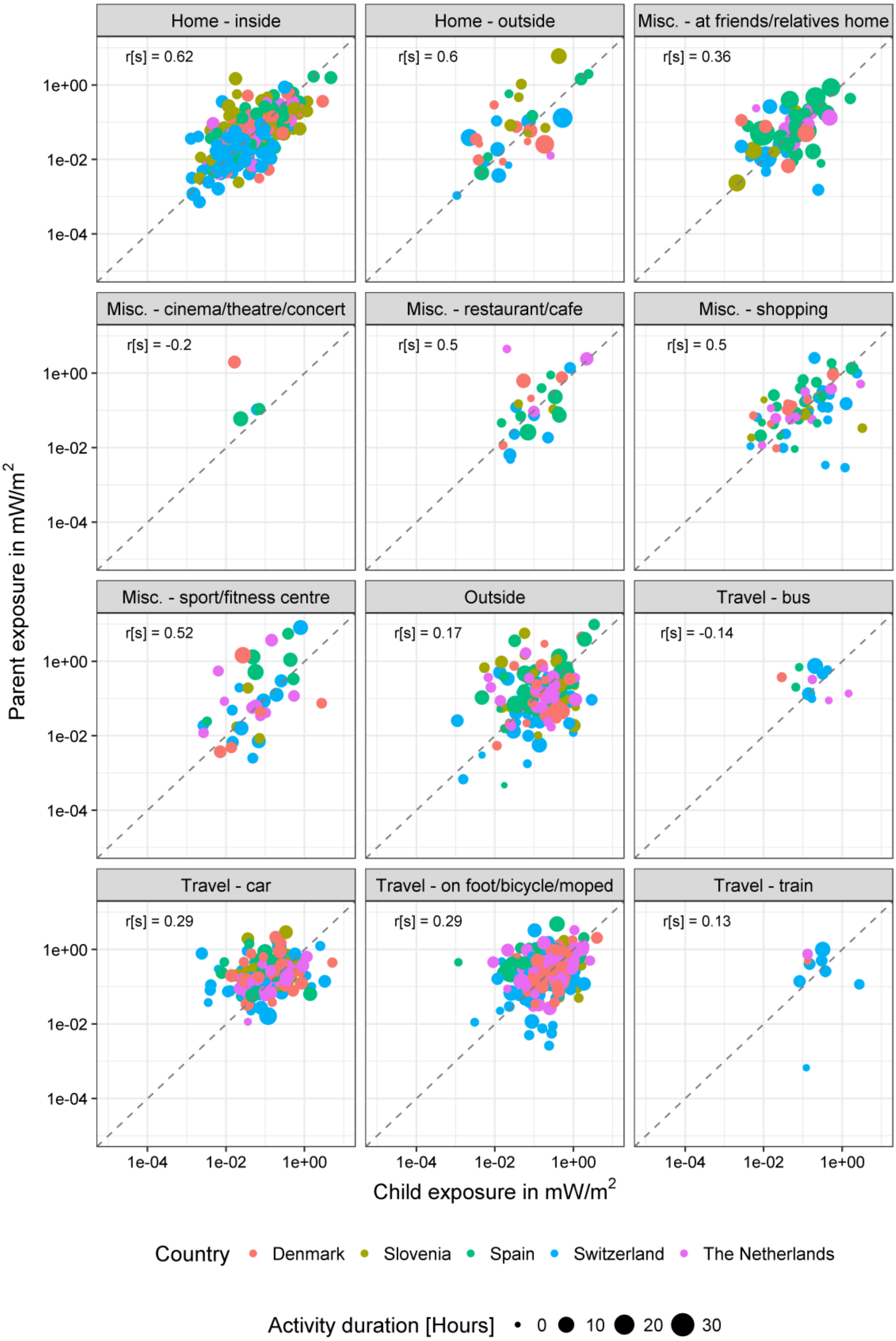


Figure 6: Exposure to downlink, uplink, broadcast, DECT, Wi-Fi, and total RF-EMF by age for the combined children's study populations of the GERoNiMO and ZüMe projects (n=294).