Environmental Research 212 (2022) 113252

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Personal radiofrequency electromagnetic field exposure of adolescents in the Greater London area in the SCAMP cohort and the association with restrictions on permitted use of mobile communication technologies at school and at home

Claudia Schmutz[a,b], Alexandra Bürgler[a,b], Narain Ashta[a,b], Jana Soenksen[a,b], Yasmin Bou Karim[c,d], Chen Shen[c,d], Rachel B. Smith[c,d,e], Rosemary H. Jenkins[c,d,f], Michael O. Mireku[c,g], Julian Mutz[c,d,h], Mikaël J.A. Maes[c,i,j], Rosi Hirst[c], Irene Chang[c], Charlotte Fleming[c], Aamirah Mussa[c], Daphna Kesary[c], Darren Addison[k], Myron Maslanyj[k], Mireille B. Toledano[c,d,e], Martin Röösli[a,b], Marloes Eeftens[a,b,*]

[a] *Swiss Tropical and Public Health Institute, Basel, Switzerland*
[b] *University of Basel, Basel, Switzerland*
[c] *MRC Centre for Environment and Health, Department of Epidemiology and Biostatistics, School of Public Health, Imperial College London, W2 1PG, United Kingdom*
[d] *National Institute for Health Research Health Protection Research Units in Environmental Exposures and Health & Chemical and Radiation Threats and Hazards, in partnership with UK Health Security Agency (UKHSA), Imperial College London, W2 1PG, United Kingdom*
[e] *Mohn Centre for Children's Health and Wellbeing, School of Public Health, Imperial College London, W2 1PG, United Kingdom*
[f] *Public Health Policy Evaluation Unit, Department of Primary Care and Public Health, School of Public Health, Imperial College London, Charing Cross Campus, The Reynolds Building, St Dunstan's Road, London, W6 8RP, United Kingdom*
[g] *University of Lincoln, School of Psychology, Lincoln, United Kingdom*
[h] *Social, Genetic and Developmental Psychiatry Centre, Institute of Psychiatry, Psychology & Neuroscience, King's College London, United Kingdom*
[i] *Department of Geography, University College London, Pearson Building, Gower Street, London, WC1E 6BT, United Kingdom*
[j] *Centre for Biodiversity and Environment Research, Department of Genetics, Evolution and Environment, University College London, Gower Street, London, WC1E 6BT, United Kingdom*
[k] *UK Health Security Agency (UKHSA), Centre for Chemical, Radiation and Environmental Hazards, Harwell Campus, Oxon, OX11 0RQ, United Kingdom*

ARTICLE INFO

Keywords:
Mobile phones
Personal exposure
Radiofrequency electromagnetic fields
Smart phones
WiFi
SCAMP

ABSTRACT

Personal measurements of radiofrequency electromagnetic fields (RF-EMF) have been used in several studies to characterise personal exposure in daily life, but such data are limitedly available for adolescents, and not yet for the United Kingdom (UK). In this study, we aimed to characterise personal exposure to RF-EMF in adolescents and to study the association between exposure and rules applied at school and at home to restrict wireless communication use, likely implemented to reduce other effects of mobile technology (e.g. distraction).

We measured exposure to RF-EMF for 16 common frequency bands (87.5 MHz–3.5 GHz), using portable measurement devices (ExpoM-RF), in a subsample of adolescents participating in the cohort Study of Cognition, Adolescents and Mobile Phones (SCAMP) from Greater London (UK) (n = 188). School and home rules were assessed by questionnaire and concerned the school's availability of WiFi and mobile phone policy, and parental restrictions on permitted mobile phone use. Adolescents recorded their activities in real time using a diary app on a study smartphone, while characterizing their personal RF-EMF exposure in daily life, during different activities and times of the day.

Data analysis was done for 148 adolescents from 29 schools who recorded RF-EMF data for a median duration of 47 h. The majority (74%) of adolescents spent part of their time at school during the measurement period.

Abbreviations: RF-EMF, radio-frequency electromagnetic fields; DECT, Digital Enhanced Cordless Telecommunications; GSM, Global System for Mobile Communications; UMTS, Universal Mobile Telecommunication System; WiFi, Wireless Fidelity; LTE, Long Term Evolution; ISM, Industrial, Scientific and Medical; DAB, Digital Audio Broadcasting; DVB-T, Digital Video Broadcasting; TETRA, Terrestrial Trunked Radio.

* Corresponding author. Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, Socinstrasse 57, P.O. Box 4002, Basel, Switzerland.

E-mail address: marloes.eeftens@swisstph.ch (M. Eeftens).

https://doi.org/10.1016/j.envres.2022.113252
Received 18 August 2021; Received in revised form 1 April 2022; Accepted 2 April 2022
Available online 12 April 2022

Median total RF-EMF exposure was 40 μW/m^2 at home, 94 μW/m^2 at school, and 100 μW/m^2 overall. In general, restrictions at school or at home made little difference for adolescents' measured exposure to RF-EMF, except for uplink exposure from mobile phones while at school, which was found to be significantly lower for adolescents attending schools not permitting phone use at all, compared to adolescents attending schools allowing mobile phone use during breaks. This difference was not statistically significant for total personal exposure.

Total exposure to RF-EMF in adolescents living in Greater London tended to be higher compared to exposure levels reported in other European countries. This study suggests that school policies and parental restrictions are not associated with a lower RF-EMF exposure in adolescents.

1. Introduction

Children and adolescents grow up surrounded by mobile communication technologies. In 2017, 44% of children in the United Kingdom aged 8–11 and 86% of children aged 12–15 had their own phone (Ofcom, 2017). The percentage of children owning a smartphone (versus a non-smartphone) has been steadily increasing in all age groups as compared to previous years (Ofcom, 2017). There are concerns about use of mobile technologies and RF-EMF emissions on children's brains, because they will endure lifelong exposures, while their brains may also be more vulnerable than those of adults (Kheifets et al., 2005). So far, findings from previous studies regarding the relationship between RF-EMF exposure and cognitive performance in children and adolescents have been inconsistent (Bhatt et al., 2017; Calvente et al., 2016; Chetty-Mhlanga et al., 2020; Foerster et al., 2018; Guxens et al., 2016; Redmayne, 2016; Roser et al., 2016; Thomas et al., 2010).

The Study of Cognition, Adolescents and Mobile Phones (SCAMP) was conceived specifically around the topic of RF-EMF. The SCAMP cohort is a prospective study of adolescents in and around Greater London (United Kingdom), which aims to investigate the cognitive and behavioural outcomes of the use of mobile communication technologies in adolescence (Toledano et al., 2019). SCAMP is therefore well-positioned to investigate typical RF-EMF exposure among the adolescent age group, determinants of this exposure, similar to previous RF-EMF measurement campaigns in children and adolescents from Denmark, the Netherlands, Slovenia, Spain, and Switzerland (Birks et al., 2018; Eeftens et al., 2018a; Gallastegi et al., 2018; Roser et al., 2017; Valič et al., 2015). No such data were available for this age group in the United Kingdom up until this time. Personal measurements, as reviewed previously (Jalilian et al., 2019; Sagar et al., 2018), are generally dominated by downlink (i.e. emissions from base stations) exposure, while exposure to WiFi, although ubiquitous, is usually relatively low. Note that this type of measurements are useful to capture environmental exposure levels but not appropriate for estimating absorbed dose, because emissions from own mobile phone (uplink) close to the body is usually substantially higher than what is measured by a portable RF-EMF meter. As a consequence, absorbed RF-EMF dose is dominated by own device use on average (van Wel et al., 2021).

To date, no study has looked into associations of different rules applied by schools or parents to reduce mobile phone use among adolescents. Typically, such measures are taken, because excessive use of e-media devices is considered distracting, or because "screen time" has been associated with negative effects on health (Jenkins et al., 2020), including reduced sleep quality (Foerster et al., 2019; Mireku et al., 2019a, 2019b), reduced physical activity (Poorolajal et al., 2020), increased obesity (Shen et al., 2021) and development of myopia (Harrington et al., 2019). However, amidst the scientific uncertainty and societal concern, it has been proposed to limit unnecessary exposure to RF-EMF where possible (Redmayne, 2016). Yet, the effectiveness of such restrictions on reducing RF-EMF exposure and mobile phone use has not been studied. We hypothesize that such rules may have direct effects on the targeted exposure source, although the magnitude is uncertain. Stringent restrictions to use of mobile phones at school and at home is expected be associated with a lower exposure to uplink and possibly total RF-EMF while at school or at home. But also indirect effects may occur. For instance in schools with WiFi options for students, pupils may use WiFi instead of mobile phone uplink bands to the same things on their phones, resulting in a lower uplink, and higher WiFi exposure. Or restricted mobile phone use during school may be compensated in the free-time resulting in no overall exposure difference.

Firstly, this study aims to characterise RF-EMF exposure measurements, made in a subset of SCAMP participants. We analyse the adolescents' exposure during different activities and in relation to sex, socio-economic status, ethnicity and phone ownership. Secondly, this study addresses the association of school or home rules targeted to mobile phone and WiFi use with measured personal exposure for uplink, WiFi and total RF-EMF. Furthermore, we make a comparison between adolescents' personal measurements while at school, and standardized spot measurements taken in the classrooms of seven of the same schools.

2. Methods

2.1. Study design

2.1.1. Recruitment of the full SCAMP cohort

The SCAMP cohort and recruitment set-up is described in Toledano et al. (2019). At baseline, the cohort consisted of 6905 pupils from 39 secondary schools, who were recruited in their first year of secondary school (School Year 7, aged 11–12 years) (Fig. 1). Eligible to participate were mixed and single-sex schools from in and around the Greater London area, initially identified from the Department of Education's educational establishments registry. State schools with a total school size of more than 200, and independent schools, which had more than 50 pupils in year 7 were eligible to take part in the study. Schools with a minimum age of 12 were not considered, neither were primary, infant, junior/middle or special schools, pupil referral units or secure units.

2.1.2. Questionnaire assessments in full SCAMP cohort

Prior to their child's inclusion, parents were sent a SCAMP information pack. Parents who did not want their child to take part in SCAMP, were asked to contact the research team to opt out. Along with the information pack, a questionnaire was sent to all parents, which included questions on mobile communication technologies at home and any parental rules related to limit their children's use of mobile phones and exposure to RF-EMF.

Of 7375 eligible pupils, a total of 6616 pupils ultimately completed the baseline school-based computer assessment of the SCAMP study between November 2014 and July 2016 Toledano et al. (2019) (Fig. 1). Participating adolescents completed an extensive computer-based assessment while at school, during regular school lessons about socio-demographics, frequency and intensity of their use of mobile technologies such as phones, laptops and tablets, and other exposure and environment-related factors and physical and mental health (Toledano et al., 2019). A follow-up assessment at school took place approximately two years after the baseline assessment.

2.1.3. Personal measurements

In a subset of 188 pupils, recruited from the full SCAMP cohort, we collected additional measurements of personal exposure to RF-EMF: a sample size similar to several prior personal monitoring studies (Birks et al., 2018; Eeftens et al., 2018a). We aimed for an approximate 1:1 ratio between boys and girls, representing different socio-economic groups, and targeting recruitment of at least one child from each school to cover the full geographical exposure range, including highly urbanized and more rural areas. To this end, pupils were given flyers containing details of the personal RF-EMF exposure measurement study for their parents. Parents who indicated their child's willingness to participate (by checking a box on the flyer and returning it to the SCAMP team) were then contacted via phone or email to arrange a home visit by a SCAMP researcher, who explained how the personal measurements worked and handed over the measurement equipment. Ethical approval was granted prior to the start of the research, and informed consent was obtained from the parents of all participants. Adolescents filled in a questionnaire similar to the school-based baseline and follow-up questionnaires, in order to gather up-to-date information about the frequency and intensity of their use of mobile technologies such as phones, laptops and tablets, and other exposure-related factors.

Personal measurements were conducted between December 2015 and November 2018 using an ExpoM-RF personal radiofrequency exposimeter (Fields At Work, Zurich, Switzerland, http://www.fieldsatwork.ch/) with integrated Geographic Position System (GPS) to measure 14 frequency bands commonly used by wireless communication and broadcasting, see Supplementary Table 1.. The equipment and methodology were previously used for the Swiss HERMES and the international GERoNiMO studies (Eeftens et al., 2018a; Roser et al., 2017). UK Health Security Agency (UKHSA) validated the ExpoM-RF devices by applying simulated RF signals at 18 predefined frequency bands including two out of band frequencies that are common in the UK: DAB Radio and TETRA downlink.

Adolescents were asked to carry an ExpoM-RF for 48 h at a sampling interval of 4 s. Where possible, measurements took place during a regular school period and included at least one full weekday (Monday to Friday). All participants kept track of their activities using a smartphone diary app installed on a study smartphone which was locked in flight mode, could not connect to WiFi and thus did not affect the measurements. The activities were pre-defined and organised into six main categories and several sub-categories:

1) Travelling (subcategories: *on foot/by bicycle/moped, train, tube, tram, bus, car*)
2) At home (subcategories: *indoors* or *garden/balcony/terrace*)
3) Outside
4) At school (subcategories: *classroom, outside/playground, canteen/elsewhere*)
5) Miscellaneous (subcategories: *cinema/theatre/concert, restaurant/café, sports centre/fitness room, at friends/relatives/acquaintances, shopping* or *other*)

The visiting SCAMP researcher asked the adolescents to behave as they usually would, making use of wireless devices as they normally would. ExpoM-RF devices were carried in a padded pouch for protection, and adolescents were asked to carry the device close to them e.g. in the school bag, but not directly on the body to avoid body shielding (Neubauer et al., 2010). When adolescents were seated or lying down (e.g. school, at home), or charging the device they were asked to put the ExpoM-RF on a nearby (non-metal) table or nightstand.

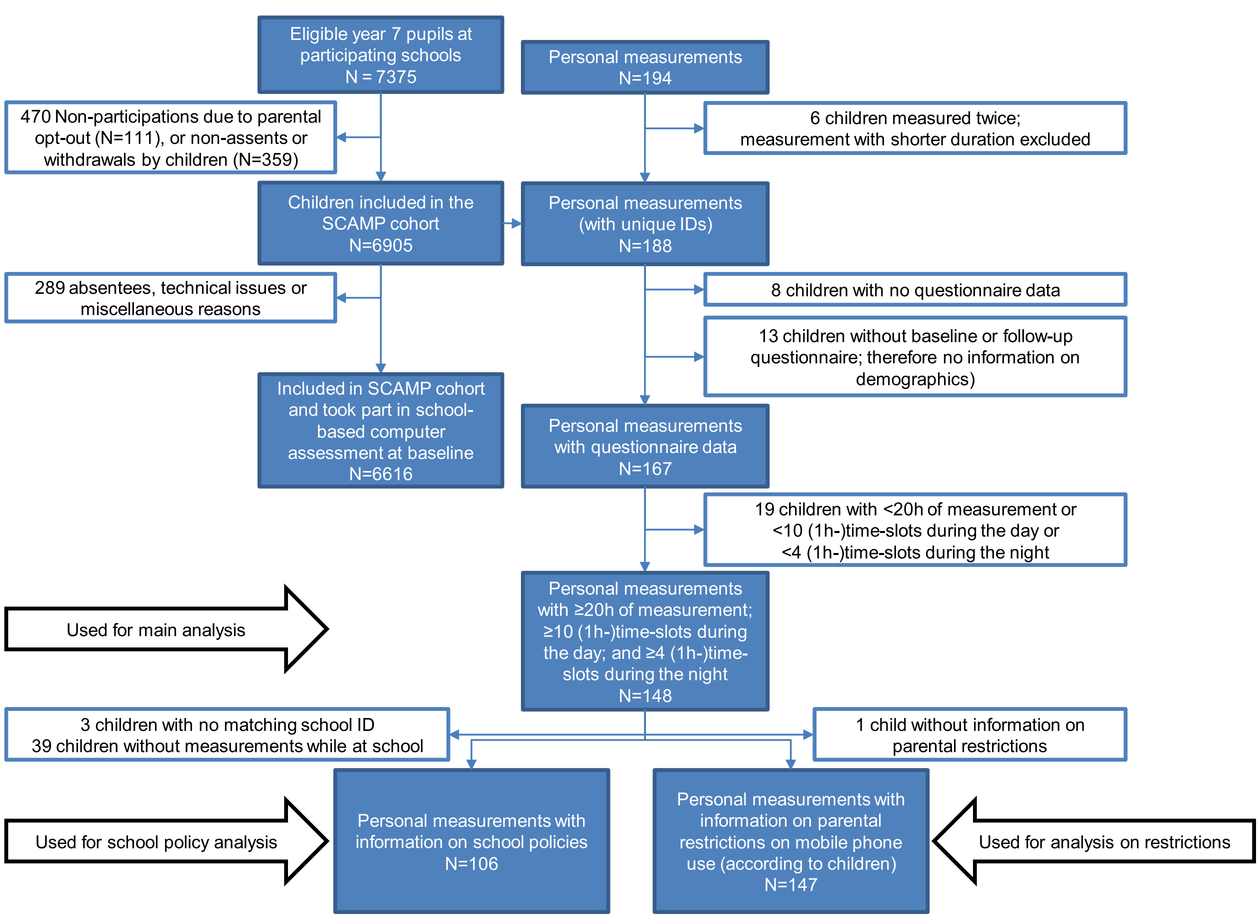

Fig. 1. Participants of the personal measurement study within the Study of Cognition, Adolescents and Mobile Phones (SCAMP) cohort.

2.1.4. Information on school policy

School representatives were asked whether they had a school WiFi access point, and if so, whether this was open to use for staff only, or for staff and students. Rules regarding the use of mobile phones in the school were also enquired: not at all permitted, only during breaks, or allowed anytime. Furthermore, it was asked if tablets, laptops and/or PCs were used during school lessons.

3. Data cleaning

3.1. RF-EMF personal measurement data

A total of 194 personal measurements were made by 188 individuals. Six participants carried the measurement device twice; of these, the measurement with fewer measurement points (shorter duration) was discarded (Fig. 1). Furthermore, adolescents with neither baseline nor follow-up questionnaire data (n = 21) and adolescents whose measurements lasted less than 20 h in total, included fewer than 10 1-h time slots during the day (6AM-10PM), or fewer than 4 1-h time slots during the night (10PM-6AM) (n = 19) were excluded from the analysis. This resulted in data from 148 adolescents being included in the main analysis.

Following several previous studies (Birks et al., 2018; Eeftens et al., 2018a), we applied the following quality control measures:

- Diary correction: We resolved any inconsistencies between the GPS of the ExpoM-RF and the participant's self-reported activity diary information by automatically flagging violations of several "logical" rules (e.g. if a participant reported travelling by bus at speeds <15 km/h; if a participant did not report any travel activity between "home" and "school"; if the participant reported being at home/at school while the GPS coordinate was more than 50 m away from their home/school (respectively); if they logged spending the night at school/a restaurant/supermarket; and/or if the participant reported being at school on the weekend). Flagged rule violations were manually evaluated by a study assistant and any incomplete, incorrect or imprecise diary entries were added or corrected if necessary (Birks et al., 2018; Eeftens et al., 2018a).
- Dynamic range correction: Values below and above the lower and upper quantitation limits were set to the reporting limits as detailed in the Online Supplementary Table S1 and (Birks et al., 2018; Eeftens et al., 2018a), which was the method shown to yield averages most similar to those obtained by the regression on order statistics (ROS) method (Najera et al., 2020). Details on the percentage of observations under the detection limit are provided in Supplementary Table S1.
- FM radio charging correction: While charging during measurements, the ExpoM-RF charging cable acts as an FM antenna and thus erroneously increases the sensitivity to the FM radio band. Charging is registered by the device, and during such activities, the FM band is corrected by substituting the median value during the same activity while the device was not charging (Birks et al., 2018; Eeftens et al., 2018a).
- Cross-talk correction: Cross-talk occurs when a signal from one frequency band is unintentionally registered in another. This is detected as a temporary correlation between the signals, and corrected by substituting the values of the "victim" band by the median value during the same activity, but while no cross-talk was registered (Eeftens et al., 2018b). This was done for the DECT, 1800 downlink and 2100 uplink frequencies. Correction was not possible for the WiMax and WiFi 5 frequency bands, which were shown in validation measurements to measure almost exclusively crosstalk from the 1800DL, DECT and 2600UL bands.

WiMax and WiFi 5 (ISM 5.8 GHz) frequencies were excluded from the analysis because the bands are heavily affected by harmonic cross-talk from bands whose multiple frequency range is in this range, following earlier studies (Birks et al., 2018; Eeftens et al., 2018a; Roser et al., 2017). The remaining frequency bands were grouped by source into downlink (the signal from the base station to the mobile device in the following bands: 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz), uplink (the signal from the mobile device to the base station in the following bands: 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz), broadcast (FM Radio and DVB-T), DECT (cordless phones), WiFi (ISM 2.4 GHz) and total (all).

3.2. Questionnaire data

In cases where sex, ethnicity or socio-economic status (SES) was obtained at several occasions (e.g. during school-based questionnaires at baseline and follow-up), responses were taken primarily from baseline (complemented by follow-up data if baseline information was missing). If both baseline and follow-up school-based questionnaire information was unavailable, data from parental questionnaires was used to fill in any missings information on socio-demographic characteristics.

We classified the adolescents into SES-levels based on the highest SES of either parent. Parent's occupation was used as an indicator for SES and classified according to the 5-level version of the National Statistics Socioeconomic Classification (NS-SEC) (Office for National Statistics, 2010). NS-SEC levels 2–5 were collapsed into one category ("NS-SEC5 Other") for comparisons to ensure sufficient numbers in each group.

The questionnaire administered at the start of the personal measurements included questions about frequency and duration of calls using the own and someone else's mobile phone, respectively. Adolescents answered these questions with answering options giving pre-specified categories. We combined responses for these questions as exposure does not depend on whether adolescents used their own phone versus someone else's. Some transformation was needed given the categorical nature of the responses. We took the average number/duration of each category, then summed the responses (e.g. frequency of calls with own device plus frequency of calls with someone else's device), divided it by two (hence, calculating the average) and then re-grouped it again into the (original) categories. We used the same process to combine the number of text messages (SMS) and "instant messages" (e.g. WhatsApp, iMessage, Google Chat, BBM) sent.

3.3. Spot measurements in schools

In order to compare the ExpoM-RF measurements with another device, and to measure exposure from bands not captured by the ExpoM-RF (in particular the WiFi 5 band), spot measurements were carried out at seven of the 39 schools using a single Narda Selective Radiation Meter (SRM) 3006. This device measured 32 frequency bands in the range of 80 MHz–5871 MHz, of which 16 frequency bands were also covered by the ExpoM-RF's used in the personal measurements campaign (Supplementary Table S2). Measurements were taken both inside and outside the school building during regular school hours. When measuring in the classroom, the researcher placed the device on a tripod in the centre of the room and at least 1 m (m) away from any visible sources and while the classrooms were vacant. When measuring outside the school building, measurements took place in the schoolyard, in open areas away from building structures and any identified sources. The spot measurements were made in the same location and at the same time using both the ExpoM-RF and Narda 3006. We averaged spot measurements over the measurement duration for each band, for all seven schools, and for inside and outside measurements separately.

3.4. Data analyses

We accounted for possible missing not-at-random data because of participants forgetting to charge the device in the evening (typically causing it to stop measuring during the night), or non-representativeness of the sample period (e.g. participants measuring during two days, but only one night, causing high-exposure daytime activities to be over-represented). To this end, we calculated 24 hourly arithmetic means, considering all measurements taken between 01:00 and 02:00, between 02:00 and 03:00 etc. We calculated combined 24h weighted averages only for individuals whose measurements represented at least 12 time slots of data available during the day (6:00–22:00) and at least 6 h of data during the night (22:00–06:00), as the arithmetic mean of these 24 time slot specific means.

We also calculated exposure by the five activity categories which the participating adolescents reported through the diary app, by taking the individual arithmetic mean while engaged in that activity. In order to study differences in exposure over time, we also calculated average exposure by day (06:00–22:00), by night (22:00–06:00), for weekdays (Mon-Fri) and for weekend days (Sat-Sun) for each participant. Individuals who did not measure during a weekend day caused the *n* to be lower for weekends.

When describing the study population, we used linear model ANOVA (R package “tableone”), trend test for ordinal variables (R package “tableone”), and Fisher’s exact tests (R package “stats”) to test the significance of the difference between groups, depending on whether variables were continuous, ordinal or categorical. We used the ANOVA to compare exposure levels between demographic groups (sex, SES and ethnicity), between activities, between day/night and workday/weekend (R package “stats”). We also used ANOVA to determine whether there was a significant association between the measured exposure to total, uplink and WiFi RF-EMF while at school and the school’s policy on three specific measures: WiFi accessibility for students, mobile phone use policies, and in-class use of computers, laptops and tablets. We were unable to include adolescents who did not attend school during the measurement period (n = 39), and adolescents for whose schools we did not have policy information (n = 3).

All database compilations, corrections, and data management tasks were done in R Studio (R Core Team,). The R package ggplot 2 was used to obtain the graphics.

4. Results

4.1. Characteristics of personal measurement cohort

Personal measurements of the 148 participants (Fig. 1) lasted on average for 46.5h (standard deviation [SD]: 13.4h; min: 20.6h, max: 86.5h) and included 42′491 measurement points per participant (SD: 12′601; min: 18′493, max: 78′946). Adolescents attended 29 different schools. The majority of participants (74%) attended school during the measurement period. Children who did not attend school during the measurement period were mostly measuring during the weekend or during school holidays.

Table 1 shows an overview of personal characteristics of study participants in the personal measurement sample and the rest of the SCAMP cohort including relevant policies and rules implemented at the participants’ homes and schools. The personal measurement sample was comparable to the rest of the SCAMP cohort in terms of age and sex, but had higher socio-economic status (SES) and differed in terms of ethnicity (Table 1). Almost all adolescents (96%; 134/139) in the personal measurement sample reported owning a mobile phone; most of the adolescents were using a smartphone (94%; 136/144) (Table 2). The majority reported having WiFi and a cordless phone at home (97% [125/129] and 74% [96/129], respectively).

In the personal measurement subsample, girls tended to report more frequent and longer calls with mobile phones than boys (average from using own phone and using someone else’s phone); however, this trend was not statistically significant (Table 2; Supplementary Figure S1). Similarly, girls tended to report a higher number of messages per day than boys (average from SMS and instant messages, not statistically

Table 1
Characteristics of study participants of the full SCAMP cohort (n = 8003) and the subset (n = 148) who took part in the personal monitoring.

	Total (N = 8003)	Personal measurement sample (N = 148)	Rest of SCAMP cohort (N = 7855)	p value[a]
Age at baseline				0.535[b]
N	6605	134	6471	
Mean (SD)	12.1 (0.4)	12.0 (0.4)	12.1 (0.4)	
Age at follow-up				0.581[b]
N	5194	124	5070	
Mean (SD)	14.3 (0.5)	14.2 (0.5)	14.3 (0.5)	
Sex				0.455[c]
N	8003	148	7855	
Male	3893 (48.6%)	67 (45.3%)	3826 (48.7%)	
Female	4110 (51.4%)	81 (54.7%)	4029 (51.3%)	
NS-SEC5 [d]				< 0.001[c]
N	6904	141	6763	
Higher managerial, administrative and professional occupations	3961 (57.4%)	119 (84.4%)	3842 (56.8%)	
Intermediate occupations	558 (8.1%)	6 (4.3%)	552 (8.2%)	
Small employers and own account workers	1149 (16.6%)	7 (5.0%)	1142 (16.9%)	
Lower supervisory and technical occupations	338 (4.9%)	5 (3.5%)	333 (4.9%)	
Semi-routine and routine occupations	849 (12.3%)	4 (2.8%)	845 (12.5%)	
Never worked and long-term unemployed	49 (0.7%)	0 (0.0%)	49 (0.7%)	
Ethnicity				< 0.001[c]
N	7825	145	7680	
White	3402 (43.5%)	98 (67.6%)	3304 (43.0%)	
Black	1179 (15.1%)	7 (4.8%)	1172 (15.3%)	
Asian	2091 (26.7%)	18 (12.4%)	2073 (27.0%)	
Mixed Race	861 (11.0%)	19 (13.1%)	842 (11.0%)	
Other/not interpretable	292 (3.7%)	3 (2.1%)	289 (3.8%)	
Restricted phone use (adolescents)				0.142[c]
N	7938	147	7791	
Yes	3938 (49.6%)	80 (54.4%)	3858 (49.5%)	
No	3849 (48.5%)	67 (45.6%)	3782 (48.5%)	
No phone	151 (1.9%)	0 (0.0%)	151 (1.9%)	

[a] For sample difference between the personal measurement sample and the rest of the SCAMP cohort.
[b] Linear Model ANOVA.
[c] Fisher’s exact test.
[d] NS-SEC5 (National Statistics Socioeconomic Classification) was obtained from the parents’ questionnaire.

Table 2
Mobile phone use of adolescents in the subpopulation of the SCAMP cohort, which took part in the personal measurements, by sex.

	Total (N = 148)	Male (N = 67)	Female (N = 81)	p value[a]
Adolescent owning a mobile phone				0.172[b]
N	139	62	77	
Yes	134 (96.4%)	58 (93.5%)	76 (98.7%)	
No	5 (3.6%)	4 (6.5%)	1 (1.3%)	
Adolescent owning/ using a smartphone				0.139[b]
N	144	64	80	
Yes	136 (94.4%)	58 (90.6%)	78 (97.5%)	
No	8 (5.6%)	6 (9.4%)	2 (2.5%)	
Frequency of calls (mobile phone)				0.626[c]
N	148	67	81	
Never	37 (25.0%)	20 (29.9%)	17 (21.0%)	
<1/day	44 (29.7%)	19 (28.4%)	25 (30.9%)	
~1/day	11 (7.4%)	4 (6.0%)	7 (8.6%)	
2-5 times/day	46 (31.1%)	20 (29.9%)	26 (32.1%)	
6-10 times/day	4 (2.7%)	0 (0.0%)	4 (4.9%)	
11-20 times/day	1 (0.7%)	0 (0.0%)	1 (1.2%)	
(Missing)	5 (3.4%)	4 (6.0%)	1 (1.2%)	
Duration of calls (mobile phone)				0.348[c]
N	148	67	81	
Never/<1 min/day	5 (3.4%)	3 (4.5%)	2 (2.5%)	
1–5 min/day	75 (50.7%)	34 (50.7%)	41 (50.6%)	
6–15 min/day	15 (10.1%)	3 (4.5%)	12 (14.8%)	
16–30 min/day	5 (3.4%)	1 (1.5%)	4 (4.9%)	
>1 h/day	1 (0.7%)	0 (0.0%)	1 (1.2%)	
(Missing)	47 (31.8%)	26 (38.8%)	21 (25.9%)	
Frequency of messages (SMS & instant)				0.075[c]
N	135	57	78	
None	8 (5.9%)	5 (8.8%)	3 (3.8%)	
1-5 per day	39 (28.9%)	18 (31.6%)	21 (26.9%)	
6-10 per day	16 (11.9%)	8 (14.0%)	8 (10.3%)	
11-40 per day	56 (41.5%)	22 (38.6%)	34 (43.6%)	
41-70 per day	16 (11.9%)	4 (7.0%)	12 (15.4%)	
Duration of internet use (mobile phone)				0.021[c]
N	146	65	81	
No phone/internet/ None	14 (9.6%)	11 (16.9%)	3 (3.7%)	
1–10 min/day	16 (11.0%)	10 (15.4%)	6 (7.4%)	
11–30 min/day	15 (10.3%)	5 (7.7%)	10 (12.3%)	
31–59 min/day	22 (15.1%)	7 (10.8%)	15 (18.5%)	
1–2 h/day	31 (21.2%)	12 (18.5%)	19 (23.5%)	
3–4 h/day	31 (21.2%)	15 (23.1%)	16 (19.8%)	
5–6 h/day	10 (6.8%)	3 (4.6%)	7 (8.6%)	
7 or more hours/day	7 (4.8%)	2 (3.1%)	5 (6.2%)	

[a] All statistical tests assumed "no difference" between males and females as the null hypothesis.
[b] Fisher's exact test.
[c] Trend test for ordinal variables.

significant). Finally, girls also reported a significantly longer duration of internet use on the mobile phones compared to boys.

4.2. RF-EMF exposure by activity, demographic characteristics and time

The median of all 24h-TWA RF-EMF exposure was 99.5 μW/m^2 (Table 3). For most participants downlink was the main contributor to overall exposure (68/148), followed by broadcast (34/148), uplink (31/148), WiFi (14/148) and DECT (1/148).

Total exposure (all bands combined) and all individual exposure bands were highest during travel (Fig. 2; Supplementary Table S3). Mean total exposure was highest during travel for 64% (94 out of 148) of participants. For the remaining participants, mean total exposure was highest while outdoors (n = 17), at home (n = 16), during miscellaneous activities (n = 14) and at school (n = 7). Lowest exposure was measured at home for total, downlink, uplink and broadcast while DECT was lowest at school and "WiFi" was lowest when adolescents were outdoors (Fig. 2; Supplementary Table S3). Exposure at home was lower than at school for downlink, uplink and total (total median 40.4 μW/m^2 at home versus 93.8 μW/m^2 at school), but higher for WiFi and DECT. Downlink, uplink and total exposure were also significantly higher during travel, outdoors and miscellaneous activities than while at home (Supplementary Table S3).

Total uplink exposure among girls was significantly higher than among boys (median: 18.6 μW/m^2 in girls *vs.* 4.8 μW/m^2 in boys), but this did not make a significant difference for total exposure (Table 4; Supplementary Figure S2). WiFi exposure was lower among adolescents with high SES compared to adolescents with "other" SES, but again there was no significant difference for total exposure. Uplink exposure was significantly higher in Black and Asian children, compared to White children, and DECT exposure was higher in Asian children, but these differences were not significant for total exposure or for any of the other bands.

Nighttime (10PM-6AM) exposure was consistently lower than daytime (6AM-10PM) exposure ($p < 0.01$) on both workdays and weekends, for all bands except broadcast (Fig. 3; Supplementary Table S4). Exposure on weekdays was comparable to exposure on weekend days both during the day and at night, for all bands (Fig. 3; Supplementary Table S4).

4.3. Association of school and home policies with RF-EMF exposure

We excluded three participants from the analysis on school policies who went to schools for which no information on school policies (regarding WiFi and mobile phone use) was available and 39 participants who did not attend school during the measurement period. The remaining 106 adolescents included in the school policy analysis went to 27 different schools. Of these 106, no adolescent went to a school, which had no WiFi at all, 48 went to schools which offered WiFi for staff only, and 58 went to schools which allowed WiFi access to both staff and students. Of the same 106 adolescents with school policy information, four attended a school where mobile phone use was allowed anytime, 45 attended a school which allowed mobile phone use only during breaks, and 57 attended a school which did not allow mobile phone use at all.

Fig. 4a–c presents the exposure to total, uplink and WiFi exposure

Table 3
Distribution of individual 24h-TWA RF-EMF exposure of adolescent in the personal measurement sample, for uplink, downlink, WiFi, broadcast and DECT sources [in μW/m^2].

Band	N	Minimum	5th percentile	25th percentile	Mean	Median	75th percentile	95th percentile	Maximum
Uplink	148	0.2	0.5	3.3	30.2	11.1	36.1	89.2	643.6
Downlink	148	0.5	2.2	12.8	81.3	31.1	60.4	206.0	2940.0
WiFi	148	2.2	3.1	4.9	17.8	7.9	16.2	42.4	550.0
Broadcast	148	0.3	1.0	2.8	111.7	7.7	34.3	212.2	10651.2
DECT	148	0.0	0.0	0.1	1.2	0.3	0.7	3.8	61.2
Total	148	9.9	24.0	55.1	242.2	99.5	163.9	625.1	10722.3

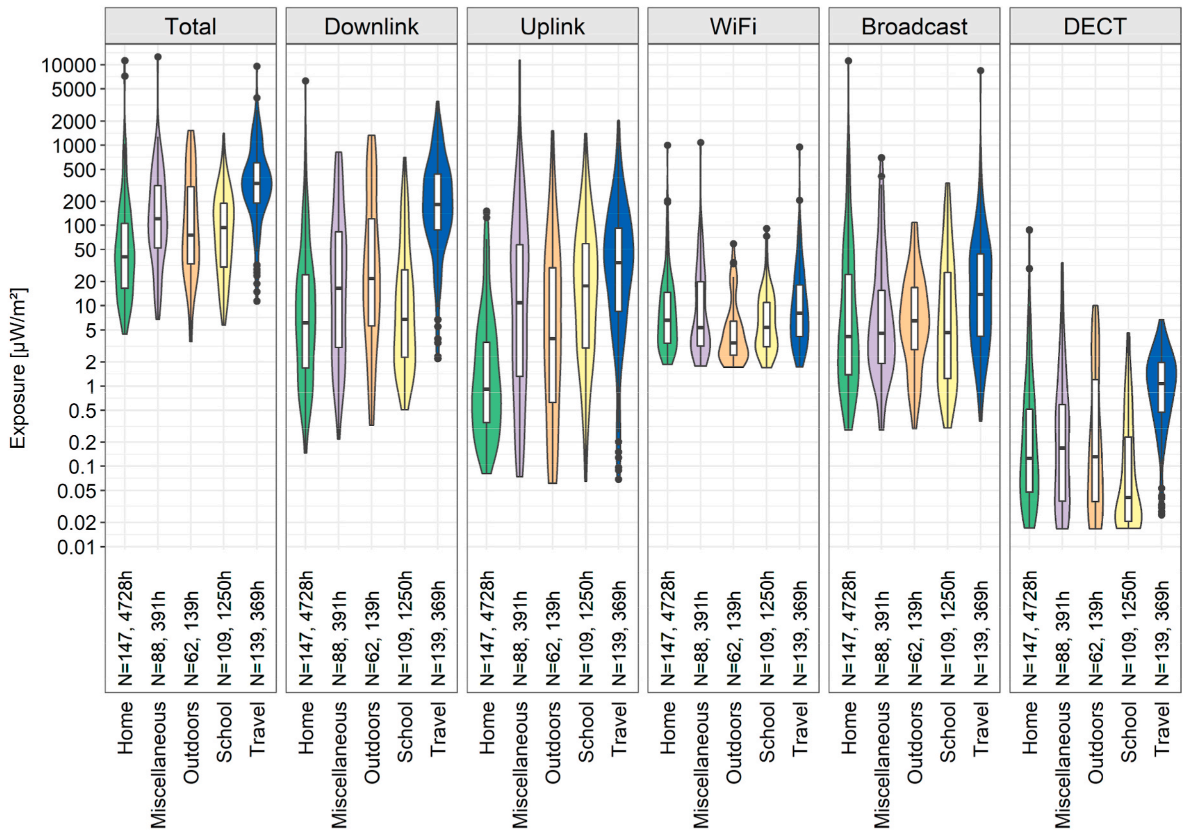

Fig. 2. Violin and boxplot of individual mean RF-EMF exposure by activity, for total exposure, downlink, uplink, WiFi, broadcast and DECT. Violins show the kernel probability density of the data at different values, where the width of the curve corresponds with the approximate frequency of occurrence of data points. Boxplots show the median as a thick line and the interquartile range (IQR) as a box. The whiskers extend to the 25th percentile – 1.5 * IQR (lower) and the 75th percentile + 1.5 * IQR (higher). Dots portray any observations for a single adolescent beyond the whiskers' range.

Table 4
Median of individual 24h-TWA RF-EMF exposures according to different demographic characteristics, for total exposure, downlink, uplink, WiFi, broadcast and DECT [in μW/m^2].

Variable	Variable level	Observations	Total	Downlink	Uplink	WiFi	Broadcast	DECT
Sex	Male	N = 67, 3140h	72.4	32.3	4.8	7.7	6.5	0.2
	Female	N = 81, 3738h	108.5	29.2	18.6[a]	8.5	9.5	0.3
NS-SEC5	NS-SEC5 High	N = 119, 5459h	94.6	31.2	10.5	7.4	7.4	0.3
	NS-SEC5 Other	N = 22, 1073h	141.6	37.0	13.1	17.8[a]	7.7	0.4
	(Missing)	N = 7, 346h	67.9	17.9	11.1	9.6	19.5	0.6
Ethnicity	White	N = 98, 4454h	88.9	32.2	8.5	7.1	7.7	0.2
	Black	N = 7, 299h	132.9	25.2	36.9[a]	8.5	5.0	0.6
	Asian	N = 18, 879h	107.6	22.2	31.3[a]	11.3	5.2	0.3[a]
	Mixed Race	N = 19, 923h	118.0	38.4	12.0	12.5	15.7	0.3
	Other/not interpretable	N = 3, 155h	41.8	35.4	2.3	5.9	2.3	0.2
	(Missing)	N = 3, 167h	110.3	26.8	15.9	6.5	28.1	0.6

[a] Indicates a statistically significant difference from the reference (first mentioned category) in ANOVA at $p < 0.05$, where log (exposure) was analyzed.

while at school, by the three different school policies we evaluated, while Fig. 4d presents exposure while at home, by parental restrictions on mobile technology use. The median [25th – 75th percentile] for each policy and each band is given below each of the plots.

Personal exposure to Wi-Fi at school was similar in schools which allowed WiFi use for staff only, and schools which allowed WiFi use for students as well (Fig. 4a). However, based on ANOVA ($p < 0.05$), total exposure was significantly higher in schools which allowed WiFi use for students, than in those who did not (Fig. 4a), but no significant differences were found for uplink or WiFi exposure.

Uplink exposure while at school was significantly lower, for adolescents attending schools not permitting mobile phone use at all, compared to schools allowing mobile phone use during breaks (Fig. 4b), but no significant differences were found for total or WiFi exposure.

Forty-five adolescents attended schools which reported use of computers, laptops and tablets, 26 adolescents went to schools which reported use of computers and tablets, while 35 adolescents went to schools which reported use of computers only during lessons. PC, laptop and tablet use during lessons (as reported by schools) was not associated with a higher total, uplink or WiFi exposure while at school, when compared to schools who used PC's only. However, higher total and uplink exposure were associated with using PC's and laptops, compared with PC's only (Fig. 4c).

Finally, parental restrictions on mobile phone use (yes/no) as reported by adolescents were significantly associated with a lower total exposure, but not (significantly) with a lower uplink or WiFi exposure

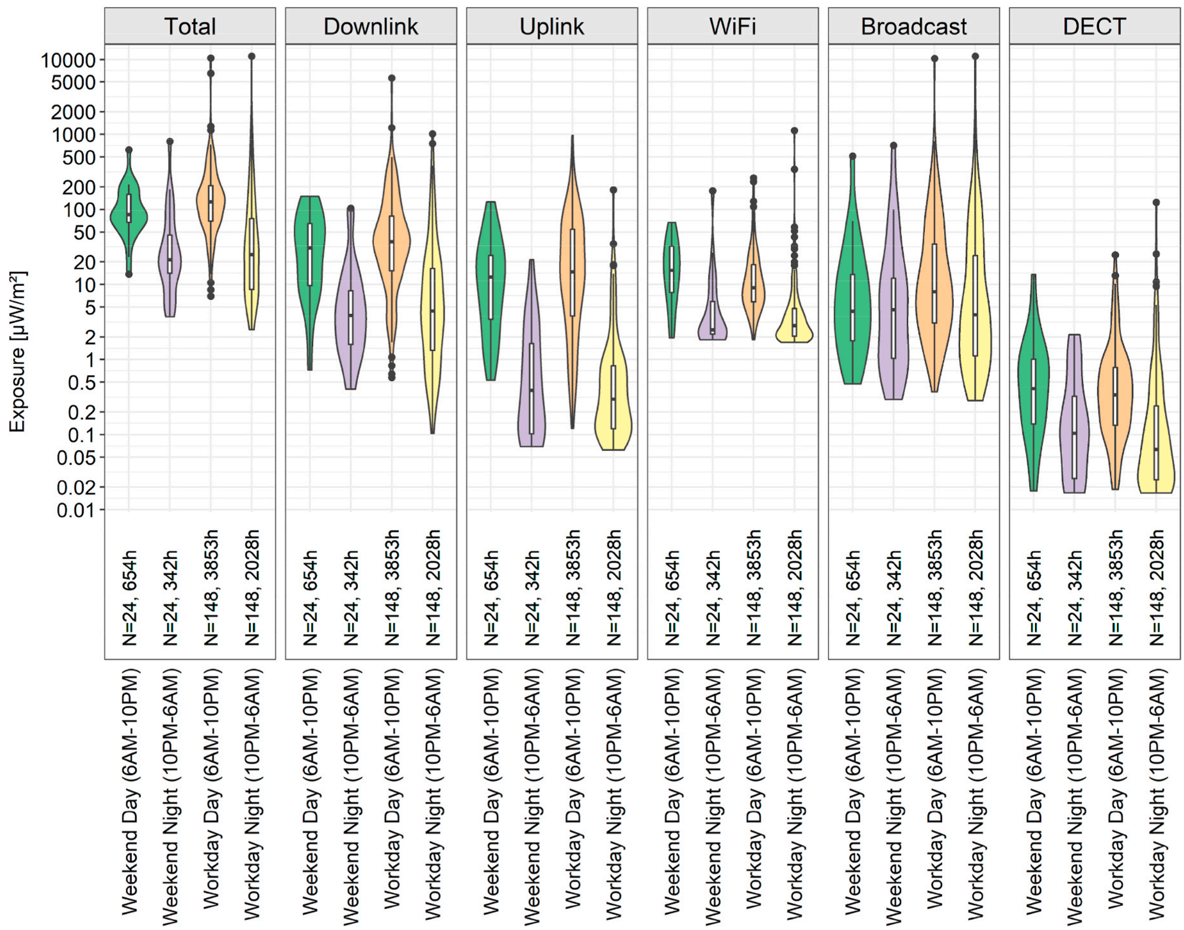

Fig. 3. Individual mean RF-EMF exposure by day (6AM - 10PM)/night (10PM - 6AM), and by weekday (Mon-Fri)/weekend day (Sat-Sun), for total exposure, uplink, downlink, WiFi, broadcast and DECT. Violins show the kernel probability density of the data at different values, where the width of the curve corresponds with the approximate frequency of occurrence of data points. Boxplots show the median as a thick line and the interquartile range (IQR) as a box. The whiskers extend to the 25th percentile – 1.5 * IQR (lower) and the 75th percentile + 1.5 * IQR (higher). Dots portray any observations for a single adolescent beyond the whiskers' range.

while at home (Fig. 4d). Fig. 4d shows that this difference is due to a combination of downlink and WiFi instead.

4.4. Spot measurements

The ExpoM-RF devices provided for comparison generally agreed well with the measurements made by the Narda SRM 3006, across the same frequency bands. We found indoor exposure in schools to be lower than outdoor exposure (Supplementary Figure S3). The differences between inside and outside are mostly driven by downlink bands which are lower indoors due to attenuation, and WiFi bands which are higher inside due to their substantial use in and around the schools (Supplementary Figure S3). All seven schools in which spot measurements were taken inside classrooms and outside the building had WiFi connections: three of them allowed students to connect and four of them only allowed staff to use it.

The levels obtained from spot measurements were lower than the average personal measurements of adolescents while at school (93.8 μW/m^2), possibly reflecting the spot measurement setup, which was not affected by very local sources, as is typical during personal measurements. The spot measurements yielded an average total RF-EMF level of 45.7 μW/m^2 in schools during spot measurements (26.1 μW/m^2 for the 14 frequencies common to ExpoM-RF) (Fig. 5). WiFi in the 5 GHz band was not reliably captured by the ExpoM-RF measurements due to cross-talk. The spot measurements showed that the WiFi 5 GHz band contributed on average 14.8 μW/m^2 (32.3%) to total RF-EMF measured in schools, and constituted 66.2% of WiFi exposure (Fig. 5). Only 26 adolescents attended one of the schools where spot measurements were carried out (specifically: 1 adolescent attended school #1, 1 attended school #2, 9 attended school #3, 7 attended school #4 and 8 attended school #6). We found overall reasonable agreement between the broadcast, downlink, uplink and WiFi levels measured by the adolescents while at school using the ExpoM-RF and the spot measurements taken in the classroom using the Narda 3006 (Supplementary Figure S4).

5. Discussion

In this study, personal RF-EMF exposure of 148 adolescents living in and around Greater London was assessed. Regulations on mobile phone and WiFi use at home and at school did not have a noticeable impact on personal RF-EMF exposure in our sample.

5.1. RF-EMF exposure pattern among teenagers living in Greater London

We found a median total RF-EMF exposure of 99.5 μW/m^2, which is generally within the range of typical personal and microenvironmental measurements, as reviewed by (Jalilian et al., 2019; Sagar et al., 2018). However, the levels observed in the present study were slightly higher compared to the personal exposure found in the five-country study GERoNiMO among 8-18 year-old children and adolescents reporting a median total exposure of 75.5 μW/m^2 (Birks et al., 2018). This may be explained by the fact that this study in the Greater London area covered almost exclusively urban areas while only about half of the children and adolescents participating in the aforementioned study lived in urban

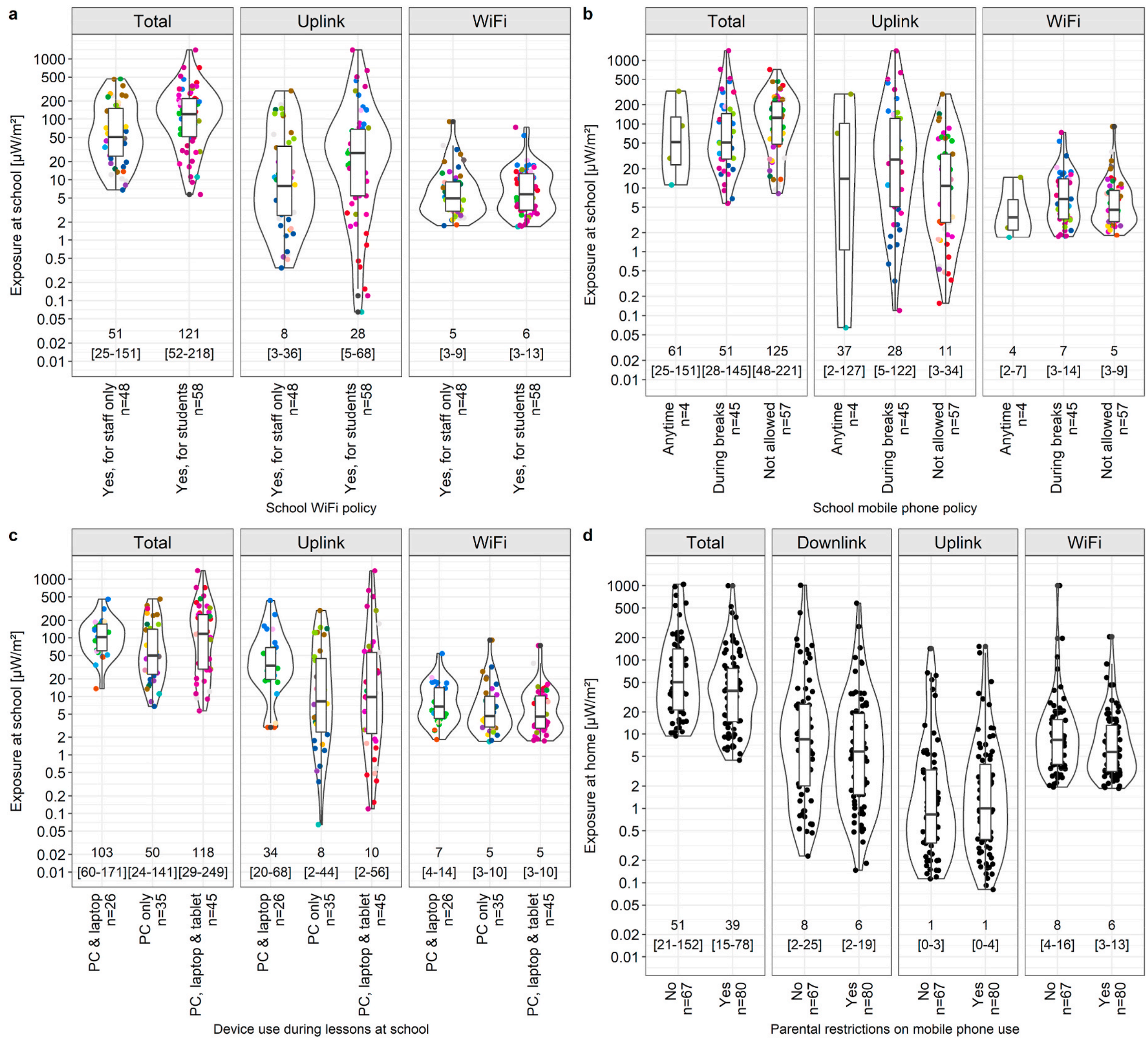

Fig. 4. Violin and boxplot of individual mean RF-EMF exposure to total RF-EMF, uplink and WiFi at school by (a) school WiFi policy, (b) school mobile phone use policy (c) school's device use during lessons, and (d) parental restrictions on mobile phone use, also including downlink exposure. Same colours represent different children going to the same schools; school attendance is not relevant for exposure while at home (Fig. 4d). Violins show the kernel probability density of the data at different values, while boxplots show the median as a thick line and the interguartile range (IQR) as a box. The whiskers extend to the 25th percentile – 1.5 * IQR (lower) and the 75th percentile + 1.5 * IQR (higher). The median and interguartile range [25th – 75th percentile] for each policy are given below each plot for total, downlink, uplink and WiFi. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

areas. In Greater London, downlink was the main contributor to overall exposure, although broadcasting can result in substantially higher exposure values in rare cases, a pattern that was also observed in GERoNiMO (Birks et al., 2018). Highest exposure levels were observed while participants were travelling as reported previously in other countries (Birks et al., 2018; Roser et al., 2017). Total exposure was much lower when adolescents reported being outdoors compared to when they reported travelling (median: 75.8 μW/m^2 *vs.* 334.3 μW/m^2), which is in contrast to what was found in GERoNiMO, where exposure while travelling (171.3 μW/m^2) was similar to exposure while outdoors (157.0 μW/m^2) (Birks et al., 2018). A possible explanation could be high building density with street canyons in London, which results in shielding of macro base stations relevant for outdoor exposure but minimal shielding of micro and nano cell base stations, which are common on travel routes where there are many people.

We found a very high exposure to broadcast in one participant (>10000 μW/m^2). This participant lived in close proximity to a major broadcast transmitter transmitting at the maximum effective radiated power of 200 kW. Such extreme outliers have to be considered when reporting summary statistics: the mean of the individual mean exposures to broadcast was heavily influenced by this single observation in our study (111.7 μW/m^2 *vs.* 40.0 μW/m^2 when excluding this adolescent). This is why we mostly report medians rather than means of individual time-weighted average exposures, although the latter directly refers to the cumulative exposure concept, mostly applied in epidemiological research.

Lower personal exposure levels during the night than during the day were also reported in previous studies (Birks et al., 2018; Bolte and Eikelboom, 2012; Eeftens et al., 2018a; Röösli et al., 2016; Roser et al., 2017). This is mainly owed to the behaviour (i.e. being at home and lack of travel) since diurnal variability of base station is relatively low (Bienkowski et al., 2015) and shielding of the building while inside.

A higher median uplink exposure at school compared to at home but comparable exposure levels from other frequency bands were also observed in a Swiss study (Roser et al., 2017). One explanation for this observation is that children and adolescents are more frequently surrounded by other people using their mobile device at school than at home.

Higher uplink exposure in girls compared to boys was also found elsewhere (Birks et al., 2018) and is assumed to be due to different

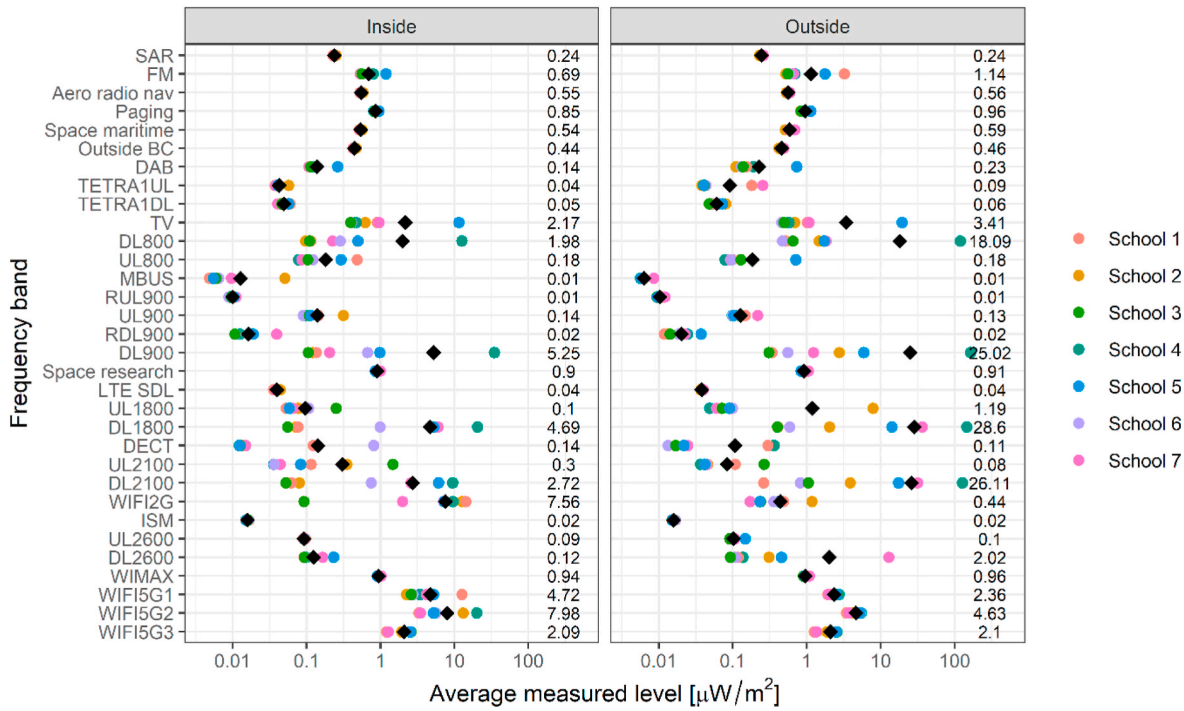

Fig. 5. RF-EMF exposure as measured inside (classroom) and outside the school building, for 32 different bands as measured by the Narda 3006. Coloured dots represent means of individual schools, and black diamonds represent the arithmetic average of all schools corresponding to the number in the margin. See Supplementary Table S2 for details on the bands measured by Narda 3006.

phone use patterns (more frequent and longer phone calls and more frequent messaging in girls).

5.2. Association between rules at home and at school and RF-EMF exposure

We identified different rules applied by schools or parents to reduce mobile phone use among adolescents and assessed their association with exposure to RF-EMF. We observed lower uplink exposure from mobile phones while at school for adolescents attending schools not permitting mobile phone use at all, compared to adolescents attending schools allowing mobile phone use during the breaks. However, uplink exposure while at school (median; 17.6 μW/m^2) is only a small contributor to the 24-h average for all frequency bands (median: 99.5 μW/m^2) and thus no corresponding difference was found for total uplink exposure.

On the other hand, restrictions may have side effects. One would expect that the availability of WiFi for students would result in lower uplink exposure, as adolescents would resort to using WiFi instead of a mobile network (3G/4G) to connect to the internet and/or send messages. However, there was no clear difference in uplink exposure between adolescents who had access to their school's WiFi network, and those who did not. Instead, the trend was rather in the opposite direction, although not significant: uplink exposure was higher in adolescents attending schools which provided WiFi access to students compared to schools with WiFi for staff only.

Only one school reported not having a WiFi network. Unfortunately, no adolescents from that school were included in the personal measurement study. Only six adolescents attended a school without any restrictions on mobile phone use; two of those adolescents, however, did not attend school during their measurement period. Therefore, our data are too scarce to conclude on any exposure pattern of this group.

The lower total exposure at home for children with parental restrictions on mobile phone use at home may be a chance finding, as the significant different in total exposure is in part related to downlink exposure (originating from base stations, and therefore unrelated to parental restrictions). Individually, neither downlink, uplink or WiFi exposure were significantly decreased for children reporting parental restrictions. We did not ask the adolescents how parents would control their mobile phone use. Hence, we do not know whether parental control would impact the duration of the children's phone use or rather the way they use their phones (e.g. for communicating rather than playing). Nevertheless, for any kind of parental control we would have expected a reduction in usage-related RF-EMF exposure (WiFi and/or uplink), which we did not observe.

5.3. Spot measurements

We found that classroom spot measurements typically indicated lower levels than personal measurements. We note that spot measurements were conducted in empty classrooms, whereas all personal measurements at school were conducted in the presence of the participating adolescent and their classmates, some of whom may have been carrying or using phones near the exposimeter, resulting in higher levels of uplink and WiFi exposure, as well as more variability. Despite these limitations, there was a moderate correlation between spot measurements and personal measurements, especially for downlink and total exposure which are less affected by own device use. Similar correlations have been shown for members of the same household (Eeftens et al., 2018a) or between model-estimated exposure at home and personal measurements (Martens et al., 2016).

5.4. Strengths and limitations

A strength of our study is that we used personal measurement devices together with a diary app to record the adolescents' exposure to RF-EMF and their activities simultaneously. This allowed for characterization of exposure during different everyday activities. It required good compliance by the study participants, but also allowed for cross-checking and correction of the reported time-activity pattern if it did not match the diary entries. The variety of data sources (data from ExpoM-RF; GPS data; diary entries; data from various questionnaires, answered by adolescents, their parents and schools) provided a comprehensive picture of the study participants and allowed for an objective comparison between measured RF-EMF exposure, time-activity behaviour and different rules applied in school and home environments related to use (duration) of mobile technologies.

Personal measurements like this may be helpful for risk perception (Ramirez-Vazquez et al., 2019). showed that the majority of adults participating in personal measurements perceived RF-EMF were less dangerous when seeing their data, substantially below the guidelines recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020). From a risk perception perspective, our paper will help to make evidence based decisions for restrictions targeted to RF-EMF devices motivated by the precautionary principle.

The SCAMP cohort in general included more affluent children than would be representative of the general population attending schools in the Greater London area (Toledano et al., 2019). This difference was magnified in the personal monitoring subpopulation, which included 84.4% children of high SES, against 56.8% for the general SCAMP cohort (Table 1) and 39.8% of the general population (Toledano et al., 2019). In addition, compared to the general SCAMP cohort, the personal monitoring subpopulation included fewer black (4.8%) and Asian (12.4%) children than the general SCAMP study (15.1% and 26.7% respectively), more white children and similar percentages of mixed race/other ethnicities (Bruton et al., 2020). A focus group study found that black and minority ethnic parents were less likely to allow children to take part in mobile phone-related research if they had concerns about the research (such as concerns of a risk to the child or lack of trust in the motivation of the researchers), if they experienced practical constraints (such as apathy or a lack of time), or if they had issues with communication about the study (Bruton et al., 2020). Therefore, our measured exposure levels might not be generalizable to the wider U.K. population. Since high-SES children measured typically lower exposure levels across all sources, this unbalance in representation, may have led to an overall underestimation in RF-EMF exposure in this study population compared to the general population.

Nowadays, most schools have WiFi networks installed. Therefore, we were lacking this particular group of participants without WiFi at school for comparison. Similarly, only few schools permit phone use at any time and hence, most adolescents in our study experienced some kind of restrictions put in place to limit their use of mobile phones.

Some technical limitations, which have been discussed in earlier studies (Bolte, 2016; Eeftens et al., 2018a; Iskra et al., 2010; Thielens et al., 2015), are inherent to the use of personal exposimeters: they measure whole body exposure rather than peak exposures to the head; body shielding cannot be prevented; and we cannot entirely correct for cross-talk.

- ExpoM-RF devices are thus designed to measure environmental RF-EMF with quasi homogeneous distribution, which is expected to work well for environmental sources (e.g. base stations, broadcast masts, WiFi access points) but not specifically accurate for quantifying exposure from devices which are used on or near the body (e.g. mobile phones, tablets). Slight changes in distance between these devices and ExpoM-RF results in considerable differences in the RF-EMF level measured and thus the sensitivity to detect differences is limited. Therefore, we cannot rule out that our approach is not sensitive enough to capture differences between absorbed RF-EMF dose from own device use. This may also imply that observed differences in uplink according to school rules would be relevant for daily absorbed RF-EMF dose, since own mobile phone use is the most relevant contributor to this exposure metric. Undoubtedly, effective reduction of personal absorbed RF-EMF needs to consider the own mobile phone use of that person. Apart from reduced usage duration and increasing the distance between the emitting phone and the body, exposure is minimized when the phone is not used while having a low downlink signal from the own provider (Mazloum et al., 2019). In these situations, use of WiFi exposure results in lower exposure than using the mobile phone network (Popović et al., 2019).
- While we tried to minimize body shielding by asking the participants to carry the exposimeter in a bag or putting it on a nearby table when they were seated or sleeping, we acknowledge that some body shielding may still have occurred, resulting in an underestimation of the exposure levels (Bolte, 2016). Lastly, considering that exposimeters are measuring whole body exposure, we could not study the associations between RF-EMF exposure and certain habits or rules such as (encouraging) the use of speakerphones for calling.
- The cross-talk correction recognized most of the measured DECT exposure as cross-talk, which resulted in substantial reduction of the DECT contribution. Nevertheless, some DECT exposure remains even in environments where such exposures would not be expected (e.g. transport). This contribution of DECT is mostly negligible compared to other sources (downlink, uplink) during these activities.

6. Conclusion

We found that total exposure to RF-EMF in adolescents living in and around Greater London tended to be higher than found in adolescents from other European countries. Consistent with previous personal monitoring studies, we found that most of this exposure originates from downlink, followed by uplink sources. School or home policies aiming to restrict the use of mobile technologies at school or at home were not consistently associated with a measurably lower RF-EMF exposure of adolescents. We further found that measurements of environmental exposure levels obtained from classroom spot measurements were moderately correlated with personal exposure levels, although somewhat lower on average, which may be explained by more communication activity when adolescents were at school, compared to spot measurements in empty classrooms.

Funding

SCAMP is independent research funded (2021–2025) by the Medical Research Council (MRC) (MR/V004190/1), and originally commissioned and funded (March 2014–Dec 2021) by the National Institute for Health Research (NIHR) Policy Research Programme (PRP) (Secondary School Cohort Study of Mobile Phone Use and Neurocognitive and Behavioural Outcomes/091/0212) via the Research Initiative on Health and Mobile Telecommunications (RIHMT) - a partnership between public funders and the mobile phone industry. This study is part supported by the MRC Centre for Environment and Health, which is currently funded by the MRC (MR/S019669/1, 2019–2024). The study is also supported by funds from the NIHR Health Protection Research Units in Environmental Exposures and Health & Chemical and Radiation Threats and Hazards, based at Imperial College London, in partnership with UK Health Security Agency (UKHSA) (HPRU-2012-10141). Infrastructure support for the Department of Epidemiology and Biostatistics, Imperial College London was provided by the NIHR Imperial Biomedical Research Centre. MBT's Chair, RBS's Fellowship and the work in this paper is supported in part by a donation from Marit Mohn to Imperial College London to support Population Child Health through the Mohn Centre for Children's Health and Wellbeing. The funders of the study had no role in the design or conduct of the study nor the reporting of the SCAMP study results. The views expressed in this paper are those of the authors and not necessarily those of the MRC, NIHR or UKHSA.

Ethics

The North West Haydock Research Ethics Committee (ref 14/NW/0347) approved the SCAMP study protocol and all subsequent amendments (ref 14/NW/0347). Head teachers consented to participation of their schools in SCAMP. Parents and adolescents were provided in advance with written information about the study and were given opportunity to opt out of the SCAMP study. In order to participate in the personal monitoring study, parents provided written consent for their children.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Martin Röösli's research is entirely funded by public or not for profit foundations. He has served as advisor to a number of national and international public advisory and research steering groups concerning the potential health effects of exposure to nonionizing radiation, including the World Health Organization, the International Agency for Research on Cancer, the International Commission on Non-Ionizing Radiation Protection, the Swiss Government (member of the working group "mobile phone and radiation" and chair of the expert group.

Acknowledgements

We would like to express our thanks to all SCAMP participants and their parents for provision of their data and/or consent to facilitate this research. We thank Dr Danielle Ashworth, Margaret Douglass, Mark Ellis, Dr Daniela Fecht, Dr John Gulliver, Dr Nick Henriquez, Stacey Jennings, Dr Gemma Knowles, William Mueller, Dr Milagros Ruiz, Annalisa Sheehan and Riitta Soininen at Imperial College London; Dr Benjamin Barratt, Dr Artemis Doutsi, Dr Rosamund Dove, and Dr Ian Mudway at King's College London; Elizabeth Booth at Birkbeck, University of London; Dr John Rogers at Delosis Ltd, London; Mikaël J. A. Maes at University College London; and Dr Jürg Fröhlich and Marco Zahner at ETH Zürich for their contributions to the project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.113252.

References

Bhatt, C.R., et al., 2017. Use of mobile and cordless phones and change in cognitive function: a prospective cohort analysis of Australian primary school children. Environ. Health 16, 62.
Bienkowski, P., et al., 2015. Electromagnetic Fields from Mobile Phone Base Station–Variability Analysis, vol. 34, pp. 257–261.
Birks, L.E., et al., 2018. Spatial and temporal variability of personal environmental exposure to radio frequency electromagnetic fields in children in Europe. Environ. Int. 117, 204–214.
Bolte, J.F., Eikelboom, T., 2012. Personal radiofrequency electromagnetic field measurements in The Netherlands: exposure level and variability for everyday activities, times of day and types of area. Environ. Int. 48, 133–142.
Bolte, J.F.B., 2016. Lessons learnt on biases and uncertainties in personal exposure measurement surveys of radiofrequency electromagnetic fields with exposimeters. Environ. Int. 94, 724–735.
Bruton, J., et al., 2020. Enabling Participation of Black and Minority Ethnic (BME) and Seldom-Heard Communities in Health Research: A Case Study from the SCAMP Adolescent Cohort Study (Research for All).
Calvente, I., et al., 2016. Does Exposure to Environmental Radiofrequency Electromagnetic Fields Cause Cognitive and Behavioral Effects in 10-year-old Boys?, vol. 37, pp. 25–36.
Chetty-Mhlanga, S., et al., 2020. Different Aspects of Electronic Media Use, Symptoms and Neurocognitive Outcomes of Children and Adolescents in the Rural Western Cape Region of South Africa, p. 109315.
Eeftens, M., et al., 2018a. Personal exposure to radio-frequency electromagnetic fields in Europe: is there a generation gap? Environ. Int. 121, 216–226.
Eeftens, M., et al., 2018b. Dealing with crosstalk in electromagnetic field measurements of portable devices. Bioelectromagnetics 39, 529–538.
Foerster, M., et al., 2019. Impact of Adolescents' Screen Time and Nocturnal Mobile Phone-Related Awakenings on Sleep and General Health Symptoms: a Prospective Cohort Study, vol. 16, p. 518.
Foerster, M., et al., 2018. A prospective cohort study of adolescents' memory performance and individual brain dose of microwave radiation from wireless communication. Environ. Health Perspect. 126, 077007.
Gallastegi, M., et al., 2018. Children's exposure assessment of radiofrequency fields: comparison between spot and personal measurements. Environ. Int. 118, 60–69.
Guxens, M., et al., 2016. Outdoor and Indoor Sources of Residential Radiofrequency Electromagnetic Fields, Personal Cell Phone and Cordless Phone Use, and Cognitive Function in 5–6 Years Old Children, vol. 150, pp. 364–374.
Harrington, S.C., et al., 2019. Risk Factors Associated with Myopia in Schoolchildren in Ireland, vol. 103, pp. 1803–1809.
ICNIRP, International Commission on Non-Ionizing Radiation Protection, 2020. RF-EMF Guidelines.
Iskra, S., et al., 2010. Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry. Radiat. Protect. Dosim. 140, 25–33.
Jalilian, H., et al., 2019. Public exposure to radiofrequency electromagnetic fields in everyday microenvironments: an updated systematic review for Europe. Environ. Res. 176, 108517.
Jenkins, R.H., et al., 2020. Social networking site use in young adolescents: association with health-related quality of life and behavioural difficulties. Comput. Hum. Behav. 109.
Kheifets, L., et al., 2005. The sensitivity of children to electromagnetic fields. Pediatrics 116, e303–e313.
Martens, A.L., et al., 2016. Residential exposure to RF-EMF from mobile phone base stations: model predictions versus personal and home measurements. Sci. Total Environ. 550, 987–993.
Mazloum, T., et al., 2019. RF-EMF exposure induced by mobile phones operating in LTE small cells in two different urban cities. Ann. Telecommun. 74, 35–42.
Mireku, M.O., et al., 2019a. Night-time Screen-Based Media Device Use and Adolescents' Sleep and Health-Related Quality of Life, vol. 124, pp. 66–78.
Mireku, M.O., et al., 2019b. Processed data on the night-time use of screen-based media devices and adolescents' sleep quality and health-related quality of life. Data Brief 23, 103761.
Najera, A., et al., 2020. Comparison of statistic methods for censored personal exposure to RF-EMF data. Environ. Monit. Assess. 192, 1–11.
Neubauer, G., et al., 2010. The Association between Exposure Determined by Radiofrequency Personal Exposimeters and Human Exposure: a Simulation Study, vol. 31, pp. 535–545.
Ofcom, 2017. Children and Parents: Media Use and Attitudes Report. London, UK.
Office for National Statistics, 2010. Volume 3 the National Statistics Socio-Economic Classification: (Rebased on the SOC2010) User Manual. Standard Occupational Classification, 2010.
Poorolajal, J., et al., 2020. Behavioral Factors Influencing Childhood Obesity: a Systematic Review and Meta-Analysis.
Popović, M., et al., 2019. Experimental analysis of individual EMF exposure for GSM/UMTS/WLAN user devices. Ann. Telecommun. 74, 79–91.
R Core Team, R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL (https://www.R-project.org/).
Ramirez-Vazquez, R., et al., 2019. Characterisation of personal exposure to environmental radiofrequency electromagnetic fields in Albacete (Spain) and assessment of risk perception. Environ. Res. 172, 109–116.
Redmayne, M., 2016. International policy and advisory response regarding children's exposure to radio frequency electromagnetic fields (RF-EMF). Electromagn. Biol. Med. 35, 176–185.
Röösli, M., et al., 2016. Persönliche Messungen von hochfrequenten elektromagnetischen Feldern bei einer Bevölkerungsstichprobe im Kanton Zürich. Swiss Tropical and Public Health Institute, Basel, Switzerland.
Roser, K., et al., 2016. Mobile phone use, behavioural problems and concentration capacity in adolescents: a prospective study. Int. J. Hyg Environ. Health 219, 759–769.
Roser, K., et al., 2017. Personal radiofrequency electromagnetic field exposure measurements in Swiss adolescents. Environ. Int. 99, 303–314.
Sagar, S., et al., 2018. Radiofrequency electromagnetic field exposure in everyday microenvironments in Europe: a systematic literature review. J. Expo. Sci. Environ. Epidemiol. 28, 147–160.
Shen, C., et al., 2021. Digital technology use and BMI: evidence from a cross-sectional analysis of an adolescent cohort study. J. Med. Internet Res. 23, e26485.
Thielens, A., et al., 2015. On-body calibration and processing for a combination of two radio-frequency personal exposimeters. Radiat. Protect. Dosim. 163, 58–69.
Thomas, S., et al., 2010. Use of mobile phones and changes in cognitive function in adolescents. Occup. Environ. Med. 67, 861–866.
Toledano, M.B., et al., 2019. Cohort profile: the study of cognition, adolescents and mobile phones (SCAMP). Int. J. Epidemiol. 48, 25–26l.
Valič, B., et al., 2015. Typical exposure of children to EMF: exposimetry and dosimetry. Radiat. Protect. Dosim. 163, 70–80.
van Wel, L., et al., 2021. Radio-frequency electromagnetic field exposure and contribution of sources in the general population: an organ-specific integrative exposure assessment. J. Expo. Sci. Environ. Epidemiol. 1–9.