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ORIGINAL ARTICLE

Analysis of personal and bedroom exposure to ELF-MFs in children in Italy and Switzerland

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Little is known about the real everyday exposure of children in Europe to extremely low-frequency magnetic fields (ELF-MFs). The aims of this study are to (i) assess personal ELF-MF exposure in children; (ii) to identify factors determining personal and bedroom ELF-MF exposure measurements in children; (iii) to evaluate the reproducibility of exposure summary measures; and (iv) to compare personal with bedroom measurements. In Switzerland and Italy, 172 children aged between 5 and 13 years were equipped with ELF-MF measurement devices (EMDEX II, measuring 40–800 Hz) during 24–72 h twice, in the warm and the cold season. In addition, 24-h measurements were taken in the bedroom of children. In our study, sample geometric mean ELF-MF exposure was 0.04 μT for personal and 0.05 μT for bedroom measurements. Living within 100 m of a highest voltage power line increased geometric mean personal exposure by a factor of 3.3, and bedroom measurements by a factor 6.8 compared to a control group. Repeated measurements within the same subject showed high reproducibility for the geometric mean (Spearman's correlation 0.78 for personal and 0.86 for bedroom measurements) but less for the 95th and 99th percentile of the personal measurements ($\leq$0.42). Spearman's correlation between bedroom and personal exposure was 0.86 for the geometric mean but considerably lower for the 95th and 99th percentiles ($\leq$0.60). Most previous studies on ELF-MF childhood leukaemia used mean bedroom exposure. Our study demonstrates that geometric mean bedroom measurements is well correlated with personal geometric mean exposure, and has high temporal reproducibility.

INTRODUCTION

Extremely low-frequency magnetic fields (ELF-MFs) originate mainly from the use of electricity (Europe 50 Hz, US or Japan 60 Hz), and have been studied as a risk factor for childhood leukaemia since the late 1970s,[1] with a current total of more than 30 epidemiological studies. During the last 10 years, several pooled analyses have been published that combined all available data with various exposure indices.[2–4] These pooled analyses consistently found statistically significant increased relative risk estimates for childhood leukaemia for high exposures to ELF-MFs (above 0.3 or 0.4 μT) compared with low exposure (below 0.1 μT). In 2001, the International Agency for Research on Cancer (IARC) examined the body of scientific literature on ELF-MFs and concluded from the subset concerning childhood leukaemia that ELF-MFs should be classified as "possibly carcinogenic to humans" based on "limited evidence of carcinogenicity in humans" and "inadequate evidence of carcinogenicity in experimental animals".[5]

Given the lack of a mechanistic explanation for the epidemiological observations chance, bias or confounding is of concern. Chance alone seems unlikely, given the consistent results of the pooled analyses. Given that no strong risk factor for childhood leukaemia has been identified that is highly correlated with

ELF-MFs, confounding is expected to play a minor role.[6] Selection bias may indeed upward bias the risk estimates but is not expected to be sufficient to explain the entire association, since studies with modelled exposure are unlikely to suffer from selection bias and also found associations.[6] Exposure misclassification for most studies, modelling or measuring bedroom exposure is most likely non-differential, and thus it rather dilutes any association than creating a spurious association.[7]

As a consequence, to better interpret the previous research on the association between childhood leukaemia and ELF-MFs better exposure information for children is needed. There is a lack of knowledge about levels and temporal patterns of ELF-MF exposure of European children as most previous personal measurement studies in children were mainly conducted in Asia[8–10] or in North America.[11–15] Several other measurement studies in North America and Europe focused either on adults[16–28] or were restricted to measurements in the bedrooms of children.[29,30] To our knowledge, for Europe only three papers with personal ELF-MF exposure measurements of children have been published including in total 183 subjects.[31–33]

Few studies looked at the reproducibility of personal measurements for adults[17,25–28] or children,[13] and did comparisons between personal and residential measurements for adults[16,17,19,22] and children.[11,14,15,31] Such comparisons are

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relevant because most studies relied on modelled or measured bedroom exposure because conducting personal measurements in epidemiological studies is both a lot of effort and also not meaningful for retrospective exposure assessment of childhood leukaemia patients, in a case control study, since they may have changed their daily routine after the diagnosis. However, personal exposure is considered most relevant from an aetiological perspective. In most cases, these comparisons were done for measures of central tendency-like arithmetic or geometric mean exposure. A couple of studies[12,17,27,34–36] assessed the correlation of mean personal exposure with other exposure indices derived from personal measurements like higher percentiles, time spent over a certain threshold or measures of variability and stability of the exposure, which were hypothesised to be associated with biological effects.[19,37–40] Within these studies Foliart et al.[12] was to our knowledge the only one referring to exposure to children, the others investigated exposure of adults and several of them focussed specifically on occupational ELF-MF exposure of electrical utility workers. Kaune et al.[17] further looked also at the correlation of such personal exposure indices different from the mean with residential fixed site measurements like mean bedroom measurements — the exposure surrogate most frequently used in epidemiological studies and linking ELF-MF exposure to an increased risk of childhood leukaemia. However, it is not clear how transferable these results are for children.

This study took place in the framework of the EU FP7 research project ARIMMORA ("Advanced Research on Interaction Mechanisms of electromagnetic exposures with Organisms for Risk Assessments") with the following aims: (i) assess personal ELF-MF exposure in children; (ii) to identify factors determining personal and bedroom exposure measurements in children; (iii) to evaluate the reproducibility of various exposure summary measures in children; and (iv) to compare personal with bedroom measurements.

METHODS

Selection of Participants

Children for this study were recruited in the age of 5–13 years in Switzerland and Italy after ethics approval had been obtained in both countries ("Ethikkommission beider Basel", "Comitato Etico ASL Milano"). Because high exposure situations are rarely to be expected in a random population sample, we recruited children out of three study groups: children living or attending school within 200 m of a high-voltage power line (hvpl; ⩾ 132 kV) or within 50 m of an underground cable ("hvpl" group); children living in a building with built-in transformer station ("transformer" group) and a convenient sample of children not belonging to the groups above for comparison ("control" group). This sampling approach increased the range of exposure situations in our study population. Upon first analysis, we split up the "hvpl" group into participants living or attending school up to 100 m from a highest voltage power line of at least 220 kV ("highest hvpl ⩽ 100 m"), participants living between 100 and 200 m from a highest hvpl ("highest hvpl > 100 m"), participants living up to 100 m from a hvpl of < 220 kV or up to 50 from an underground cable ("low hvpl ⩽ 100 m") and participants living between 100 and 200 m from a hvpl of < 220 kV ("low hvpl > 100 m"). See the additional material for a depiction of distance from hvpl and hvpl type for the participants living or attending school within 200 m of a hvpl. The "transformer" group we split up further into participants living in a house with transformer ("transformer") and participants living directly adjacent to a transformer ("transformer close"). Only three participants fell into this group. The rational for the latter division is that previous measurement studies have demonstrated that mean ELF-MF exposure at home is only elevated in apartments directly adjacent to the transformer.[41–43] The recruitment procedure was different between the two countries. In Switzerland, we received address information of all eligible participants (e.g., living in a building with a transformer station or in the vicinity of a power line, or none of both) from several urban and suburban communities and randomly contacted families in the respective groups. In Italy, children were recruited through contacting schools and personal contacts with volunteer families, all living in the area of Milan and neighborhood. To be included in the study, the families had to understand

Italian, German or English. Written consent was obtained from all families. Within families more than one child could participate.

Study Protocol

Measurements were conducted between 21 April 2012 and 20 December 2013 in Switzerland and Italy adopting a study protocol for personal radio frequency measurements[44] adapted for ELF-MF measurements. Measurements were conducted with portable EMDEX II meters (frequency range 40–800 Hz, sensitivity range from 0.01 to 300 μT). The children were carrying with them an EMDEX II device for 24–72 h (2–3 full days), accompanied by a GPS logger (Qstarz BT-Q1000XT GPS data logger). The EMDEX II sample rate was set to 30 s. Assisted by their parents, they filled in a time-activity diary, supplementing the measurements with information on location and behaviour of the children. In addition, a questionnaire about possibly exposure relevant factors was given to the parents. Measurements in the bedroom of children were conducted before and after the 24–72 h of personal measurement period in order to obtain a full day (24 h) bedroom measurement. Thus, a specific measurement period may look as following: the child receives the device at 1700 hours on the first day and puts it under or close to the bed. The second and third days the child carries around the measurement device, and when going to bed on the third day the device is put under or close to the bed again where it remains until collected by the study assistant at 1700 hours on the fourth day. During the personal measurements, the children carried the device in their schoolbag or backpack and at home they took it with them into the different rooms and placed it nearby. To evaluate reproducibility and possible seasonal variations in exposure due to variability in electricity consumption[45] or the behaviour of the children, measurements were conducted mostly twice in the same child during the warm as well as during the cold season. We defined "cold" and "warm" season by the dates of clock changes of central European time and central European summer time (last weekend in October and March). The mean interval between the two measurements was 182 days. To measure typical daily activities measurements were postponed if a child was sick during the scheduled measurement days. The EMDEX II devices were checked against a calibration standard before the start of the measurement campaign in May 2012 and after the first year of measurements in November 2012, at the "Foundation for Research on Information Technologies in Society" (IT'IS) in Zurich (Switzerland) using a certified AMCC Helmholz coil.

Data and Data Management

For each participant and each personal and bedroom measurement, we calculated various summary measures (mean, geometric mean, median and percentiles) using only complete measurement days (defined such that at least 90% of a full day had to be available in the measurement). We calculated the summary measures both for each full day as well as from all available full days of a participant's seasonal measurement. We will refer to the latter as "total exposure". Because bedroom measurements were taken before and after the personal measurement study, we combined part-day measurements to one full day when they met the mentioned criteria without overlapping hours (e.g., from 17:00 to 24:00 hours on day 1 and from 0:00 to 17:00 hours on day 4). In addition, in Switzerland we were sometimes able to place an additional EMDEX II device under or close to the bed of a child, which remained there also during the personal measurement. In these cases (11 and 19 in the warm and cold seasons, respectively), we regarded the data of these devices collected during the days of personal measurement as bedroom measurements, and derived the total bedroom exposure indices from these measurements. If, in addition, 24-h bedroom measurements from before and after the personal measurement were available, we calculated 24-h summary measurements also for these data; resulting in 19 additional 24-h bedroom observations. For the personal measurements, we ended up with 172 children with at least one, but mostly two full days of measurements. For 154 participants, this was the case in both seasons. Because of practical constraints, it was not always possible to obtain a full day also for the bedroom measurements. From 156 children, we could obtain at least one (up to four) full days and for 90 children this was the case in both seasons (see Supplementary Table S.1 in the Supplementary Material for a data overview).

Statistical Analysis

The association of various temporal and personal factors with ELF-MF exposure measures was investigated by means of linear mixed models

Table 1. Overview of study population ($n = 172$).

	N	%
Sex		
Male	94	54.7
Female	78	45.3
Age (years)		
5–6	25	14.5
7–8	47	27.3
9–10	59	34.3
11–13	41	23.8
Study group		
Control	63	36.6
Transformer	47	27.3
Transformer close	3	1.7
Low hvpl > 100 m	12	7.0
Low hvpl ≤ 100 m	24	14.0
Highest hvpl > 100 m	8	4.7
Highest hvpl ≤ 100 m	15	8.7
Country		
Switzerland	86	50.0
Italy	86	50.0
Urbanity		
Urban	127	73.8
Suburban	45	26.2

using the statistical software R (The R Project, http://www.r-project.org/), and specifically the packages "lme4" and "lmerTest". We chose several summary measures (arithmetic mean, geometric mean, median and percentiles) as dependent variable, constructing a linear mixed model for each of them. The variables: country, season, gender, age, weekend, urbanity and study group served as explanatory variables in the full models. In order to take into account measurement duration and, to give the same weights to each measurement we used the 24-h summary measures as the unit of observation, using a random intercept for repeated measurements within one child as well as for children within the same family (three-level model). We log-transformed the dependent variables to achieve an approximately constant residual variance and report back-transformed model coefficients representing factorial changes of the ELF-MF exposure values. For various exposure relevant factors, we also tested interaction with the study group variable using a log-likelihood test between the model with and without interaction term.

The reproducibility of the two exposure assessment methods (personal and bedroom measurements) was addressed by comparing for each individual the total exposure between the warm and the cold season. Thus, we selected only the seasonally matched samples (Table 1). For the summary measures mentioned above we calculated Pearson's and Spearman's correlation coefficients. In addition, we calculated the percentage of measurement pairs with an absolute exposure difference of ≤ 0.05 μT or a relative difference of ≤ 20%. Regarding the mean, geometric mean and median, we regarded measurement pairs fulfilling these criteria to be in good agreement.

The fourth aim of the study was to compare personal measurements with bedroom measurements. This comparison was done in 242 pairs of total personal and bedroom exposure observations from the same season. Again Pearson's and Spearman's correlation coefficients as well as percentage of agreement as defined above were calculated. In addition, sensitivity and specificity of a binary exposure classification with the cutoffs of 0.1 and 0.2 μT were calculated. The same cutoff values were used in the paper of Forssén et al.[31]

To qualitatively describe the correlation estimates in the paper, we use a scale[46] where "0–0.19 is regarded as very weak, 0.2–0.39 as weak, 0.40–0.59 as moderate, 0.6–0.79 as strong and 0.8–1 as very strong correlation". When we refer to the quality of reproducibility/comparability, we use the same terms but refer to the last two categories as "high"/"good" and "very high"/"very good" reproducibility/comparability.

RESULTS

Data Overview

In total, we collected 634 24-h personal measurements from 172 participants and 311 24-h bedroom measurements from 156 participants out of 120 different families. In Switzerland, participation rate was ~ 30% for all three original groups "control", "hvpl" and "transformer". In Italy, participation rate was not assessed due to the different recruitment procedure. Table 1 gives an overview on our study population.

The arithmetic mean of the total personal exposure was 0.07 μT with an interquartile range (IQR) of 0.05 μT (geometric mean: 0.04 μT; IQR: 0.03 μT). Arithmetic mean bedroom exposure was 0.06 μT with an IQR of 0.04 μT (geometric mean: 0.05 μT; IQR: 0.04 μT). Figure 1 shows the distribution of several summary measures calculated from the total personal and bedroom exposure for the broadband (40–800 MHz) frequency range. The respective figure for the harmonic (100–800 MHz) frequency range can be found in the Supplementary Material (Supplementary Figure S.1).

On average, the children spent 42% of their time at home during night, 26% at home during day, 18% in school, 8% outdoors, 4% elsewhere (unspecified) and 2% in public transports or car.

Exposure Relevant Factors

Personal measurements. Table 2 shows the impact of various factors on the 634 daily personal broadband ELF-MF exposure levels (arithmetic and geometric mean as well as 95th and 99th percentile). Among the considered factors, living or attending school close (≤ 100 m) to a highest voltage power line (i.e., "highest hvpl ≤ 100 m" group) or living in a house or apartment directly adjacent to a transformer had the largest effect on both arithmetic and geometrical mean and 95th percentile personal ELF-MF exposure value (Table 2). Children within these groups had an around three ("highest hvpl ≤ 100 m") and 2.5 ("transformer close") times higher mean exposure compared to the other groups and about 2.3 and 1.8 times higher 95th percentile values. For the 99th percentiles, model estimates were about 1.6 and 1.8 times higher (but not any more statistically significant) for the "highest hvpl ≤ 100 m" and "transformer close" group, respectively. As for the other factors, only country and gender had significant effects on the majority of the listed summary measures. According to the model, living in Italy resulted in an ~ 35–40% decrease of exposure throughout the investigated summary measures and male participants had an around 10–20% lower exposure metrics. Models for other summary measures (median, 75th percentile) showed similar patterns for all factors (data not shown).

We further investigated group–season and group–weekend interactions while keeping all the covariates from Table 2 in the model. We added the "transformer close" group to the "highest hvpl ≤ 100 m" group for this analysis as the sample size of the former was too small for the model structure. Figure 2 depicts the other-covariate adjusted mean exposure values for the group–season and group weekend interaction. While both, season and weekend, did not show substantial effects in the simple models of Table 2, allowing for group-specific effects revealed a significant influence for both covariates. Most pronounced were increased personal exposure levels for the "highest hvpl ≤ 100 m" group during weekend and the cold season, whereas exposure levels in the other groups were not as much and less consistently affected. In general, the effects were accentuated in the high percentiles although for season an interaction with the 99th percentile was not observed any more (data not shown). For weekend, no interaction with the median was found (data not shown). We also tested a third order interaction among season, country and group, however, the model fit was not increased compared to the model with the second order interactions (data not shown). We further looked at group–country and group–gender interactions but they

did not improve the model fit or did not yield substantial changes in the group–country effects compared to the simpler model (data not shown).

The summary measures derived from the harmonic content (100–800 Hz) of the personal ELF-MF exposure were around 2.5–3 times higher for the "transformer close" group while the other
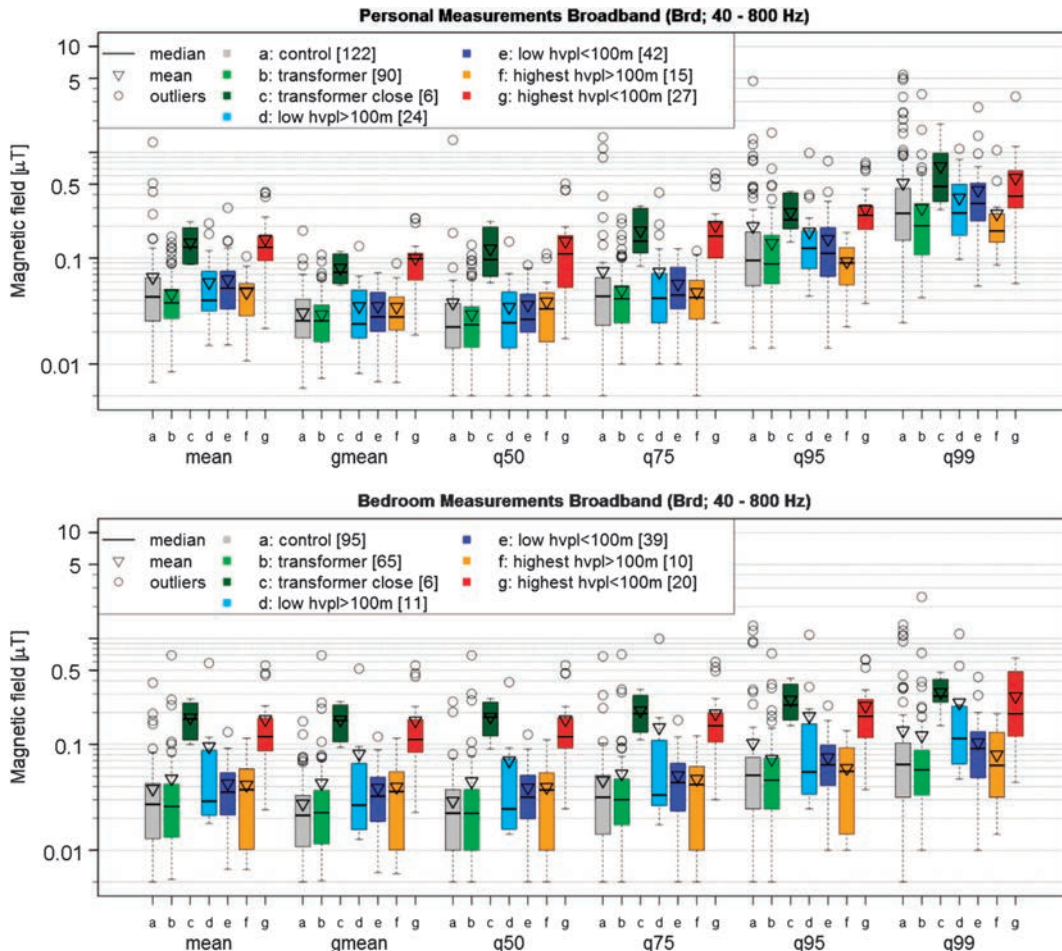

Figure 1. Boxplots of summary measures (mean, geometric mean and median, and 75th, 95th and 99th percentile) per group derived from the total exposure of the personal and bedroom measurements during the warm and cold seasons. The numbers in brackets give the number of observations per group (personal measurements: *n* total = 326; bedroom measurements: *n* = 246).

Table 2. Results of multivariable regression models on the broadband (40–800 Hz) ELF-MF 24-h personal exposure measurements (*n* total = 634).

Covariables	Dependent variables: exposure metrics			
	Model 1: arithmetic mean	Model 2: geometric mean	Model 3: 95th percentile	Model 4: 99th percentile
Season: cold[a]	1.02 (0.94, 1.10)	1.06 (1.00, 1.12)*	1.00 (0.89, 1.11)	0.96 (0.84, 1.09)
Urbanity: urban[b]	1.13 (0.82, 1.56)	1.13 (0.83, 1.53)	1.10 (0.79, 1.52)	1.19 (0.84, 1.68)
Country: IT[c]	0.67 (0.54, 0.82)***	0.64 (0.53, 0.78)***	0.60 (0.49, 0.75)***	0.65 (0.52, 0.82)***
Age[d]	0.99 (0.97, 1.02)	1.00 (0.97, 1.02)	1.01 (0.97, 1.04)	1.01 (0.97, 1.05)
Gender: male[e]	0.88 (0.79, 0.98)*	0.93 (0.84, 1.03)	0.86 (0.75, 0.99)*	0.78 (0.66, 0.92)**
Weekend: yes[f]	0.99 (0.90, 1.08)	1.02 (0.95, 1.08)	0.93 (0.82, 1.06)	0.93 (0.80, 1.08)
Group: transformer[g]	0.86 (0.67, 1.10)	0.93 (0.74, 1.18)	0.86 (0.67, 1.12)	0.75 (0.57, 0.98)*
Group: transformer close[g]	2.45 (1.12, 5.34)*	2.30 (1.09, 4.86)*	1.81 (0.81, 4.06)	1.78 (0.76, 4.19)
Group: low hvpl > 100 m[g]	0.96 (0.64, 1.44)	1.04 (0.71, 1.54)	1.01 (0.67, 1.54)	0.88 (0.56, 1.37)
Group: low hvpl < 100 m[g]	1.17 (0.88, 1.55)	1.09 (0.83, 1.43)	1.12 (0.82, 1.53)	1.30 (0.93, 1.82)
Group: highest hvpl > 100 m[g]	0.91 (0.56, 1.48)	1.05 (0.66, 1.67)	0.73 (0.44, 1.21)	0.68 (0.40, 1.17)
Group: highest hvpl < 100 m[g]	3.01 (1.91, 4.74)***	3.33 (2.16, 5.16)***	2.30 (1.44, 3.69)***	1.59 (0.97, 2.60)

The table shows the model coefficients of the covariates (season, urbanity, country, age, gender, weekend and study group) for the target variables (mean, geometric mean, 95 percentile and 99th percentile). The coefficients are back-transformed, representing factorial change of the exposure for the listed covariables. The 95% confidence intervals are given in brackets. The stars symbolise the significance range (*$0.05 \geq P > 0.01$; **$0.01 \geq P > 0.001$; ***$P \leq 0.001$). [a]Reference group is the warm season. [b]Reference group is suburban. [c]Reference group is Switzerland. [d]Age in years centered on mean age (~9 years). [e]Reference group is female. [f]Reference group is school day. [g]Reference group is "control" group.
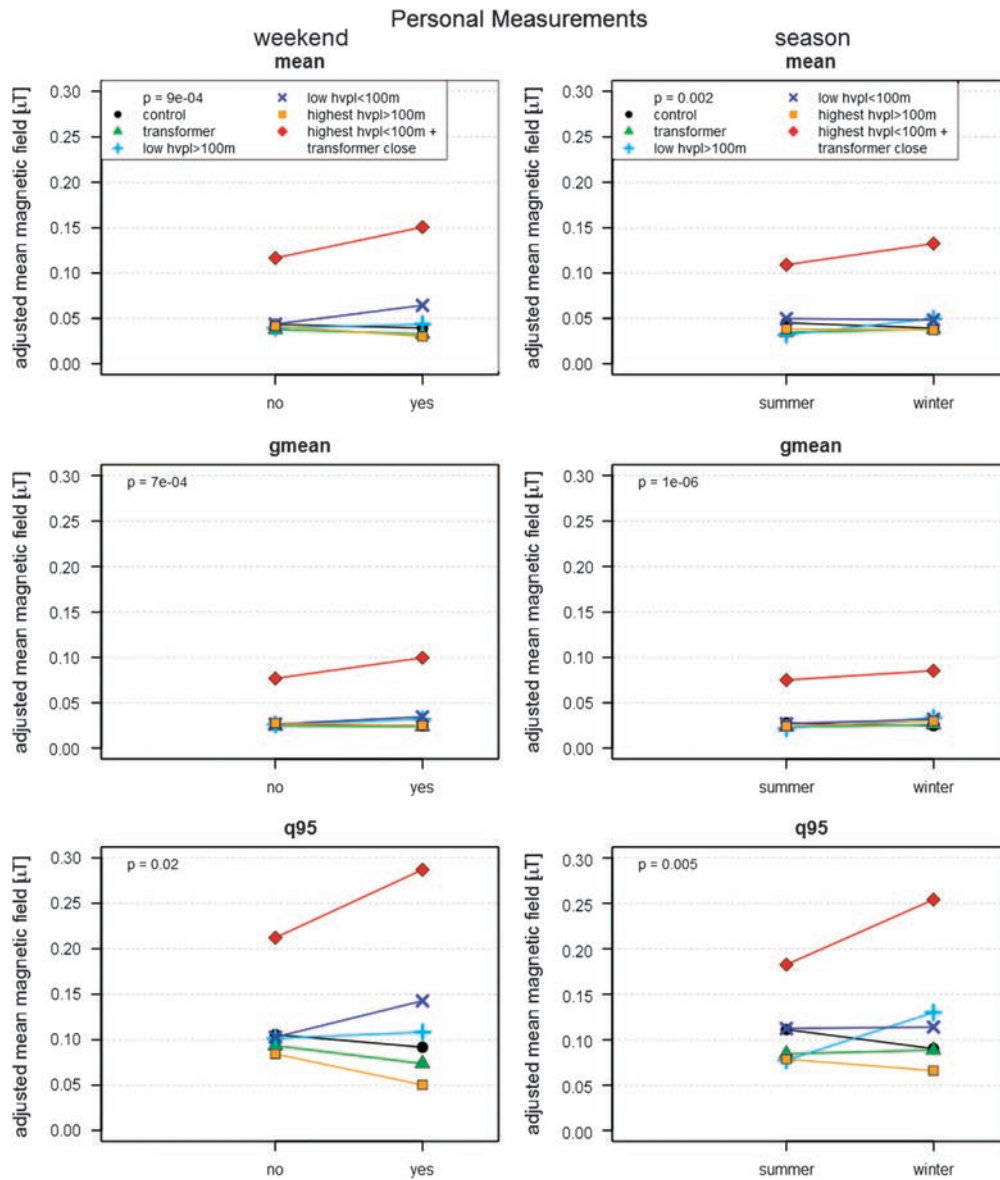
Figure 2. Group-specific weekend and season effects for the 24-h personal exposure measurements (arithmetic and geometric mean, 95th percentile*). *P*-value refers to the interaction term in the model. *Adjusted for age, urbanity, country, gender and either season or weekend.

groups showed no substantial differences according to the linear mixed regression models (data not shown).

Bedroom measurements. Factors affecting the 311 daily broadband bedroom measurements are shown in Table 3. The results were similar to the results for personal measurements in direction of the association. The model coefficients for country and gender were similar to the personal measurements whereas the increases for the "highest hvpl ≤ 100 m" and "transformer close" group were considerably higher than for the personal measurements.

In contrast to the personal measurements, the group–weekend interaction for the "highest hvpl ≤ 100 m" group was not found for the bedroom measurements and rather a decline on the weekend was seen for the "low hvpl > 100 m" group. The group–season interaction, however, was similar but more pronounced (Figure 3).

Reproducibility

Personal measurements. Figure 4 (first row) shows scatterplots for the arithmetic and geometric mean as well as the 99th percentile

derived from each total personal exposure measurement in the warm and cold seasons (154 measurement pairs). In Table 4, the reproducibility measures for further summary measures are displayed.

Pearson's and Spearman's correlations were highest for the geometric mean, with lower correlations for the arithmetic mean and decreasing correlation coefficients for the high percentiles. Also agreement, defined as measurement pairs with $< 0.05\,\mu T$ or 20% difference was best for the geometric mean (96%) and tended to decrease with increasing percentiles.

To take into account the observed group–weekend and group–season effects, we also compared adjusted total personal measurements representing warm season measurements taken on workdays. The adjustment yielded almost identical correlation coefficients indicating that seasonal and weekend effects are not crucial for the reproducibility of personal measurements.

We further investigated whether restricting the personal measurements to 24 h would substantially change our estimates. Where available we selected a weekend measurement in one season and a workday measurement in the other season. We

Table 3. Results of multivariable regression models on the broadband (40–800 Hz) ELF-MF 24-h bedroom exposure measurements (*n* total = 311).

Covariables	Dependent variables: exposure metrics			
	Model 1: arithmetic mean	Model 2: geometric mean	Model 3: 95th percentile	Model 4: 99th percentile
Season: cold[a]	1.05 (0.95, 1.16)	1.05 (0.97, 1.15)	0.99 (0.87, 1.12)	1.02 (0.88, 1.17)
Urbanity: urban[b]	1.19 (0.72, 1.96)	1.18 (0.73, 1.92)	1.20 (0.69, 2.10)	1.41 (0.82, 2.42)
Country: IT[c]	0.66 (0.48, 0.90)**	0.61 (0.45, 0.83)**	0.71 (0.50, 1.01)	0.78 (0.56, 1.10)
Age[d]	0.99 (0.94, 1.04)	0.98 (0.93, 1.03)	0.99 (0.93, 1.05)	1.01 (0.95, 1.07)
Gender: male[e]	0.79 (0.64, 0.97)*	0.80 (0.65, 0.98)*	0.82 (0.65, 1.04)	0.83 (0.65, 1.06)
Weekend: yes[f]	0.94 (0.83, 1.06)	0.97 (0.87, 1.08)	0.90 (0.78, 1.05)	1.00 (0.84, 1.18)
Group: transformer[g]	0.97 (0.67, 1.42)	1.02 (0.70, 1.47)	0.89 (0.59, 1.35)	0.89 (0.60, 1.35)
Group: transformer close[g]	5.44 (1.82, 16.28)**	5.98 (2.05, 17.42)**	4.56 (1.37, 15.22)*	4.68 (1.48, 14.76)**
Group: low hvpl > 100 m[g]	1.64 (0.86, 3.12)	1.58 (0.85, 2.95)	1.69 (0.82, 3.45)	2.35 (1.16, 4.74)*
Group: low hvpl < 100 m[g]	1.31 (0.85, 2.04)	1.42 (0.93, 2.18)	1.24 (0.76, 2.03)	1.17 (0.73, 1.89)
Group: highest hvpl > 100 m[g]	1.35 (0.63, 2.88)	1.49 (0.71, 3.10)	1.13 (0.49, 2.63)	1.38 (0.61, 3.12)
Group: highest hvpl < 100 m[g]	5.99 (2.92, 12.27)***	6.81 (3.39, 13.67)***	4.54 (2.05, 10.04)***	4.79 (2.22, 10.34)***

The table shows the model coefficients of the covariates (season, urbanity, country, age, gender, weekend and study group) for the target variables (mean, geometric mean, 95th percentile and 99th percentile). The coefficients are back-transformed, representing factorial change of the exposure for the listed covariables. The 95% confidence intervals are given in brackets. The stars symbolise the significance range (*0.05 ≥ *P* > 0.01; **0.01 ≥ *P* > 0.001; ***P* ≤ 0.001). [a]Reference group is the warm season. [b]Reference group is suburban. [c]Reference group is Switzerland. [d]Age in years centered on mean age (~9 years). [e]Reference group is female. [f]Reference group is school day. [g]Reference group is "control" group.

found similar patterns as for the full dataset and the correlations decreased only slightly.

Bedroom measurements. Figure 4 (second row) also shows the scatterplots for the arithmetic and geometric mean as well as the 99th percentile derived from the 90 total bedroom measurements conducted in both seasons and Table 4 contains the corresponding comparison coefficients. Pearson's and Spearman's correlation coefficients for bedroom measurements were higher than corresponding correlations for personal measurements for all exposure measures but the geometric mean (for Pearson's correlation). Correlation coefficients also tended to decrease with increasing percentiles but Spearman's correlation was still quite high for the 95th and the 99th percentile (0.83 and 0.73). Since the bedroom measurements were based on only 90 pairs whereas the personal measurements were based on 159 pairs, we did also a reproducibility analysis of the personal measurements restricted to the 90 pairs of observations that were available for the bedroom measurements and found similar patterns as for the full dataset (data not shown).

Comparison between Personal and Bedroom Exposure Measurements

We compared total exposure of personal with bedroom measurements for all pairs of concurrently conducted measurements in the cold and the warm season (*n* = 242). Figure 5 (first row) shows scatterplots for the mean, geometric mean and the 99th percentile and Table 5 contains the correlation coefficients, level of agreement and sensitivity and specificity for different cutoff values. For sensitivity and specificity, we considered personal exposure as gold standard for the measurement period and bedroom measurements as exposure proxy and used cutoff values of 0.1 μT and 0.2 μT to differentiate between exposed and non-exposed children. Choosing a cutoff value of 0.1 μT, we observed exceedance for 38 arithmetic mean, 12 geometric mean and 18 median personal measurements. For a cutoff value of 0.2 μT, corresponding numbers were 11, 2 and 4, respectively. The Pearson's and Spearman's correlations tended to be highest for the geometric mean and somewhat lower for other summary measures with a decreasing trend with increasing percentiles.

Figure 5 (second row) also demonstrates that geometric bedroom mean exposure is strongly correlated with arithmetic mean personal exposure but correlation is weak with personal 99th percentile and cumulative time > 0.4 μT.

DISCUSSION

Data Overview and Exposure Relevant Factors

In our sample, geometric mean of total personal ELF-MF exposure was 0.04 μT (IQR 0.03 μT) and geometric mean of total bedroom exposure was 0.05 μT (IQR 0.04 μT). We found high reproducibility of bedroom and personal measurements for mean values but less so for higher percentiles. Similarly, the correlation between bedroom and personal measurements was strong for mean values and considerably weaker for higher percentiles or cumulative time above a threshold of 0.4 μT.

Living or attending school within 100 m of a power line with highest voltage (≥220 kV) had the largest impact on the personal ELF-MF broadband exposure. Still, the arithmetic mean exposure of these children was on average moderate with ~ 0.15 μT, and all but two total exposure values in this group were below 0.4 μT. However, our data indicate that children living further away (100–200 m) or within 50 m of an underground cable are overall not higher exposed to ELF-MFs than other children. This finding is in line with the study of Forssén et al.[31] where personal and stationary measurements in the houses of 97 adults and children living < 50, 50–99 or > 100 m away from a power line were collected. Time-weighted geometric mean personal exposure was 0.53 μT for children living within 50 m of a hvpl, 0.12 μT for children between 50 and 100 m and 0.04 μT for children living further away. Vistnes et al.[32] reported similar findings from 34 24-h personal exposure measurements with children. Geometric mean personal exposure was 0.39 μT for children living within 50 m of a 300 kV hvpl, 0.09 μT for children between 50 and 100 m and 0.065 μT for children living between 100 and 200 m and 0.025 μT for children living further away. However, for 31 children attending also a school located about 24 m from the power line, the geometric mean exposure was higher with 0.58, 0.3, 0.14 and 0.06 μT, respectively. Valič et al.[33] reported an average personal mean exposure of 0.29 μT from 16 observations ranging from 0.05 to 1.35 μT with 6 out of 16 participants (below 17 years) living close to a transformer or hvpl according to self-reports.

In our study, personal mean exposure of children living in a house with built-in transformers was, on average, not increased because in our sample most of the participants did not live in an
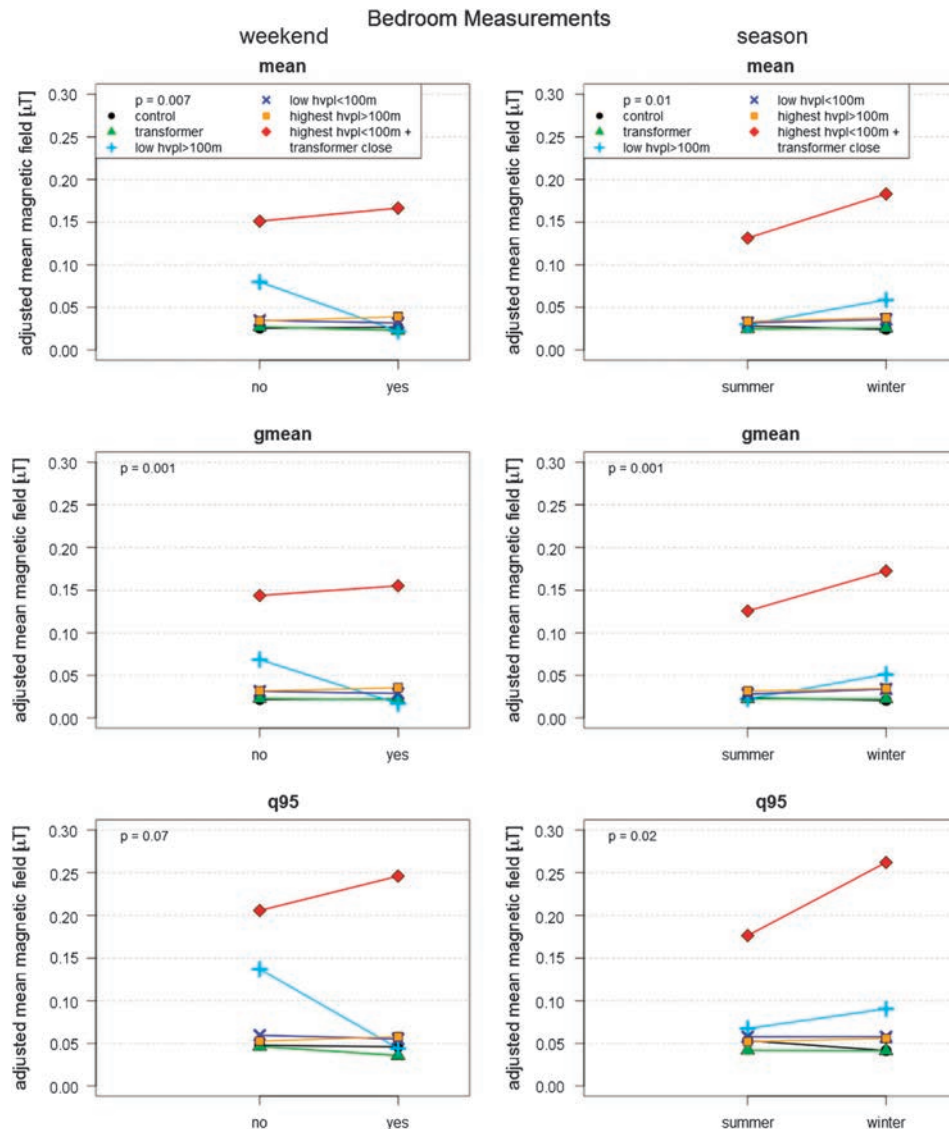
Figure 3. Group-specific weekend and season effects for the 24-h bedroom exposure measurements (arithmetic and geometric mean, 95th percentile*). *P*-value refers to the interaction term in the model. *Adjusted for age, urbanity, country, gender and either season or weekend.

apartment directly adjacent to a transformer. The three partici-pants living in apartments or houses directly adjacent to a transformer had exposure levels comparable with the "highest hvpl ≤ 100 m" group. Previous measurement studies have demon-strated that mean ELF-MF exposure at home is only elevated in apartments directly adjacent to the transformer,[41–43] and such an increase was also observed to a somewhat lower extent for personal exposures of adult inhabitants.[24] However, it has not yet been evaluated whether the exposure pattern of inhabitants could still be affected and, we hypothesised that the 95th and the 99th percentiles of the personal exposures might be affected by passing strong exposure sources more frequently. However, neither for children in the "low hvpl ≤ 100 m", "low hvpl > 100 m", nor the "transformer" group we found elevated 95th and 99th personal exposure percentiles compared to the control group.

We expected to find higher exposure values in the cold than in the warm season due to a higher consumption of electricity in winter for heating and illumination in Switzerland (20% higher compared summer during our study period[47]) and at least to a small degree — in Northern Italy (only few percentage of difference between warm and cold seasons[48]). The observed seasonal in our

models was relatively weak and did not reach statistical significance for most personal and bedroom measures. However, when modelling it as group–season interaction we found that in the "highest hvpl ≤ 100 m" group personal and bedroom exposure was increased in the cold season compared to the warm season whereas this pattern was not observed in the other groups. This indicates that seasonal changes in electricity consumption is only relevant for highly exposed children whereas in the low-exposure range, the seasonal effect is of minor relevance compared to the random data variability. Children may spend more time indoor than outdoor in the cold season and, this may have also contributed to the seasonal differences of the personal measurements but not the bedroom measurements, which are independent of the behaviour of the children. Other studies[17,30] also found lower temperature or colder seasons to be associated with higher ELF-MF exposure.

For the weekend, we found a similar group–weekend interac-tion with higher personal exposure values during weekend compared to school days in the "highest hvpl ≤ 100 m" group. The fact that this weekend pattern was not found for the bedroom measurements indicates that this is not due to variation in the source strength but due to the child's behaviour. This is also
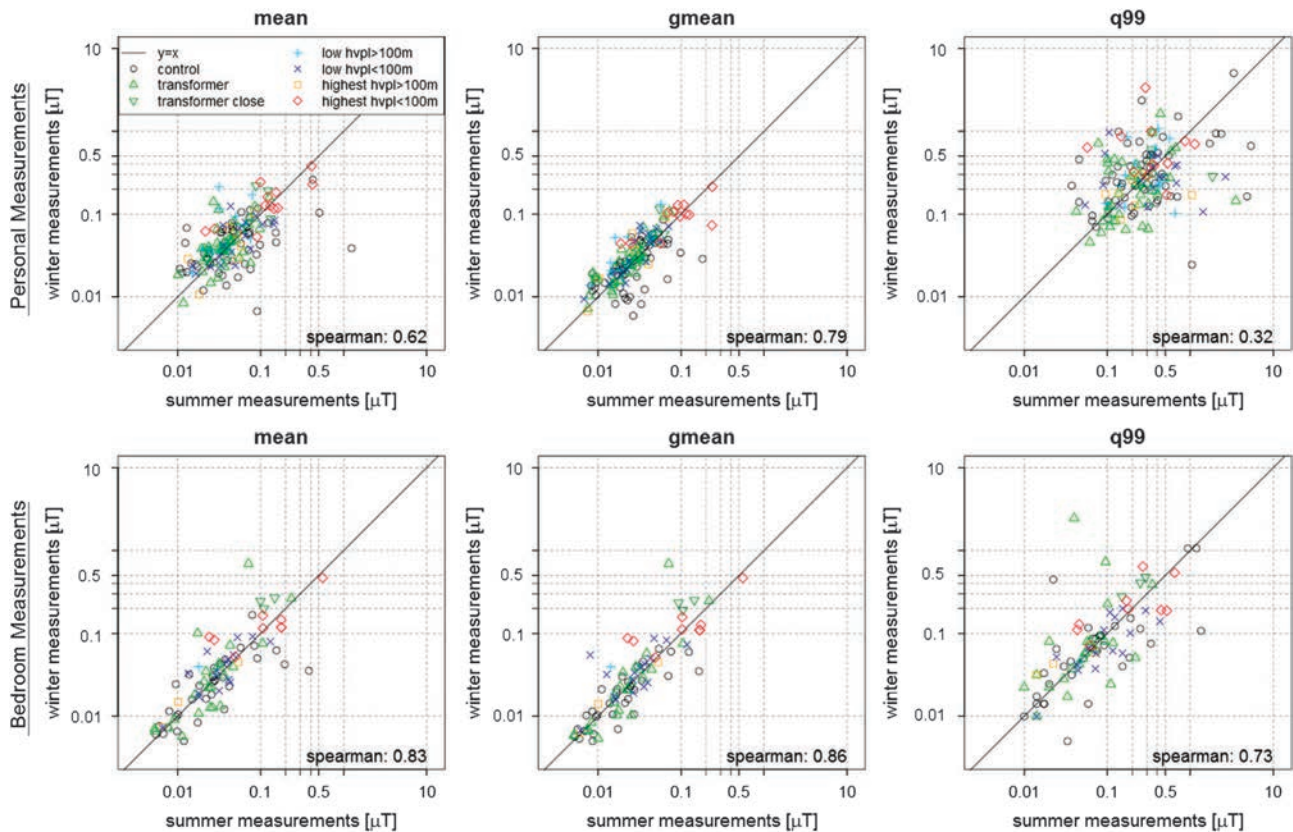
Figure 4. Reproducibility of total personal and bedroom exposure measurements. The scatterplots show cold *vs* warm season measurements for the mean, geometric mean and 99th percentile (personal measurements: $n = 154$; bedroom measurements: $n = 90$). The Spearman's rank correlation coefficient is also given.

Table 4. Reproducibility measures for total personal ($n = 154$) and bedroom ($n = 90$) exposure measurements.

Reproducibility measures	Measure type	Exposure metrics				
		Arithmetic mean	Geometric mean	Median	95th percentile	99th percentile
Pearson's correlation	Personal	0.37 (0.24, 1.00)***	0.71 (0.64, 1.00)***	0.32 (0.20, 1.00)***	0.16 (0.03, 1.00)*	0.27 (0.14, 1.00)***
	Bedroom	0.56 (0.43, 1.00)***	0.65 (0.54, 1.00)***	0.63 (0.51, 1.00)***	0.45 (0.30, 1.00)***	0.36 (0.20, 1.00)***
Spearman's correlation	Personal	0.62***	0.79***	0.83***	0.42***	0.32***
	Bedroom	0.83***	0.86***	0.86***	0.83***	0.73***
Diff $\leq 0.05\,\mu T$ or rel. diff $\leq 20\%$ (%)	Personal	85	96	94	49	27
	Bedroom	83	88	85	79	68

For each summary measure of each exposure assessment method, the correlations and the percentage of measurement pairs that differ $< 0.5\,\mu T$ or 20% is given. The stars symbolise the significance range (*:= $0.05 \geqslant P > 0.01$; **:= $0.01 \geqslant P > 0.001$; ***:= $P \leqslant 0.001$).

supported by the diary information. On average, the children spent a larger fraction of their day at home during day on the weekend (~40%) than during schooldays (~20%) whereas for the night time there were no substantial differences. For the "highest hvpl ≤ 100 m" and "transformer close" group, the difference was smaller but still apparent with 32% of time spent at home during day on the weekend and 24% during school days.

Personal and bedroom ELF-MF exposure values in Italy were about 35–45% lower than in Switzerland and lower exposure levels have been found in boys compared to girls. No obvious explanation could be found and, we argue that these findings should not be over interpreted. We used a multivariable model and, thus the relatively small differences in gender ratio between sampling groups are not expected to be responsible for the observed gender difference. Since the exposure difference was

seen in both, personal and bedroom measurements, gender-related behaviour differences are unlikely to play a role. More plausible seems to be a random variability in the selection of the sample. In any case, in absolute terms, the differences are very small (mean country difference: $0.01\,\mu T$; mean gender difference: $0.01\,\mu T$).

Reproducibility

By comparing the repeated measurements per subject, we could demonstrate that bedroom measurements are better reproducible than personal measurements (Table 4), which has been hypothesised because bedroom measurements are less affected by variability in the behaviour of the children. Also Kaune et al.[17] reported higher Spearman's correlation coefficients for bedroom arithmetic mean exposure (0.91 and 0.84) than for personal arithmetic mean exposure (0.80 and 0.76) of women aged 20–77
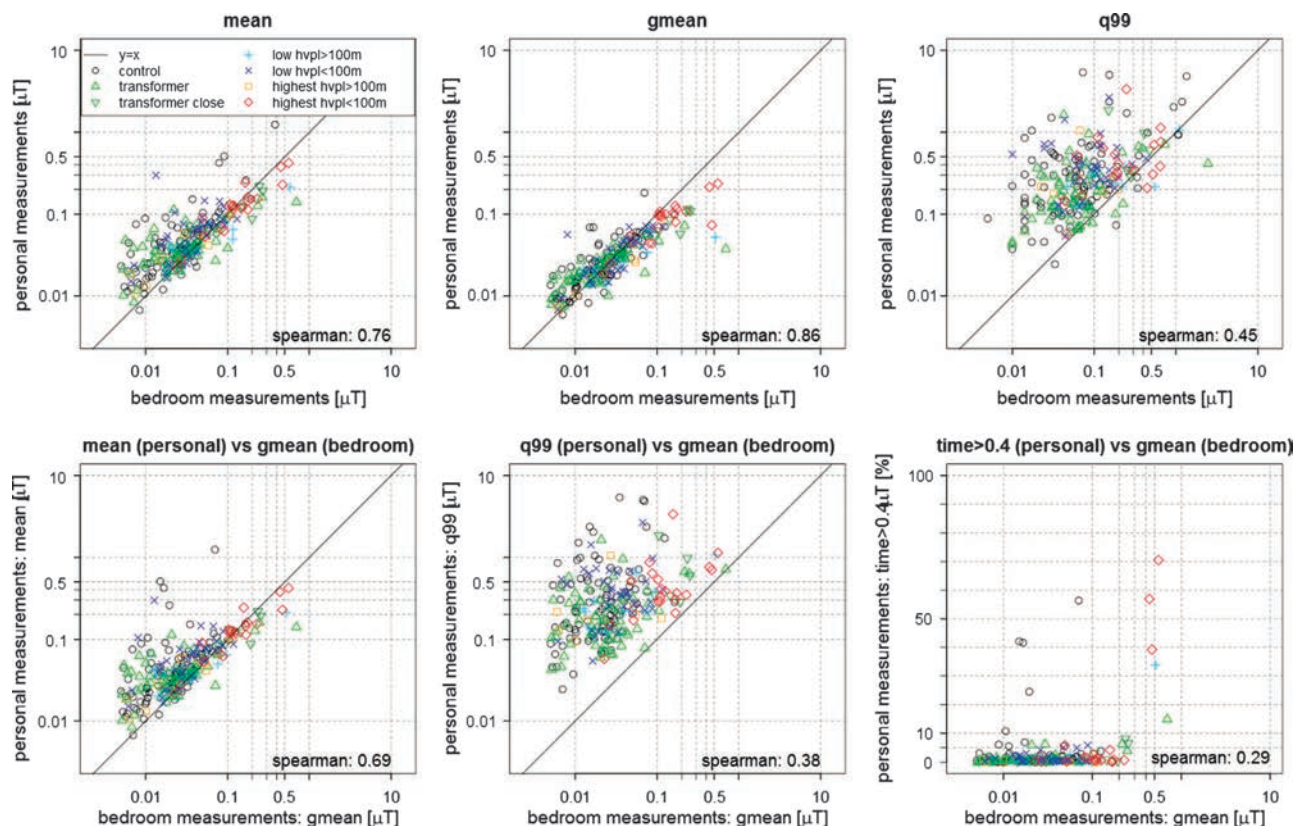
Figure 5. Comparison of total personal and bedroom exposure for the mean, geometric mean and 99th percentile (first row and second row) comparison between total personal exposure of the arithmetic mean, 99th percentile and proportion of measurements $> 0.4\,\mu$T with total bedroom geometric mean exposure ($n = 242$). The Spearman's rank correlation coefficient is also given.

Table 5. Comparison between personal and bedroom exposure measurements ($n = 242$).

Comparability measure	Exposure metric				
	Arithmetic mean	Geometric mean	Median	95th percentile	99th percentile
Pearson's correlation	0.59 (0.52, 1.00)***	0.67 (0.61, 1.00)***	0.39 (0.3, 1.00)***	0.73 (0.67, 1.00)***	0.33 (0.23, 1.00)***
Spearman's correlation	0.76***	0.86***	0.88***	0.60***	0.45***
Diff ≤ 0.05 μT or rel. diff ≤ 20% (%)	87	91	93	60	18
Sensitivity to 0.2 μT[a]	0.55 (0.23, 0.83)	1.00 (0.09, 1.00)	0.75 (0.19, 0.99)	0.39 (0.26, 0.52)	0.24 (0.17, 0.32)
Specificity to 0.2 μT[a]	0.98 (0.95, 0.99)	0.97 (0.94, 0.99)	0.96 (0.92, 0.98)	0.97 (0.93, 0.99)	0.99 (0.94, 1.00)
Sensitivity to 0.1 μT[b]	0.68 (0.51, 0.82)	0.92 (0.62, 1.00)	0.94 (0.73, 1.00)	0.47 (0.38, 0.56)	0.41 (0.35, 0.48)
Specificity to 0.1 μT[b]	0.97 (0.93, 0.99)	0.93 (0.88, 0.96)	0.96 (0.92, 0.98)	0.97 (0.92, 0.99)	0.97 (0.84, 1.00)

For each summary measure, the correlations and the percentage of measurement pairs that differ $< 0.5\,\mu$T or 20% is given. Also the sensitivity and specificity for different cutoff values are reported. The stars symbolise the significance range (*:= $0.05 \geqslant P > 0.01$; **:= $0.01 \geqslant P > 0.001$; ***:= $P < 0.001$). [a]For the 95th and 99th percentile, the sensitivity and specificity is given for a cutoff of 1 μT instead of 0.2 μT. [b]For the 95th and 99th percentile, the sensitivity and specificity is given for a cutoff of 0.5 μT instead of 0.1 μT.

and when comparing repeated 48-h measurements separated by 3 and 6 months, respectively.

Since the biological relevant exposure measure to cause childhood leukaemia is not known, we evaluated the reproducibility of various exposure measures representing cumulative exposures (arithmetic mean), cumulative log-transformed exposure (geometric mean) or peak exposure effects (95th and 99th percentiles). For bedroom and on a lower level also for personal measurements, we found best reproducibility for the geometric mean exposure. Foliart et al.[12] also concluded that "the geometric mean is less sensitive to outliers and is a more stable metric than time weighted average". In their study, Spearman's rank

correlation coefficient for repeated (separated by 1 year) measurements of 255 children within a childhood leukaemia survival study and with stable residency was 0.6. The high percentiles of personal exposure, however, turned out to be only poorly reproducible in our study. The very high reproducibility of geometric mean bedroom measurement is a relevant finding for epidemiological exposure assessment. This demonstrates that 24-h bedroom measurements, which are done in many epidemiological studies, fairly well represent mean long-term ELF-MF exposure in the bedroom. However, from an etiological perspective one is interested how well mean bedroom measurements represents long-term personal exposure, which is discussed in the following.

Comparison between Personal and Bedroom Exposure Measurements

We found mean (arithmetic, geometric or median) bedroom measurements to be strongly (to very strongly) correlated with mean personal exposure measures (Table 5). The correlation we found is somewhat higher than for other studies in adults that reported those correlation coefficients between 0.5 and 0.8,[15–17,19,22] which is partly due to our sampling strategy to maximise the exposure range of the sample. In addition, it may reflect the fact that children spend more time at home than adults, in particular the very young children. Friedman et al.[11] reported results in line with our findings with Spearman's rank correlation of 0.75 between 24-h personal and bedroom measurements for children under 9 years and 0.41 for children in the age of 9–14 years.

Friedman et al.[11] suggested that alternative metrics, for example, peak exposure would probably be strongly correlated with the mean. While in our study, this correlation was still reasonably strong within an exposure assessment method (see Supplementary Material; Supplementary Tables S.2 and S.3), the correlation was weak when comparing bedroom (geometric) mean exposure with personal peak exposure (Figure 5). This means that the epidemiological surrogate "mean bedroom exposure" is unlikely to adequately reflect peak exposure values of children, which indicates that the observed epidemiological association is unlikely be caused by peak ELF-MF exposure. Also Kaune et al.[17] concluded that bedroom or residential measurements are unlikely to represent short-term variability of personal measurements.

Our data also demonstrate that the bedroom geometric means consistently overestimate the geometric mean personal exposure for children being highly exposed at home whereas it tends to underestimate personal exposure of children with low exposure at home (Figure 5). This pattern was also seen in the Swedish study.[31] Children with high exposure values at home had lower exposure measurements elsewhere (e.g., at school) whereas for children with low exposure at home exposure measurements elsewhere were not markedly different. This means that the epidemiological surrogate geometric mean bedroom exposure is expected to overestimate the true exposure range in any epidemiological study population. Earlier studies also drew the same conclusion.[16,19]

Harmonic Content

We did not find group differences in the harmonic content of the personal or bedroom measurements, except for the very small sample of participants living in an apartment or home directly adjacent to a transformer that showed an increased but still low average harmonic content ($< 0.05\,\mu$T). The geometric mean broadband bedroom measurements were not well correlated with the harmonic frequency range (Spearman's rank correlation: < 0.5) of the personal measurements, in particular for children exposed $> 0.1\,\mu$T (Spearman's rank correlation, approximately -0.25). Thus, the harmonic content is unlikely to play a major role for the observed epidemiological association between mean ELF-MFs at home and childhood leukaemia as the children living close to a hvpl do not seem to be exposed to higher harmonics than the general population.

Limitations

Selection bias might have affected our results. It is conceivable that families concerned about magnetic field exposure were more likely to participate, and that the number of electrical appliances at home is reduced in such families yielding an underestimation of exposure. However, the findings on comparability of personal and bedroom exposure would not be affected by selection bias. According to a systematic literature review on residential ELF-MFs in Europe, 30% of the population is exposed below 0.01 μT and 20% above 0.05 μT.[49] In our sample geometric mean bedroom exposure of the control group (the study group closest to the "general population"), was below 0.01 μT in 20% and above 0.05 μT in 13% of the measurements, which is similar to the above results from Grellier et al.[49] For the corresponding personal measurements, the respective percentages were 13% and 14%. However, it has again to be noted that our study population was not a random sample of children as children with potentially higher exposures were oversampled.

A limitation of our study is the lack of children attending a school within 100 m of a highest hvpl (see Supplementary Material; Supplementary Figure S.2) in our sample. Vistnes et al.,[32] however, found that the correlation between geometric mean personal exposure and calculated fields at home was still high (0.81 and 0.96 for Pearson's and Spearman's correlation, respectively) for children attaining a school very close to a 300 kV hvpl. This indicates that even in such cases bedroom measurements would still be a reasonable exposure proxy for epidemiological studies.

Because of the fact that the measurement devices were not worn on the body at home ELF-MFs from household appliances may be somewhat underestimated because they are often localised. However, dosimetric calculations within the ARIMMORA project demonstrated that ELF-MF exposure from near-field sources are less relevant compared to long-term more uniform exposures from transformers and power lines.[50]

We used a sampling rate of 30 s but do not think that this has substantially influenced our results on peak exposure, as Mezei et al.[28] have shown for a data set of personal measurements in pregnant women that, the 99th percentile was unaffected by the sampling rate. A small test with two EMDEX II with 3- and 30-s sampling rate confirmed these findings.

CONCLUSIONS

Our study indicates that personal measurements are very useful to identify factors relevant for exposure in children such as temporal variation in electricity consumption as well as the behaviour of the children. In our study, geometric mean of personal measurements was highly reproducible and very strongly correlated with the geometric mean of bedroom measurements, the exposure metric, which is usually used in epidemiological studies on childhood leukaemia. This demonstrates that geometric mean bedroom exposure (either measured or modelled) is expected to represent long-term ELF-MF exposure of children. Reproducibility and respective correlations were lower for high percentiles or for cumulative exposure time above a threshold indicating that such exposure circumstances are unlikely to be the reason for the observed increased leukaemia risks in epidemiological studies.

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