Personal radiofrequency electromagnetic field exposure measurements in Swiss adolescents

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ABSTRACT

Background: Adolescents belong to the heaviest users of wireless communication devices, but little is known about their personal exposure to radiofrequency electromagnetic fields (RF-EMF).
Objectives: The aim of this paper is to describe personal RF-EMF exposure of Swiss adolescents and evaluate exposure relevant factors. Furthermore, personal measurements were used to estimate average contributions of various sources to the total absorbed RF-EMF dose of the brain and the whole body.
Methods: Personal exposure was measured using a portable RF-EMF measurement device (ExpoM-RF) measuring 13 frequency bands ranging from 470 to 3600 MHz. The participants carried the device for three consecutive days and kept a time-activity diary. In total, 90 adolescents aged 13 to 17 years participated in the study conducted between May 2013 and April 2014. In addition, personal measurement values were combined with dose calculations for the use of wireless communication devices to quantify the contribution of various RF-EMF sources to the daily RF-EMF dose of adolescents.
Results: Main contributors to the total personal RF-EMF measurements of 63.2 $\mu W/m^2$ (0.15 V/m) were exposures from mobile phones (67.2%) and from mobile phone base stations (19.8%). WLAN at school and at home had little impact on the personal measurements (WLAN accounted for 3.5% of total personal measurements). According to the dose calculations, exposure from environmental sources (broadcast transmitters, mobile phone base stations, cordless phone base stations, WLAN access points, and mobile phones in the surroundings) contributed on average 6.0% to the brain dose and 9.0% to the whole-body dose.
Conclusions: RF-EMF exposure of adolescents is dominated by their own mobile phone use. Environmental sources such as mobile phone base stations play a minor role.

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1. Introduction

Mobile phones and other wireless communication devices emitting radiofrequency electromagnetic fields (RF-EMF) are nowadays omnipresent and undergo a rapid development. In 2014, there were almost 7 billion mobile phone subscriptions worldwide, corresponding to 96% of the population (ICT, 2015). In Switzerland, the number of mobile phone subscriptions reached 11.5 million in 2014, what corresponded to 141% of the population (ICT, 2015). The proportion of the world population covered by a 2G mobile phone network grew from 58% in 2001 to 95% in 2015 and mobile internet access increased 12 times since 2007 reaching 47% of the population in 2015 (ICT, 2015). Along that line, the

ownership and use of wireless communication devices is growing. A recent representative survey in 1086 adolescents aged between 12 and 19 years in Switzerland revealed that 98% of the adolescents owned a mobile phone, 76% a computer or laptop, and 29% a tablet (Willemse et al., 2014). This development leads to ubiquitous exposure to RF-EMF in our everyday environment, but little is known about the extent of personal exposure to RF-EMF, in particular in adolescents. As a result, the current World Health Organization (WHO) research agenda for radiofrequency fields rates the quantification of personal exposures high priority (WHO, 2010).

Adolescents spend most of their time at home and in school. Spot measurements of environmental RF-EMF in different European countries showed that exposure at home was mainly caused by mobile phone base stations and cordless phone (Digital Enhanced Cordless Telecommunications (DECT)) base stations (Breckenkamp et al., 2012; Tomitsch and Dechant, 2015; Tomitsch et al., 2010; Verloock et al.,

2014a; Verloock et al., 2014b; Vermeeren et al., 2013) or WLAN (Wireless Local Area Network) access points (Breckenkamp et al., 2012). Main contributors to the environmental exposure in schools in Belgium and Greece were mobile phone base stations, radio broadcast transmitters and WLAN access points (Verloock et al., 2014a; Verloock et al., 2014b; Vermeeren et al., 2013).

Data from spot measurements are useful to estimate exposure to RF-EMF in our everyday environments, but personal exposure to RF-EMF depends not only on exposure levels in different environments, but also on individual behaviours such as the use of wireless communication devices and time spent in various environments (Röösli et al., 2010). Personal measurements are measurement campaigns where volunteers carry a portable measurement device during their everyday life activities. Such measurements enable to measure at times and places representative of real-life situations.

Personal measurements in Europe were mainly conducted in adults (Bolte and Eikelboom, 2012; Frei et al., 2009; Thomas et al., 2008a; Thuróczy et al., 2008; Valic et al., 2009; Viel et al., 2009); measurements in children and adolescents are scarce. Researchers in Hungary conducted in 2009 personal measurements in 31 school teachers as a proxy for children's exposure (Juhasz et al., 2011). In Slovenia, measurements in 18 children and adolescents (5–17 years) were performed in 2010/2011 (Valic et al., 2015), and in Germany, measurements in 1524 adolescents (13–17 years) were conducted in 2006/2007 (Thomas et al., 2008b). However, since then smartphones have been introduced and the use of wireless communication devices in this age group has changed tremendously. Measurements in Austria and Switzerland indicate that RF-EMF exposure in residential areas may have increased over the last few years (Tomitsch and Dechant, 2015; Urbinello et al., 2014).

Exposure to RF-EMF can be divided into two different types, the exposure from environmental sources such as broadcast transmitters, mobile phone base stations, cordless phone base stations, WLAN access points, and mobile phones in the surroundings (far-field), and the exposure from the use of wireless communication devices such as mobile phones, cordless phones and computers, laptops and tablets connected to WLAN (near-field). It is known that personal measurements may not adequately record the latter part of exposure, because measured values depend highly on the distance between the emitting source and the measurement device, which is not necessarily the same as the distance between the emitting source and the body (Bolte, 2016; Inyang et al., 2008; Röösli et al., 2010). Thus, to obtain a comprehensive overview on the personal RF-EMF exposure, personal measurements need to be combined with dosimetric approaches that quantify absorbed RF-EMF by the body.

The aim of this paper is to describe the personal RF-EMF exposure of Swiss adolescents in daily life and evaluate factors affecting personal exposure. Further, it is aimed to use personal measurements to estimate average contributions from far-field and near-field sources to the total absorbed RF-EMF dose by using a recently developed RF-EMF dose modelling approach (Roser et al., 2015a).

2. Methods

2.1. HERMES study

The HERMES (Health Effects Related to Mobile phonE use in adolescentS) study, a cohort study conducted in Central Switzerland, aims to prospectively investigate whether the exposure to RF-EMF emitted by mobile phones and other wireless communication devices causes behavioural problems and non-specific health disturbances or affects cognitive function in adolescents (Roser et al., 2015b; Roser et al., 2016; Schoeni et al., 2016; Schoeni et al., 2015a; Schoeni et al., 2015b). The baseline investigation took place between June 2012 and March 2013; the follow-up investigation was conducted approximately one year later. The study participants filled in a paper and pencil questionnaire at school during school time supervised by two study managers.

Participants could indicate whether they were willing to participate in the measurement study. Furthermore, paper and pencil questionnaires for the parents were distributed and they were asked to send these back directly to the study managers.

2.2. Personal measurements

Personal measurements were conducted in a subgroup of the HERMES study participants. The participants of the personal measurements were selected so that they represented a broad range of the HERMES cohort according to basic criteria such as age, gender, school level, and urbanization of home and school place. Data collection took place between May 2013 and April 2014. The instructions for the personal measurements were given at school. The participants were instructed to carry the portable measurement device, a so-called exposimeter, for three consecutive days. They were asked to carry the exposimeter in a padded hip bag if they were moving and to place it in their vicinity, but not directly on the body, when not moving. During the night, they were instructed to charge the exposimeter and place it on their bedside table or close to their bed but not directly on the floor.

Two versions of the ExpoM-RF exposimeter (the current version and a not commercialized prototype) were used to measure 12 frequency bands ranging from DVB-T (Digital Video Broadcasting – Terrestrial, centre frequency of 620 MHz) to ISM 2.4 GHz (Industrial, Scientific and Medical 2.4 GHz, 2450 MHz) (Fields at Work, 2015; Lauer et al., 2011) with a measurement range of frequency specific lower reporting limits up to 5 V/m (upper reporting limit; Table 1). The sum of them is referred to as total personal RF-EMF measurements (Table 1). The devices have the size of $16 \times 8 \times 3–5$ cm and a weight of 300 g.

A sampling interval of 4 s was used. The devices were calibrated before the start of the measurements in January 2013, again in January 2014, and after the measurements in February 2015. Additionally, the participants kept a time-activity diary installed as an application on a smartphone provided by the study managers. The smartphone was operating in flight-mode to prevent influencing the measurements. The diary contained predefined locations categorized into home, school, outdoors, train, bus, car, and various locations. During the measurement period, GPS coordinates were recorded by the diary smartphone. At the end of the measurement period, they filled in a short questionnaire on exposure relevant factors such as WLAN at home, ownership of mobile phone subscription or prepaid mobile phone, and their mobile phone use during the measurement period (Table 2). Missing values in this questionnaire were imputed using answers to the same questions in the baseline or follow-up HERMES questionnaire whichever was temporally closer. The information about WLAN at school was obtained from the teacher or the head of the school during the school visit.

Ethical approval for the conduct of the study was received from the ethical committee of Lucerne, Switzerland on May 9, 2012.

2.3. Data cleaning

The personal measurement data were occasionally disrupted because of technical failures or because participants forgot to charge the device during night. We considered only those measurements which lasted at least 23 h and which had corresponding diary entries available for analysis. Diaries were manually cleaned for implausible chronologies of diary entries (e.g. being at school followed by being at home without a period of outdoor, public transport or car in-between) using the smartphone-recorded GPS coordinates and visualisation of the paths and the measurements corresponding to the diary entries.

2.4. Data analysis

2.4.1. Calculation of mean values

The calculations were performed in power flux density unit (μW/m^2). According to the sensitivity range specified by the manufacturer,

Table 1
Frequency range and reporting limits of the used frequency bands measured by the ExpoM-RF exposimeter (the current version and a not commercialized prototype). The sum of these bands is named total personal RF-EMF measurements.

Frequency band	Description	Frequency range [MHz]	Lower reporting limit [V/m]	Upper reporting limit [V/m]
TV	Television broadcast transmitter	470–790	0.0025	5
LTE 800 Downlink[a]	Transmission from mobile phone base station to handset	791–821	0.0025	5
LTE 800 Uplink[a]	Transmission from mobile phone handset to base station	832–862	0.0025	5
Uplink 900[b]	Transmission from mobile phone handset to base station	880–915	0.0025	5
Downlink 900[c]	Transmission from mobile phone base station to handset	925–960	0.0025	5
Uplink 1800[b]	Transmission from mobile phone handset to base station	1710–1785	0.0025	5
Downlink 1800[c]	Transmission from mobile phone base station to handset	1805–1880	0.0025	5
DECT	Digital Enhanced Cordless Telecommunications	1880–1900	0.0025	5
Uplink 1900[b]	Transmission from mobile phone handset to base station	1920–1980	0.0015	5
Downlink 2100[c]	Transmission from mobile phone base station to handset	2110–2170	0.0015	5
LTE 2600[a]	Transmission from mobile phone base station to handset and vice versa (combined downlink and uplink)	2500–2690	0.0125	5
WLAN	Wireless Local Area Network	2400–2485	0.0025	5

[a] Belongs to the total RF-EMF, but is not considered for the frequency band specific analyses.
[b] Belongs to the summarized uplink band; Uplink = Uplink 900 + Uplink 1800 + Uplink 1900.
[c] Belongs to the summarized downlink band; Downlink = Downlink 900 + Downlink 1800 + Downlink 2100.

measurements were left censored at the frequency specific lower reporting limit and right censored at 5 V/m (upper reporting limit; Table 1).

Total refers to the sum of the frequency bands listed in Table 1, *Uplink* (RF-EMF emitted from mobile phone handsets) to the sum of the uplink frequency bands Uplink 900, Uplink 1800 and Uplink 1900, and *Downlink* (RF-EMF emitted from mobile phone base stations) to the sum of the downlink frequency bands Downlink 900, Downlink 1800 and Downlink 2100 (see Table 1 for exact definitions of frequencies).

To account for interruption of measurements (e.g. from lack of charging), we calculated for each participant the average exposure for 6 time slots (5 time slots during daytime: 06:00–07:59, 08:00–11:59, 12:00–13:59, 14:00–16:59, 17:00–21:59, 1 time slot for night-time: 22:00–05:59). Mean exposure for the whole measurement period was then calculated as time-weighted average of these time slots. Mean

exposure for the day refers to the time-weighted average of the 5 daytime slots. Mean exposure for workdays was calculated in the same way as the mean exposure for the whole measurement period but taking into account only measurements on workdays, the same was applied for the weekend exposure. If for one day a time slot was missing, a time-weighted average was calculated with adjusted weights. Measurements with more than one missing time slot or missing night measurements were excluded. Mean exposure for the locations home, school, outdoors, train, bus, car and various locations was calculated taking into account all available measurements per participant at these locations according to their time-activity diary.

2.4.2. Evaluation of possibly exposure related factors

To address factors possibly affecting personal RF-EMF measurements, we compared the measurements of adolescents with and

Table 2
Characteristics of the personal measurements sample (n = 90) and the HERMES follow-up cohort (n = 425) and p-value for the *t*-test statistics for age and for the χ^2 test statistics for the other characteristics (significant results (p < 0.05) are indicated in bold).

	Personal measurements (n = 90)			HERMES follow-up cohort (n = 425)			
	n	Number	Percentage (%)	n[a]	Number	Percentage (%)	p-Value χ^2
Personal characteristics							
Age (years)	90	15.1 (13.2–17.2)		425	15.0 (13.2–17.8)		0.80 (*t*-test)
Sex: female	90	57	63.3	425	254	59.8	0.44
School level: college preparatory high school	90	21	23.3		97	22.8	0.90
Nationality							**0.01**
Swiss		81	90.0		341	80.2	
Mixed		4	4.4		59	13.9	
Foreign		5	5.6		25	5.9	
WLAN at school and at home							
WLAN at school	90	34	37.8	425	168	39.5	0.70
WLAN at home	90	86	95.6	342	319	93.3	0.31
Not switching off WLAN at home	86	61	70.9	310	208	67.1	0.37
Mobile phone use							
Owning a mobile phone	90	90	100.0	425	416	97.9	0.12
Owning a smartphone	90	85	94.4	416	398	95.7	0.52
Having a mobile phone subscription	90	41	45.6	416	234	56.3	**0.01**
Mobile phone switched off during night	90			413			0.13
No (Almost never or never/sometimes)		66	73.3		270	65.4	
Yes (frequently/almost always or always)		24	26.7		143	34.6	
Using mobile internet on the mobile phone	90	83	92.2	415	387	93.3	0.66
Use WLAN for internet on the mobile phone	83			385			0.10
Yes (about half of the time/always)		69	83.1		340	88.3	
No (no/sometimes)		14	16.9		45	11.7	

[a] Missing values in the HERMES follow-up cohort: 83 for WLAN at home, 9 for Not switching off WLAN at home, 3 for Mobile phone switched off during night, 1 for Using mobile internet on the mobile phone and 2 for Use WLAN for internet on the mobile phone.

without WLAN at school and at home, respectively as well as the impact of switching off the WLAN modem at home during the night. Regarding mobile phone use, we evaluated the impact of having a subscription or using a prepaid mobile phone, reporting to switch off the mobile phone during the night, and the use of internet on the mobile phone (with and without WLAN).

2.4.3. Sensitivity analyses

A sensitivity analysis was conducted to evaluate the impact of the manual diary cleaning on the study results by conducting analyses with and without corrected diary entries.

The adjacent Downlink 1800, DECT and Uplink 1900 bands are a challenge for personal RF-EMF exposimeters because cross-talk occurs between these bands (Lauer et al., 2012). To correct values for potential cross-talk, a data-driven correction algorithm was developed (manuscript in preparation). The development of the algorithm was based on personal measurements in 115 Swiss adolescents and adults. First, distinct exposure windows with similar exposure patterns were defined. Within these exposure windows, the correlations between DECT measurements and the 1800 MHz base station signal (Downlink 1800) and the 1900 MHz mobile phone handset signal (Uplink 1900), respectively were calculated. If the correlations were above a defined threshold value, it was corrected for cross-talk within the respective window. The ratio between the respective two signals was used to decide on the direction of the cross-talk. The median of the exposure at the corresponding location was used to substitute the affected values. A sensitivity analysis was conducted with this correction algorithm to assess the impact of this correction on the results of the personal measurements.

2.4.4. Use of personal measurements for dose estimations

Using the average exposures measured during the personal measurements, we applied a recently developed RF-EMF dose modelling approach (Roser et al., 2015a) that combines the exposure from near-field and far-field RF-EMF sources to put the personal measurements in the context of dose calculations for a typical (average) HERMES participant. The far-field component aggregates the measured or modelled exposure from environmental sources such as radio and television (TV) broadcast transmitters, mobile phone base stations, cordless phone base stations, WLAN access points as well as other people's mobile phones to a RF-EMF dose estimate using specific absorption rates (SAR) from the literature (Lauer et al., 2013). A short description can be found in the Supplementary material. For TV broadcast, mobile phone base stations, DECT base stations and WLAN access points we used the average of all personal measurements. The radio FM (Frequency Modulation) broadcasting band was not yet included in the prototype version of the ExpoM-RF and thus time-weighted average modelled exposure at home and at school of the participants was used instead (Bürgi et al., 2010; Bürgi et al., 2008). To estimate the contribution of uplink exposure from other people's mobile phones (far field), we used the mean uplink measurements of all participants that reported not to use mobile internet on their mobile phone, because their personal measurements are less affected by own mobile phone use. Note that all participants owned a mobile phone.

The near-field component of the dose model assesses RF-EMF dose from the use of wireless communication devices (mobile phones, cordless phones, computers, laptops and tablets connected to WLAN) by combining the duration of wireless device use with literature derived SAR values for the brain and the whole body for each of these exposure situations (Gati et al., 2009; Hadjem et al., 2010; Huang et al., 2014; Lauer et al., 2013; Persson et al., 2012; SEAWIND Sound Exposure and Risk Assessment of Wireless Network Devices Final Summary Report, 2013).

To obtain the wireless device use durations of a typical HERMES participant we used the wireless device use data of the whole HERMES cohort. For estimating average own mobile phone use in the sample, we used average operator-recorded call duration of all HERMES participants who gave consent to provide their data. For data traffic on the mobile phone and the use of computer, laptop and tablet with WLAN, the mean duration was obtained from the written HERMES questionnaire of all study participants. For the duration of DECT phone calls, the same duration as for mobile phone calls was assumed. This resulted in the typical HERMES participant with the following wireless device use each day: 1.85 min mobile phone and DECT phone calls, 11.5 min of mobile phone data traffic via network and 30.6 min via WLAN, 57.6 min of computer, laptop and tablet use while connected to WLAN, and having the mobile phone 4.42 h close to the body assuming stand-by data traffic of the mobile phone close to the body for this time period.

3. Results

3.1. Personal measurements

From 439 students who participated in the baseline investigation of the HERMES study, 221 (50.3%) volunteered to participate in the personal measurement study (Fig. 1). Thereof 121 adolescents were selected for participation in the personal measurements and 101 out of these 121 measurement sequences had at least 23 h of measurements and corresponding diary entries. Thereof 95 had a diary of sufficient quality to attribute measurements to locations. Five of these sets had more than one missing time slot and were excluded. This resulted in 90 measurements included in the analysis. The personal measurements lasted on average 72.3 h (SD = 21.7 h, range: 23.0–121.2 h) and 62,710 (range: 21,455–112,653) single measurements per participant were recorded. A subsample of 38 out of the 90 measurement sequences had measurements on both workdays and weekend days available and was used for the comparison of workdays and weekend measurements.

3.2. Characteristics of study participants

The mean age of the participants was 15.1 years and 57 (63.3%) participants were female (Table 2). The majority (90.0%) had Swiss nationality. Thirty-four participants attended a school with WLAN, 86 had WLAN at home and thereof, 61 reported not to switch off their WLAN modem at home during the night.

All participants owned a mobile phone at the time of the personal measurements and most of these devices (94.4%) were smartphones. About half of the participants (45.6%) had a mobile phone subscription with a mobile phone operator; the others used prepaid mobile phones. A quarter (26.7%) indicated to switch off their mobile phone during the night. Of the 83 participants using mobile internet on their mobile phone, 83.1% regularly used WLAN for that connection. According to t-test and χ^2 test statistics, the participants of the personal measurements were comparable to the HERMES follow-up cohort (n = 425) according to age, sex, school level, WLAN at school and at home, owning a mobile phone or a smartphone and mobile phone use except that more Swiss adolescents were included (p-value = 0.01) and less participants had a mobile phone subscription (p-value = 0.01) (Table 2).

3.3. Mean exposure and contribution of different RF-EMF sources

Total personal RF-EMF measurements were on average 63.2 μW/m^2 (0.15 V/m). Median total RF-EMF measurements were considerably lower (25.5 μW/m^2, Table 3) reflecting the highly skewed data distribution (Fig. S1 in Supplementary material). The exposure from mobile phones (uplink) contributed most (67.2% of total RF-EMF) (Table 3 and Fig. 2). Exposure from fixed site transmitters contributed 26.5% (downlink: 19.8%, TV broadcast transmitters: 6.7%). WLAN exposure accounted on average for 3.5% and DECT exposure for 1.3%. Uplink 900 and downlink 900 contributed most to average uplink and downlink exposure, respectively.
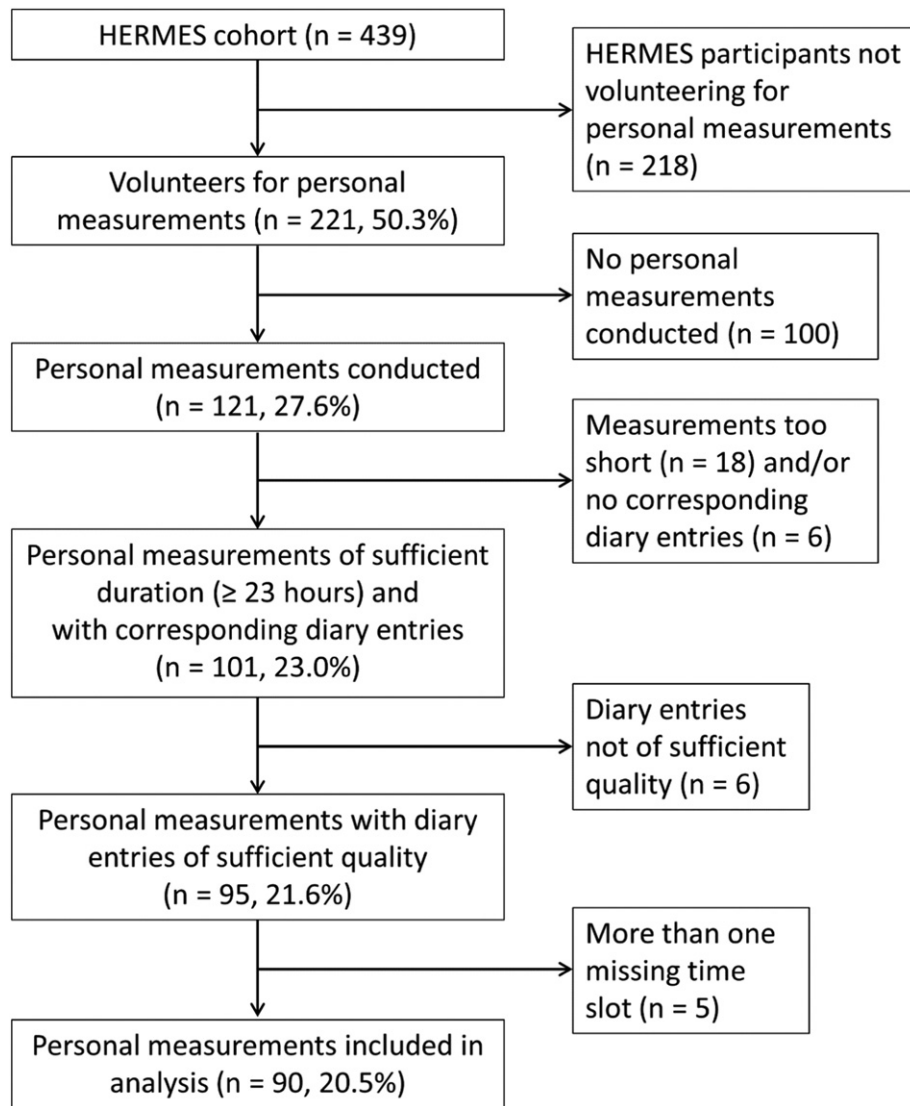
Fig. 1. Participants of the personal measurements consisting of a subgroup of the participants of the HERMES cohort.

Table 3
Summary statistics for the whole measurement period per frequency band, for uplink, downlink and total RF-EMF measurements ($\mu W/m^2$) and total RF-EMF measurements in V/m.

Frequency band	Mean (%)		Min	5th percentile	25th percentile	Median	75th percentile	95th percentile	Max
TV	4.26	(6.7)	0.08	0.13	0.41	0.62	2.33	11.84	169.78
Uplink 900	24.59	(38.9)	0.02	0.20	1.38	6.03	27.54	88.17	263.61
Downlink 900	9.40	(14.9)	0.19	0.35	1.38	3.33	10.35	44.61	103.24
Uplink 1800	7.23	(11.4)	0.02	0.08	0.19	0.44	1.81	17.46	327.07
Downlink 1800	1.42	(2.3)	0.04	0.07	0.23	0.62	1.39	4.96	19.45
DECT	0.83	(1.3)	0.02	0.02	0.02	0.07	0.36	3.99	14.71
Uplink 1900	10.67	(16.9)	0.01	0.01	0.06	0.81	4.24	30.45	373.49
Downlink 2100	1.67	(2.6)	0.03	0.04	0.15	0.43	1.87	6.85	17.19
WLAN	2.18	(3.5)	0.03	0.05	0.24	0.56	1.72	11.63	23.88
Uplink[a]	42.49	(67.2)	0.07	0.38	2.51	12.15	39.64	177.22	664.88
Downlink[b]	12.50	(19.8)	0.34	0.62	2.12	5.07	13.47	51.36	107.99
Total[c]	63.23		1.78	5.92	11.34	25.49	70.86	240.41	682.90
Total[c] [V/m]	0.15		0.03	0.05	0.07	0.10	0.16	0.30	0.51

[a] Uplink = Uplink 900 + Uplink 1800 + Uplink 1900.
[b] Downlink = Downlink 900 + Downlink 1800 + Downlink 2100.
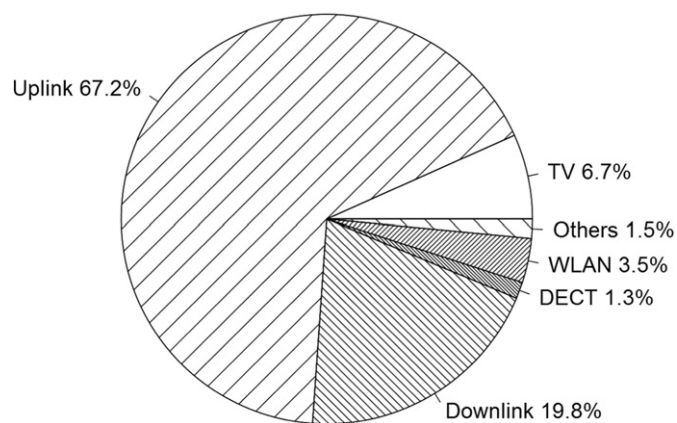[c] Total refers to the total RF-EMF measurements considering the twelve frequency bands listed in Table 1.

Fig. 2. Mean contributions of different sources to the total personal RF-EMF measurements (in power flux density). Mean = 63.2 μW/m² (0.15 V/m). *Others* refers to the frequency bands LTE 800 Downlink, LTE 800 Uplink and LTE 2600.

3.4. Personal measurements at different locations

Regarding different locations, adolescents' average total personal RF-EMF measurements were highest when spending time in public transport and cars (839.4 μW/m² in cars, 676.3 μW/m² in buses and 537.1 μW/m² in trains) (Fig. 3 and Tables S1 and S2 in Supplementary material). The lowest measurements were measured at school (59.6 μW/m²) and at home (31.1 μW/m²).

3.5. WLAN at school and at home

The presence of WLAN at school and WLAN at home had little impact on average WLAN measurements (Fig. 4 and Tables S3 and S4 in Supplementary material). Participants attending a school with WLAN (34 participants (Table 2) consisting of 32 adolescents having WLAN at home and at school and two adolescents having WLAN at school but not at home) had slightly higher mean WLAN exposure than participants without WLAN at their school (2.9 μW/m² vs. 1.5 μW/m²). If the
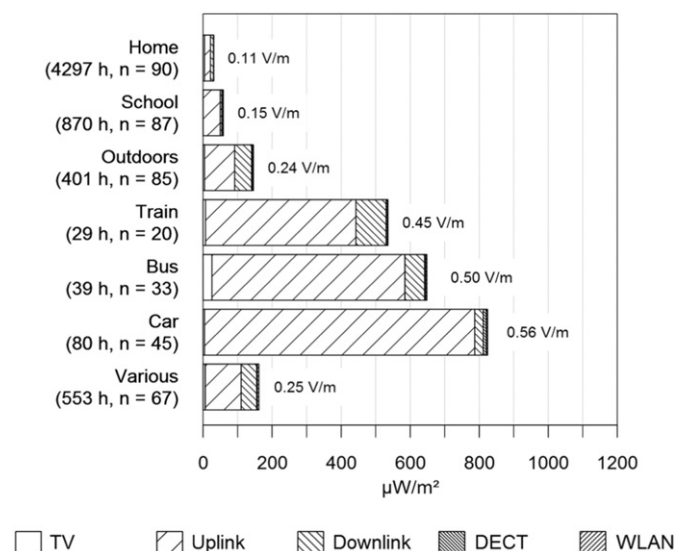
Fig. 3. Mean RF-EMF measurements from different sources at different locations. The hours in brackets indicate cumulative measurement duration at the corresponding location, n indicates the number of participants with measurements assigned to the location according to the diary. Total mean RF-EMF measurements at the locations are additionally added in V/m. The corresponding numbers and median values can be found in Tables S1 and S2 in the Supplementary material.
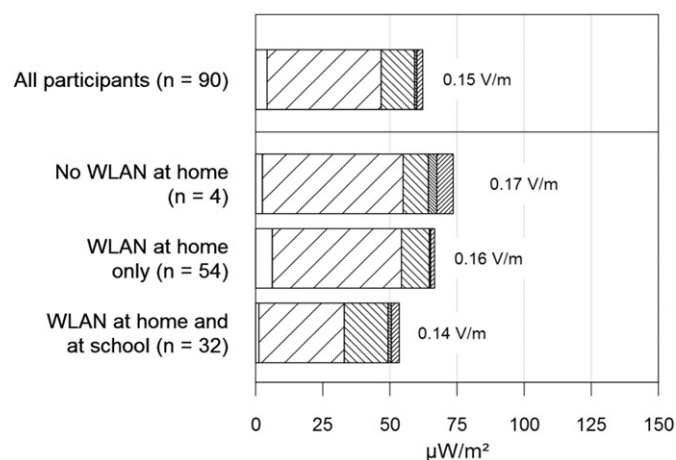

Fig. 4. Mean RF-EMF measurements for all participants (n = 90) and mean measurements for *No WLAN at home* (n = 4), *WLAN at home only* (n = 54) and *WLAN at home and in school* (n = 32). Total mean RF-EMF measurements per group are additionally added in V/m. The corresponding numbers and median values can be found in Tables S3 and S4 the Supplementary material.

comparison was restricted to the measurements taken in the school, the difference was somewhat larger (7.4 μW/m² vs. 1.0 μW/m²). Only four participants had no WLAN at home (thereof two had WLAN at school). Overall their mean WLAN measurements were higher (6.0 μW/m²) than for the other two groups. However, their WLAN measurements at home were indeed minimal (0.02 W/m²).

Participants, who reported *not* to switch off WLAN modem at home during night, had higher WLAN measurements at home compared to the participants who switched off WLAN at home (0.9 vs. 0.4 μW/m²). For the whole measurement period, the WLAN measurements were increased as well (2.6 vs. 0.7 μW/m²).

3.6. Mobile phone use related factors

Fig. 5 demonstrates that the own mobile phone has a substantial impact on personal uplink measurements (see Tables S5 and S6 in Supplementary material for details). For instance, participants with a subscription had higher uplink measurements compared to those using prepaid mobile phones (78.0 vs. 12.8 μW/m²). The use of internet by mobile phone was associated with higher uplink measurements as well (45.3 vs. 8.9 μW/m²). Those stating not to use WLAN by mobile phone had higher uplink measurements compared to those who used WLAN (68.1 vs. 40.7 μW/m²), but strikingly, the difference in WLAN measurements was marginal between these two groups (2.7 vs. 2.3 μW/m²).

3.7. Diurnal variation of personal measurements

Total RF-EMF measurements were clearly increased during daytime compared to night-time (80.8 vs. 28.1 μW/m²) (Fig. 6 and Tables S7 and S8 in Supplementary material).

For 38 (42.2%) participants we had measurements on workdays and on weekend days available. For those, mean RF-EMF measurements were slightly higher on weekend days compared to workdays (57.3 vs. 51.0 μW/m²). The diurnal pattern was similar on workdays and on weekends, total measurements increased with progressing time of the day (Fig. 7 and Table S9 in Supplementary material).

3.8. Use of personal measurements for dose estimations

Using the recently developed RF-EMF exposure surrogate (Roser et al., 2015a) and the personal measurements, the daily dose for different
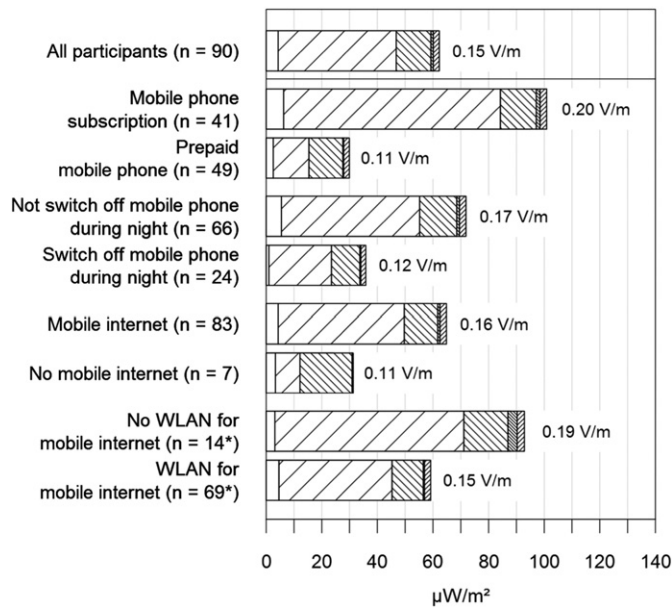
Fig. 5. Mean RF-EMF measurements for all participants and mean RF-EMF measurements for the mobile phone related factors having a mobile phone subscription (compared to using a prepaid mobile phone), not switching off the mobile phone during the night and the use of internet on the mobile phone (with and without WLAN). Total mean RF-EMF measurements per group are additionally added in V/m. The corresponding numbers and median values can be found in Tables S5 and S6 in the Supplementary material. *Note, that the groups *No WLAN for mobile internet* and *WLAN for mobile internet* include only participants using mobile internet on the mobile phone (n = 83).

exposure sources was calculated for the typical (average) HERMES participant (Figs. 8 and 9 and Table S10 in Supplementary material).

Far-field exposure contributed 6.0% to the brain dose and 9.0% to the whole body dose. The most relevant far-field contributor was downlink with 2.6% for the brain and 3.7% for the whole body dose. WLAN contributed on average 0.2% to the brain dose and 0.5% to the whole body dose. Using the mobile phone for calls was the most relevant contributor to the average brain RF-EMF dose (77.0%). For the whole body dose mobile phone calls contributed 23.6%, data transmission via mobile phone
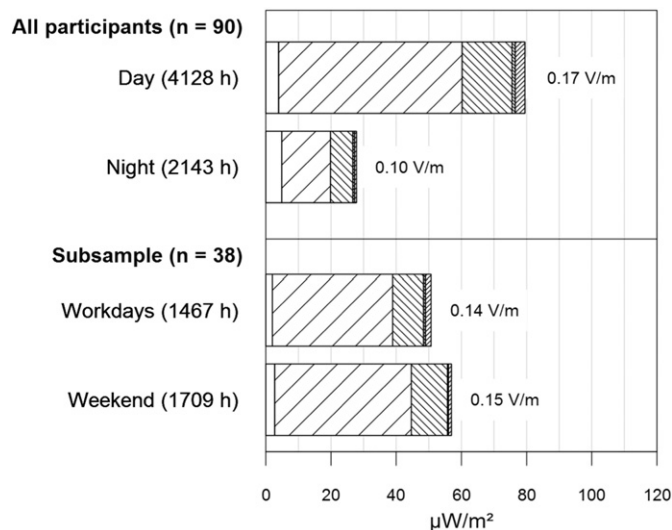

Fig. 6. Diurnal variation of mean RF-EMF measurements: For daytime and night-time (n = 90) and for workdays and weekend (n = 38) for different RF-EMF sources. Total mean RF-EMF measurements per time of the day and type of day are additionally added in V/m. The corresponding numbers and median values can be found in Tables S7 and S8 in the Supplementary material.
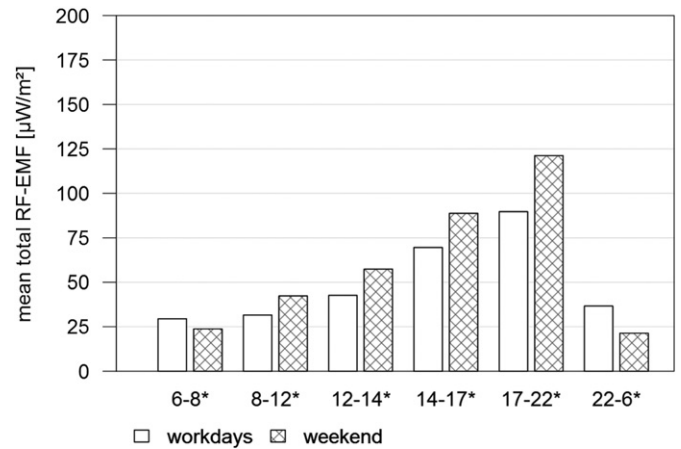

Fig. 7. Diurnal variation of the mean total RF-EMF measurements on workdays (white bars) and on weekends (shaded bars) based on data from the subsample of 38 participants with workdays and weekend measurements available. The corresponding numbers and median values can be found in Tables S9 in the Supplementary material. *Note that these time slots correspond to the time slots 06:00–07:59, 08:00–11:59, 12:00–13:59, 14:00–16:59, 17:00–21:59, and 22:00–05:59.

network 7.0% and data transmission via WLAN 18.7%. Carrying a mobile phone on the body in stand-by mode contributed 1.6%. The use of WLAN by computers, laptops and tablets contributed 35.3% to the whole body dose.
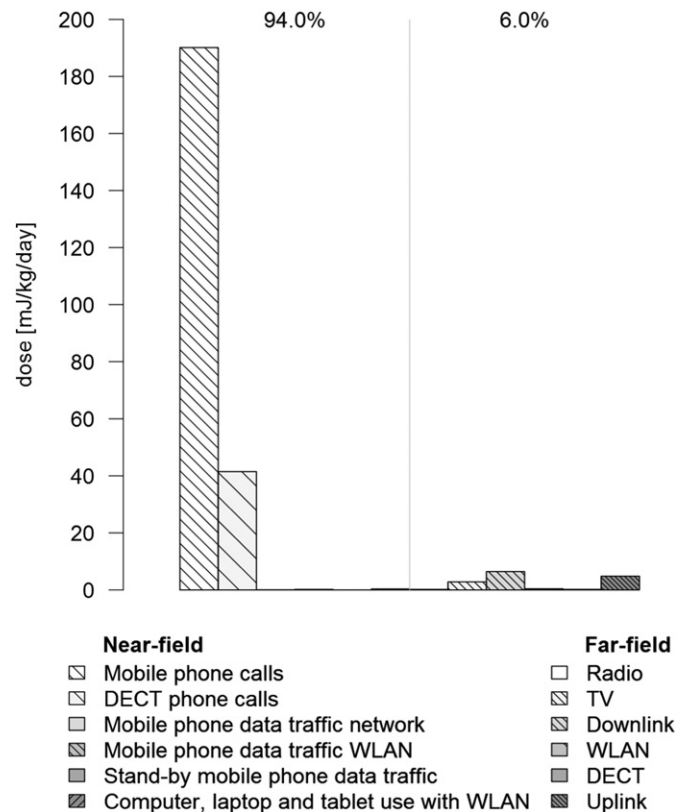

Fig. 8. Daily brain dose from the use of wireless communication devices (near-field dose; left side of the graph) and environmental sources (far-field dose; right side of the graph) for the typical (average) HERMES participant. *Numbers above the bars indicate the percentage of the near-field and the far-field dose on the total dose, respectively. *Average daily device use in HERMES: 1.85 min mobile phone and DECT phone calls, 11.5 min of mobile phone data traffic via network and 30.6 min via WLAN, 57.6 min of computer, laptop and tablet use while connected to WLAN and having the mobile phone on the body for 4.42 h.
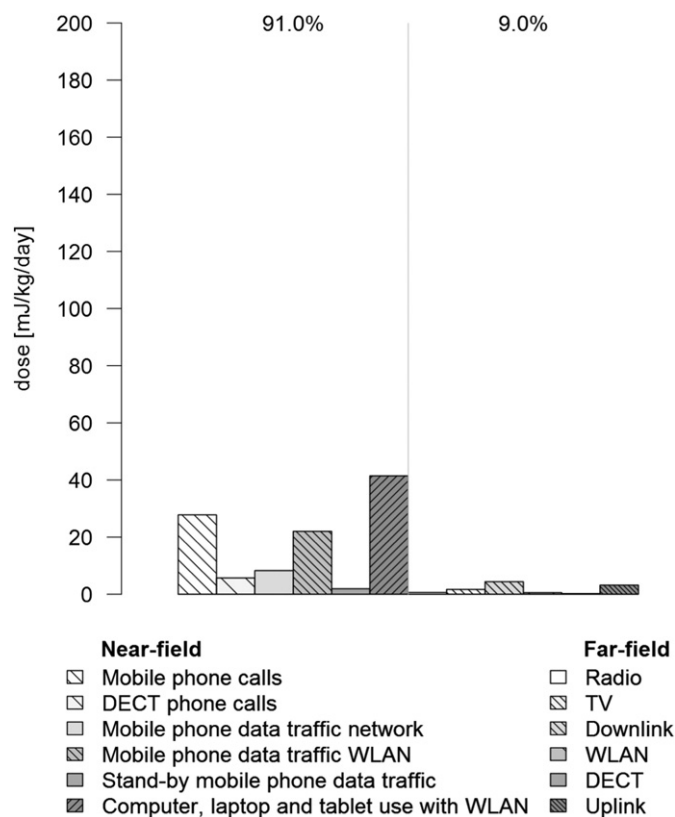
Fig. 9. Daily whole body dose from the use of wireless communication devices (near-field dose; left side of the graph) and environmental sources (far-field dose; right side of the graph) for the typical (average) HERMES participant. *Numbers above the bars indicate the percentage of the near-field and the far-field dose on the total dose, respectively.

3.9. Sensitivity analyses

3.9.1. Diary cleaning

In a sensitivity analysis, we compared our results with an analysis based on a dataset with original (uncleaned) diary entries. This analysis showed that diary cleaning is relevant for locations and activities with short durations (train and bus), whereas measurements with long durations (home and school) were barely affected (Table S11 in Supplementary material). These differences were driven by changes in the uplink measurements and to a lesser extent by changes in the downlink measurements.

3.9.2. DECT correction algorithm

The applied DECT correction algorithm reduced the average DECT measurements by a factor of 5.8 (Table S12 in Supplementary material). Since DECT measurements were a small part of the total measurements (1.3% on average), the reduction factor was small for the total measurements (factor of 1.1) and the contribution of the different sources to the total exposure did change only minimally (63.2% vs. 67.2% for uplink, 18.7% vs. 19.8% for downlink, 3.2% vs. 3.5% for WLAN, 6.3% vs. 6.7% for TV and 7.1% vs. 1.3% for DECT). Regarding different locations reduction factors were highest in buses and cars (36.8 and 15.0, respectively). For details see Tables S12, S13, S14, S15 and S16 in Supplementary material.

4. Discussion

Main contributors to the personal RF-EMF measurements of our study participants were mobile phones (uplink) followed by mobile phone base stations (downlink). Uplink was particularly high in adolescents using the internet on their mobile phone. The mean contribution from WLAN exposure was low, even for adolescents having WLAN at school and at home. Using personal measurements and combining them with data on the usage of wireless devices for a comprehensive dose calculation of the typical HERMES participant revealed that far-field sources contributed 6.0% to the total RF-EMF dose of the brain and 9.0% to the whole body dose, whereas 94% and 91% of the total RF-EMF dose of the brain and the whole body, respectively originated from near-field sources.

4.1. Comparison with other studies

The prototype version of the ExpoM-RF used in this measurement study does not measure radio FM (88–108 MHz) broadcasting as done in most other previous studies. However, on average, radio FM is a small contributor in our study (on average 1.7 $\mu W/m^2$ at home and 0.8 $\mu W/m^2$ at school according to geospatial propagation modelling for the HERMES cohort) and thus, in the following paragraph, our measurements are compared with other personal measurement studies that had included radio FM.

Measured personal total RF-EMF exposure varied across studies, ranging from 21.5 $\mu W/m^2$ in German children to 180 $\mu W/m^2$ in Dutch adults (Bolte and Eikelboom, 2012; Frei et al., 2009; Thomas et al., 2008a; Thomas et al., 2008b; Thuróczy et al., 2008; Valic et al., 2015; Viel et al., 2009) (Table 4). These discrepancies may be explained by different study populations (children, adolescents and adults), different measurement devices, diverse data processing (for instance dealing with measurements below the reporting limit of the devices) and different study settings (place and time). The most comparable study in terms of study population is the German measurement study in 1524 adolescents in 2006/2007 (Thomas et al., 2008b), in which measured total exposure for uplink, downlink, DECT and WLAN was 24.0 $\mu W/m^2$ during waking hours what is considerably lower compared to the mean daytime measurements for the same frequency bands in our study (75.5 $\mu W/m^2$). However, at that time smartphones were not yet available and the use of mobile internet, the most relevant exposure factor in our study, was not an issue. Our small sample of 7 participants not using mobile internet had a mean exposure of 31.5 $\mu W/m^2$ what is similar to the German study. In newer studies in adults, higher exposure levels were measured: 130 $\mu W/m^2$ in Switzerland (Frei et al., 2009) and 180 $\mu W/m^2$ in the Netherlands (Bolte and Eikelboom, 2012) compared to 63.2 $\mu W/m^2$ in our study. These measurements were done in adults and in mostly urban areas, whereas our study area mainly consisted of rural places. In addition, lower exposure levels in schools for adolescents compared to workplaces for adults may contribute to the lower exposure levels in our study.

We found uplink and downlink being the dominant sources (67.2% and 19.8% of the total exposure in our study). In other personal measurement studies the contribution of different sources was distributed more equally (Bolte and Eikelboom, 2012; Frei et al., 2009; Thuróczy et al., 2008; Viel et al., 2009). Possible explanations for this discrepancy may include low network coverage in our rural study area and longer mobile internet use in adolescents compared to adults.

4.2. Measurements at different locations and times

Our finding of high measurement values when travelling (537.1 $\mu W/m^2$ in trains, 676.3 $\mu W/m^2$ in buses and 839.4 $\mu W/m^2$ in cars in our study) confirms previous results although some variations in levels have been observed in different studies; for instance for the exposure in trains: 1160 $\mu W/m^2$ in a Swiss measurement study (Frei et al., 2009), 354 $\mu W/m^2$ in the Netherlands (Bolte and Eikelboom, 2012) and 175 $\mu W/m^2$ in France (Viel et al., 2009). Measurements at home (31.1 $\mu W/m^2$ in our study) were in general lower compared to previous personal measurement studies (levels of 172 $\mu W/m^2$ (Bolte and Eikelboom, 2012), 100 $\mu W/m^2$ (Frei et al., 2009) and 106.2 $\mu W/m^2$

Table 4
Comparison with other personal measurement studies. Results of the current study are shown in bold.

Country	Sample size	Study population	Measurement period	Exposimeter	Additional information	24 h exposure [µW/m²]					
						Total	Uplink	Downlink	DECT	WLAN	
Switzerland	**90**	**Adolescents**	**May 2013–April 2014**	**ExpoM-RF**	**• Exposimeter carried in a padded hip bag when moving, in their vicinity when not moving** **• DECT correction algorithm applied**	**63.2**	**42.5**	**12.5**	**0.8**	**2.2**	**HERMES**
Switzerland	166	Adults	April 2007–February 2008	EME Spy 120	• Exposimeter worn on belt or in backpack when moving, in their vicinity when not moving • Mobile phone and cordless phone calls excluded • Reporting limit = 6.6 µW/m²; ROS method for non-detects applied (Helsel, 2005)	130.0	37.9	41.6	29.5	5.3	Frei et al. (2009)
Hungary	21	Adults	June–July 2005	DSP-090	• Exposimeter worn on the body when moving, in their vicinity when not moving • Reporting limit = 6.6 µW/m²; non-detects set to reporting limit	70.3	23.8	24.2	–	–	Thuróczy et al. (2008)
Germany	3000	Children and adolescents	February 2006–December 2007	ESM-140	• Exposimeter worn on arm • No differentiation between uplink and downlink possible due to exposimeter limitations • Only daytime data • Reporting limit = 6.6 µW/m²; non-detects set to reporting limit/2	22.8	–	–	–	–	Thomas et al. (2008b)
Germany	329	Adults	January 2005–August 2006	ESM-140	• Exposimeter worn on arm • No differentiation between uplink and downlink possible due to measurement device limitations • Only daytime data • Reporting limit = 6.6 µW/m²; non-detects set to reporting limit/2	24.0	–	–	–	1.1	Thomas et al. (2008a)
The Netherlands	98	Adults	2009	EME Spy 121	• Exposimeter worn on right hip at fixed angle • Mobile phone and cordless phone calls excluded • Reporting limit = 6.6 µW/m²; ROS method for non-detects applied (Helsel, 2005)	180.0	67.5	22.9	57.1	25.4	Bolte and Eikelboom (2012)
Slovenia	18	Children and adolescents	February 2010–March 2011	EME Spy 120	• Reporting limit = 6.6 µW/m²; non-detects set to reporting limit	75.2[a]	–	26.2	13	9.6	Valic et al. (2015)
France	377	Adults	December 2005–September 2006	EME Spy 120	• Exposimeter worn on body (waist or over shoulder) when moving, in their vicinity during night • Reporting limit = 6.6 µW/m²; ROS method for non-detects applied (Helsel, 2005)	22.7[b]	4.3	5.1	3.6	3.8	Viel et al. (2009)
Slovenia	54	Adults	July 2007–November 2008	EME Spy 120	• Exposimeter worn on the belt, in pouch or backpack when moving, in their vicinity when not moving • Reporting limit = 6.6 µW/m²; non-detects set to reporting limit	–	25.7	42.1	8.2	7.7	Valic et al. (2009)

[a] Total without uplink since exposure to mobile phones was not evaluated in the study.
[b] Own calculation of the sum of all frequency bands for the Total. The original paper reports a Total of 107.2 µW/m², which does not fit the sum of the frequency bands.

(Viel et al., 2009)). Since personal measurements in children and adolescents are rare, reported levels in schools are scarce. Mean measurements of 59.6 µW/m² in our study were much lower than levels of spot measurements in schools in Belgium and Greece (325.2 to 424.7 µW/m²) (Verloock et al., 2014a; Vermeeren et al., 2013). Note that these spot measurements intended to assess highest values, whereas personal measurements represent typical values.

Slightly increased exposure at weekend compared to workdays (+12% in mean measurements) and clearly decreased exposure during night-time compared to daytime (−65% in mean measurements) was observed in other personal measurement studies as well (Bolte and Eikelboom, 2012; Frei et al., 2009; Viel et al., 2009). Personal measurements conducted by researchers in Belgium using 28 predefined exposure scenarios also found that uplink and DECT measurements were clearly decreased during night-time compared to daytime (Joseph et al., 2008). Increased exposure during afternoon hours compared to morning hours was found in German children and adolescents as well

(Thomas et al., 2008b), whereas in German adults no difference in exposure for morning and afternoon hours was observed (Thomas et al., 2008a). A similar diurnal pattern of increasing exposure with progressing time of the day was observed in Dutch adults (Bolte and Eikelboom, 2012).

4.3. DECT measurements

Average DECT measurements in our sample (0.8 µW/m²) were considerably lower compared to personal measurements in Switzerland in 2007 (29.5 µW/m² (Frei et al., 2009)), but comparable to measurements in France in 2006 (3.6 µW/m² (Viel et al., 2009)) using both EME Spy 120 devices (SATIMO, France). Part of the difference in the measurements in Switzerland can be explained by the fact that the previously used measurement device EME Spy 120 overestimated DECT measurements (Lauer et al., 2012). Another reason for the lower DECT exposure may be the introduction of eco mode DECT phones. Eco mode phones

emit only if they are used for calls, whereas conventional DECT phones also emit RF-EMF in stand-by mode. This explanation is in line with a spot measurement survey in Austrian households (Tomitsch and Dechant, 2015). They found a 60% reduction in mean DECT exposure between 2006 and 2012 and a mean DECT exposure of 3.0 µW/m² for households without DECT phone or an eco mode DECT phone compared to 420.7 µW/m² for households with a conventional DECT phone (Tomitsch and Dechant, 2015).

4.4. WLAN measurements

Our WLAN measurements (on average 2.2 µW/m²) were similar to personal measurements in Switzerland (5.3 µW/m² (Frei et al., 2009)) and Germany (1.1 µW/m² (Thomas et al., 2008a)) between 2005 and 2008.

We found WLAN at school and at home having minor impact on personal exposure. There is a public debate whether schools should install WLAN in their buildings. Our measurements demonstrate that this exposure source is of minor relevance compared to other RF-EMF sources. Attending a school with or without WLAN yields 0.2% difference in total whole body RF-EMF dose, and similarly, the impact of switching off WLAN at home during the night is minor (0.2% of whole body dose). Measurements in Austrian households found a more pronounced difference in WLAN exposure for households with WLAN compared to those without or switched off WLAN access point (68.9 vs. 2.7 µW/m²). However, they did not measure average exposure but intended to measure the highest value at bedside (Tomitsch and Dechant, 2015).

4.5. Uplink measurements

Uplink measurements were on average 42.5 µW/m² in our study.

Our results indicate that mainly using the internet on the mobile phone increases personal uplink measurements. For the participants using mobile internet, mean uplink measurements ranged from 0.1 to 664.9 µW/m²; for the remaining 7 participants not using internet on the mobile phone uplink exposure ranged from 0.7 to 17.7 µW/m².

Although, in principle it is not possible to disentangle the contribution of the uplink exposure caused by the own mobile phone from the exposure from other people's mobile phones, our comparison of mobile internet users and non-users clearly demonstrates that the own mobile phone plays a considerable role for personal uplink measurements. In a previous Swiss study the difference of personal uplink measurements between people with and without a mobile phone was small (42 vs. 20 µW/m² (Frei et al., 2009)) leading to the conclusion, that personal mobile phone use contributed relatively little to the personal measurements (Frei et al., 2010). Since then, type of mobile phones has changed remarkably and 94% of our measurement study participants owned a smartphone. These participants reported to use their mobile phone on average 12 min per day for internet use via mobile phone network and 31 min per day for internet use via WLAN. In addition, emissions in stand-by mode may also be more relevant for smart phones than for old style phones as it was observed in a measurement study investigating exposure from mobile phones in stand-by mode when travelling (Urbinello and Röösli, 2013).

4.6. Use of personal measurements for dose estimations

The dose calculation integrating near-field and far-field sources clearly demonstrates that the RF-EMF exposure of adolescents is mainly driven by the use of wireless devices close to the body. For the typical HERMES participant, 94.0% of the brain and 91.0% of the whole body dose originated from wireless device use. Far-field sources are thus less relevant. For instance, the brain dose of the average downlink exposure during 24 h corresponds to a GSM (Global System for Mobile Communications, here Uplink 900 or Uplink 1800) mobile phone call duration of 2.6 s and an UMTS (Universal Mobile Telecommunications

System, here Uplink 1900) call duration of 6.1 min. For the whole-body dose, 15.0 s GSM and 34.2 min UMTS call duration correspond to the mean downlink exposure of one day. This demonstrates that precautionary measures to reduce far-field exposure sources have limited impact on the exposure situation of adolescents. However, the type of network (GSM, UMTS or WLAN) and the connection quality interacts with the mobile phone and determines its output power. Thus, from a precautionary point of view, to efficiently reduce exposure, one should more systematically investigate, which measures are most relevant to reduce RF-EMF emissions of wireless devices, in particular when browsing the internet since this is often done by adolescents. The potential of such measures is exemplarily demonstrated in our measurement study by the fact that mean uplink measurements were decreased, whereas mean WLAN measurements were not increased for participants who reported to regularly use WLAN on their mobile phone compared to those who do not use WLAN for mobile internet.

Obviously, dose calculations are subject to uncertainty, but nevertheless, this approach is considered useful to combine exposure from near-field and far-field sources to one exposure surrogate.

4.7. Strengths and limitations of personal measurements

Personal measurements allow investigating the exposure during all activities of everyday life of adolescents. Thus, measured exposure is assumed to represent true exposure taking into account individual behaviour (Röösli et al., 2010). However, personal measurements also have limitations. They are costly, time-consuming and ask for a big effort from the participants. This often results in a relatively small study sample as in our study (90 adolescents out of 439 HERMES participants). Furthermore, selection bias may be of concern since adolescents who are willing to make the effort to participate may be different from non-participants. However, our participants were comparable to the HERMES follow-up cohort expect regarding nationality and having a mobile phone subscription. Since we found having a mobile phone subscription associated with higher uplink measurements the considerable contribution of the uplink exposure on the total RF-EMF exposure may be even underestimated.

We were not able to control the positioning of the exposimeters during the personal measurements. However, we instructed the participants in person and in detail about how to handle the exposimeter during the measurements. Furthermore, we provided detailed information sheets and the participants had the possibility to contact us at any time during the measurements in the case of uncertainties or questions.

Other limitations come with body worn exposimeters per se; cross-talk between adjacent frequency bands, interference of measurements by the body (body shielding) and the use of wireless communication devices operating close to the body.

Cross-talk occurs if emitted power in one frequency band is measured and reported in another band. Of particular concern is cross-talk concerning the DECT band (1880–1900 MHz) which is narrow and adjoins the downlink 1800 (1805–1880 MHz) and the uplink 1900 (1920–1980 MHz) bands (Lauer et al., 2012). We approached that problem in a sensitivity analysis applying a DECT correction algorithm. The correction resulted in 82.6% decrease in average DECT exposure and 6.1% decrease in total exposure (Table S12 in Supplementary material). Changes in the contribution of the different sources were minor.

Body shielding arises if the body is between the RF-EMF emitting source and the exposimeter. For one single measurement, shielding can reduce the measurement by a factor 10 or even higher (Blas et al., 2007; Iskra et al., 2010). However, for average exposure, the situation is less dramatic. Numerical simulations (Gryz et al., 2015; Iskra et al., 2010; Neubauer et al., 2010) and test measurements (Bolte et al., 2011) have shown that underestimation depends on the type of measurement device, on the frequency band, on the position of the measurement device on the body and on human shape, and was up to 50% in total. We instructed the participants to place the exposimeter in

their vicinity, but not directly on the body, when not moving. Thus, in our study body shielding mostly affects the measurements taken during travel.

Another limitation of personal measurements with exposimeters is the assessment of the exposure from wireless communication devices operating close to the body (Bolte, 2016; Inyang et al., 2008; Röösli et al., 2010). To deal with that challenge, we combined the personal measurements with a recently developed exposure surrogate combining exposure from environmental sources with exposure from the use of devices (Roser et al., 2015a), a unique feature of our study.

Our measurement study was conducted in a rural area; thus, our results might not be generalizable to urban areas and adolescent populations in other countries. Therefore, more measurement studies in this age population covering a larger variety of urbanization degree are needed.

5. Conclusions

Our results indicate that the main contributor to total RF-EMF measurements of adolescents is their mobile internet use on the mobile phone. For those not using the mobile internet, downlink is most relevant. WLAN at school and at home have minor impact on personal RF-EMF measurements. By combining personal measurements with dose calculations from the use of wireless communication devices close to the body, we were able to demonstrate that the exposure from environmental sources plays a minor role compared to the use of wireless communication devices. In conclusion, in our study of 90 adolescents living in primarily rural areas of Switzerland we did not find any indication that adolescents are highly exposed to RF-EMF despite their frequent wireless device use.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2016.12.008.

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