Exposure assessment for mobile phone use and radiofrequency electromagnetic fields and the application in a Swiss cohort study

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HERMES Study

The HERMES (Health Effects Related to Mobile phonE use in adolescentS) study was funded by the Swiss National Science Foundation (SNSF) (project number 138190, 2012 - 2014).

Two PhD theses result from the HERMES study. This thesis focuses on the exposure assessment and on behaviour and concentration capacity of adolescents. The complementary thesis of Anna Schöni covers the topics health symptoms and memory performance of adolescents.

The articles included in this thesis are cited using the corresponding article number in this thesis; the articles included in Anna Schöni's thesis are cited using the conventional citing style of this thesis. A list of the publications resulting from the HERMES study can be found at the end of the thesis.

Summary

Background

Mobile phones and other wireless communication devices emitting radiofrequency electromagnetic fields (RF-EMF) are nowadays omnipresent and adolescents are among the heaviest users. This results in ubiquitous RF-EMF exposure, though little is known about the levels of this exposure, especially in adolescents.

Exposure to RF-EMF can be divided into two parts, the exposure from the use of wireless communication devices (near-field) and the exposure from environmental sources (far-field). In previous studies, the near-field exposure was quantified using the amount of device use only. The RF-EMF exposure resulting from the device use, however, is not only dependent on the duration of use, but additionally for instance on the mode of use and the network used for mobile phone calls. The far-field exposure from fixed site transmitters such as broadcast transmitters for radio and television (TV) and mobile phone base stations was modelled using geospatial propagation models or measured using portable RF-EMF measurement devices. But this part of the exposure also depends on the duration a person is exposed to modelled or measured exposure levels. Therefore a dosimetric approach is needed that allows taking into account these additional aspects of exposure and to combine the near-field and the far-field exposure to one exposure surrogate.

Since the mobile phone use increased in the last decade, there is concern that this use may have a negative impact on adolescents. To date, epidemiological studies in adolescents are scarce. In addition, the ones existing used self-reported device use that is known to be inaccurate and the amount of device use was used as proxy for the RF-EMF exposure not taking into account other RF-EMF sources. Furthermore, most of these studies were of cross-sectional design not allowing to draw conclusions about causal relationships between mobile phone use and health, behaviour and cognitive function of adolescents. To overcome these limitations, the HERMES (Health Effects Related to Mobile phonE use in adolescentS) study was conducted.

Objectives

The objective of the HERMES study was to prospectively investigate whether mobile phone use and the use of other wireless communication devices or RF-EMF exposure have an impact on the health and the behaviour of adolescents and if cognitive function of adolescents is affected by these exposures.

The objectives of this thesis were to improve the exposure assessment for mobile phone use and RF-EMF exposure and to investigate its relations to behavioural problems and concentration capacity of adolescents.

Methods

The HERMES study was a prospective cohort study with a one year follow-up period. It was conducted in Central Switzerland in adolescents attending the 7th school grade. The investigation took place in the schools during school time and consisted of filling in a paper and pencil questionnaire and performing computerized cognitive tests. In addition, a questionnaire for the parents was distributed that was directly sent back to the study managers.

Additionally to the amount of mobile phone and other device use, problematic aspects of mobile phone use such as loss of control, withdrawal, negative life consequences and craving were asked in the questionnaire.

In a subgroup of the study participants, personal RF-EMF measurements were conducted. The participating adolescents carried a portable measurement device for three consecutive days and filled in a time-activity diary to record their locations during the measurement period.

The questionnaire data and the personal RF-EMF measurements together with geospatial propagation modelling for the exposure originating from fixed site transmitters at home and in the schools as well as operator-recorded mobile phone use data for a subgroup of the study participants were used to develop an RF-EMF exposure surrogate combining the exposure from the use of wireless communication devices and environmental sources. This exposure surrogate was then used to conduct cross-sectional and longitudinal analyses of RF-EMF exposure and behaviour and concentration capacity of adolescents.

Results

439 adolescents participated in the HERMES study (participation rate of 36.8%) with a follow-up rate of 96.8%. Operator records were available for 234 adolescents and personal RF-EMF measurements were available for a subgroup of 90 adolescents.

We found that problematic mobile phone use in adolescents was related to behavioural problems such as hyperactivity, conduct problems, emotional symptoms and antisocial behaviour and impaired health related quality of life (HRQOL) facets such as home life and school environment.

The main contributor to the measured personal RF-EMF exposure was the mobile internet use on the mobile phone. For the adolescents not using mobile internet, mobile phone base stations contributed most to their exposure. Having wireless internet (WLAN) at home and attending a school with WLAN had very little impact on the average measured WLAN exposure.

According to the developed RF-EMF exposure surrogate combining near-field and far-field exposure, the exposure from environmental sources such as fixed site transmitters, cordless phone and WLAN base stations and mobile phones in the surroundings plays a minor role compared to the exposure from the use of wireless communication devices (mobile phones, cordless phones, computers, laptops and tablets connected to WLAN). The near-field dose accounted for 98.4% of the brain dose and 94.0% of the whole body dose.

In applying the developed RF-EMF dose surrogate in combination with use measures derived from self-reported device use and operator-recorded mobile phone use, the relations to behavioural problems and the concentration capacity of adolescents were investigated. No systematic pattern in relation to RF-EMF exposure was observed indicating no causal relationship between RF-EMF exposure and behavioural problems and concentration capacity of adolescents.

Conclusions

Environmental sources play a minor role for the RF-EMF exposure of adolescents compared to the use of wireless devices. Having WLAN at home and attending a school with WLAN have very little impact on the average measured WLAN exposure. The use of mobile internet results in higher measured exposure from mobile phones. Therefore, precautionary measures to reduce the exposure to RF-EMF should focus on the use of wireless devices.

The behaviour and the concentration capacity of adolescents were not affected by RF-EMF exposure. In contrary, behavioural problems and impaired HRQOL were associated with problematic aspects of mobile phone use. Therefore, problematic mobile phone use should be considered if dealing with adolescents showing behavioural problems or impaired mental health.

The HERMES study was the first study applying a comprehensive exposure assessment including operator-recorded mobile phone use and cumulative RF-EMF dose calculations. The study provided new insights into the mobile phone use of Swiss adolescents and its impact on health, behaviour and cognitive function using a longitudinal approach allowing to draw conclusions about causal relationships. The applied methods can be used in future epidemiological studies on RF-EMF exposure and its influence on humans.

List of abbreviations, units and definitions

Abbreviations

95% CI	95% confidence interval
DECT	Digital enhanced cordless telecommunications
EMF	Electromagnetic field
FM	Frequency modulation
GSM	Global system for mobile communication
HRQOL	Health related quality of life
ICNIRP	International Commission on Non-Ionizing Radiation Protection
KIDSCREEN	Health related quality of life Questionnaire
LTE	Long term evolution
MPPUS	Mobile Phone Problem Use Scale
RF-EMF	Radiofrequency electromagnetic field
SAR	Specific absorption rate
SDQ	Strengths and Difficulties Questionnaire
UMTS	Universal mobile telecommunications system
TV	Television
WHO	World Health Organization
WLAN	Wireless local area network

Units

Hz	Hertz (unit of the frequency)
kHz	Kilohertz (10^3 Hz)
MHz	Megahertz (10^6 Hz)
GHz	Gigahertz (10^9 Hz)
s	Second
V/m	Volt per meter (unit of the electrical field strength)
W/m²	Watt per square meter (unit of the power flux density)
Ω	Ohm (unit of the electrical resistance)

Definitions

Downlink	Transmission from mobile phone base station to mobile phone handset
Exposimeter	Portable RF-EMF measurement device
Fixed site transmitter	Fixed RF-EMF transmitter such as mobile phone base station or broadcast transmitter (radio and TV)
Uplink	Transmission from mobile phone handset to mobile phone base station

1 Introduction

Mobile phones and other wireless communication devices emitting radiofrequency electromagnetic fields (RF-EMF) nowadays are omnipresent and they undergo a rapid development. In Switzerland, the number of mobile phone subscriptions increased from 4.6 Mio (corresponding to 65 subscriptions per 100 inhabitants) in 2000 to 11.5 Mio (corresponding to 141 subscriptions per 100 inhabitants) in 2014 (ICT 2015). Accordingly, the ownership and use of wireless communication devices is growing and adolescents are among the heaviest mobile phone users. A recent representative survey in 1,086 adolescents in Switzerland revealed that 98% of the adolescents own a mobile phone, 76% a computer or laptop and 29% a tablet (Willemse et al. 2014). Furthermore, the use of these devices is frequent, 94% of the adolescents used their mobile phone daily or several times per week for exchanging messages via internet-based applications, 87% for browsing the internet, 53% for gaming and 61% for checking their e-mails (Willemse et al. 2014). These developments result in ubiquitous exposure to RF-EMF and adolescents may be more susceptible to RF-EMF because of their still proceeding development (Kheifets et al. 2005). In addition, they will experience longer exposure to RF-EMF from mobile phone use, because they started using their mobile phone at an early age. However, little is known about personal exposure to RF-EMF, especially in adolescents and epidemiological research investigating possible RF-EMF effects in adolescents is scarce. Therefore, the current WHO research agenda for radiofrequency fields rates the quantification of personal exposures and prospective cohort studies of adolescents with outcomes including behavioural disorders high priority (WHO 2010). To contribute to fill these knowledge gaps, the HERMES (Health Effects Related to Mobile phonE use in adolescentS) study, a prospective cohort study conducted in Central Switzerland, was launched. The HERMES study aimed at prospectively investigating 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 functions in adolescents. A further aim of the study was to improve the exposure assessment for mobile phone use and RF-EMFs, what is still considered a major challenge in this field of research.

1.1 Problematic mobile phone use

The frequent use of mobile phones especially among adolescents may have a negative impact on daily life and thus may be considered problematic. Since the introduction of the term “internet addiction” (Internet addiction: The emergence of a new clinical disorder by Young (1996)), the first mention of addiction in the context of device use, a large variety of measures for problematic device use have been developed, and this especially holds for problematic mobile phone use. But no definitions or measures have been established so far (Billieux 2012). This consequently translates into a variety of measures used and a wide range of observed prevalence rates. A Spanish review of the literature summarized findings from 15 studies using different scales and ad hoc definitions of problematic mobile phone use and found prevalence rates ranging from no occurrence of problematic mobile phone use to more than a third of the studied population described as being problematic users depending on the measures and cut-off points used and the population studied (Pedrero Perez et al. 2012). For instance Malay researchers did not find problematic mobile phone use measured by the 27-item Mobile Phone Problem Use Scale (MPPUS) developed by Bianchi and Phillips (2005) in a sample of 386 students (Zulkefly and Baharudin 2009) whereas a survey in Spanish adolescents using a one-item measure asking about symptoms of dependence on the mobile phone found a prevalence rate of 38% (Protégeles 2005).

Most of the conducted studies so far investigating problematic mobile phone use made use of the amount of mobile phone use as proxy for problematic use; few studies looked at problematic mobile phone use measured with different scales. Since problematic mobile phone use seems not only to consist of a large amount of mobile phone use, but problematic aspects known for other addictions as well, these aspects should be considered if measuring problematic mobile phone use. Furthermore, a measure should be developed that can be widely used and validated.

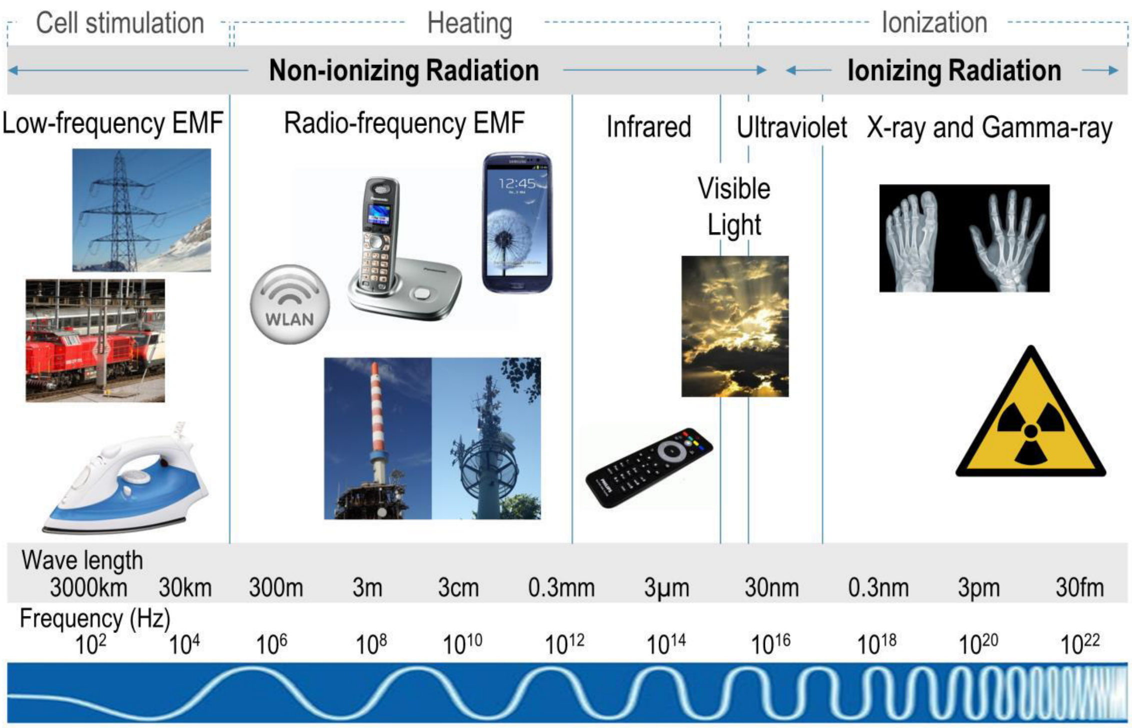
The MPPUS developed by Bianchi and Phillips (2005) is a widely used 27-item questionnaire addressing different aspects of addiction such as tolerance, escape from other problems, withdrawal, craving and negative life consequences. It showed good internal consistency and is validated in an adult sample. Despite of those strengths, it is long and tends to be somewhat redundant which may be a problem for research in adolescents. Further, it has not yet been evaluated in adolescents. For that reason, we aimed at developing a short MPPUS suitable for research in adolescents.

Regarding adverse effects, problematic mobile phone use was found to be associated with increased chronic stress, extraversion, increased depression and decreased emotional stability in young adults (Augner and Hacker 2012), extraversion and low self-esteem in adults (Bianchi and Phillips 2005) and depressive symptoms in adolescents (Yen et al. 2009). Furthermore, adolescents with problematic use were more likely to be aggressive, be victims of aggression and to have low self-esteem (Yang et al. 2010). A South Korean study in mostly male adolescents found more depressive symptoms, more difficulty in expression of emotions, higher anxiety and lower self-esteem in excessive mobile phone users (Ha et al. 2008).

1.2 Radiofrequency electromagnetic fields

The electromagnetic spectrum can be divided into non-ionizing and ionizing radiation (Figure 1). Waves belonging to ionizing radiation carry enough energy to break bonds between molecules, whereas waves belonging to non-ionizing radiation do not have this property. Non-ionizing radiation can be further subdivided into low-frequency electromagnetic fields, RF-EMFs, infrared and visible light. Ultraviolet marks the transition to the ionizing radiation, ionizing radiation consists of x-ray and gamma-ray radiation. This division is based on the frequency of the wave. Frequency is defined as the number of times the wave oscillates per second and is measured in Hertz (Hz), where 1 Hz corresponds to one oscillation per second. The corresponding wave length is defined as the distance between two successive points of the same phase measured in the direction of propagation of the wave. RF-EMFs are used to transmit information over long distances and are the basis of broadcasting and mobile telecommunication and all over the world.

Figure 1. The electromagnetic spectrum.



To limit exposure to RF-EMF, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has set exposure limits (ICNIRP 1998). These limits are frequency-dependent and for the general public they range from 28 V/m for broadcast transmitters to 61 V/m for mobile phone base stations using frequencies > 2000 MHz. In Switzerland, precautionary limits that are about ten times lower than the ICNIRP limits have been set (ONIR 1999). These hold for one single fixed site transmitter and locations where people usually spend a lot of time, such as homes, schools and offices. These limits are set to 4 to 6 V/m for mobile phone base stations and 3 V/m for broadcast transmitters.

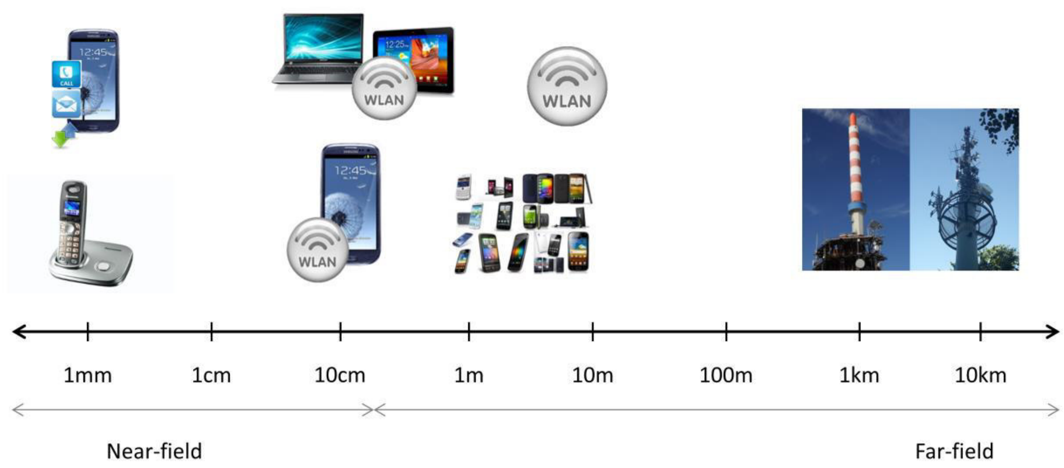
For devices emitting RF-EMF, the limits set by the ICNIRP relate to the specific absorption rate (SAR). The SAR is a measure of the amount of power absorbed by a certain tissue per mass. The limits are set to 0.08 W/kg for whole body exposure and 2 W/kg for localized exposure of the head and the trunk (ICNIRP 1998).

1.3 Exposure assessment

In epidemiology, exposure is determined using measured variables as proxies for the true exposure. Thus, the aim of exposure assessment in epidemiology is to find sound surrogate measures representing the exposure of interest.

The exposure to RF-EMF is related to fixed site transmitters used for broadcasting and mobile telecommunication on the one hand and wireless communication devices on the other hand. Based on these two types of sources, RF-EMF exposure can be divided into two parts, a far-field part consisting of the exposure from environmental sources and a near-field part containing the exposure from the use of wireless communication devices (Figure 2). As a basic rule, far-field conditions occur for distances above one wave length of the RF-EMF. For instance, for frequencies of 800 MHz and 2600 MHz the corresponding wave lengths are 37.5 cm and 11.5 cm, respectively. Thus for mobile phones operating in the frequency range from 800 to 2600 MHz, the exposure from the use of the own mobile phone corresponds to the near-field and the exposure from mobile phones in the surroundings corresponds to the far-field.

Figure 2. An illustration of near-field and far-field sources emitting RF-EMF.



For RF-EMF, a lot of proxies are used to quantify the exposure. For instance, simple proxies are the distance to the closest transmitter for fixed site transmitters exposure or the average duration of mobile phone calls for the exposure from mobile phones. More advanced proxies are for instance RF-EMF measurements and different types of modelling for the exposure from fixed site transmitters or the calculation of the absorbed energy by the body from the use of wireless communication devices.

The applied exposure assessment methods in the HERMES study include geospatial propagation modelling of exposure from fixed site transmitters, personal measurements using portable RF-EMF measurement devices (so-called exposimeters) carried by volunteers, self-reported mobile phone use data collected using questionnaires, objectively recorded mobile phone use data provided from mobile phone operators and dose calculations combining near-field and far-field exposures.

1.3.1 Geospatial propagation modelling

Exposure from fixed site transmitters such as broadband transmitters and mobile phone base stations can be estimated using geospatial propagation models (Beekhuizen et al. 2013; Breckenkamp et al. 2008; Briggs et al. 2012; Bürgi et al. 2010; Bürgi et al. 2008; Elliott et al. 2010; Ha et al. 2007; Merzenich et al. 2008). Such a model called NISMap based on a comprehensive database of transmitters in the study area, the three-dimensional topography and a three-dimension building model of the study area was developed for parts of Switzerland (Bürgi et al. 2010; Bürgi et al. 2008) and applied to residencies of study participants of a Swiss cohort study (Bürgi et al. 2010; Frei et al. 2009a). Such models can easily be applied to large study populations, because the exposure can be assigned based on any location of interest (for instance residency, school place or workplace). However, such models are restricted to exposures from fixed site transmitters and are therefore not able to predict exposures from other sources such as small cells (low power mobile phone base stations), WLAN hotspots in buildings or public places, WLAN and cordless phone base stations in buildings and mobile phones in the surroundings.

1.3.2 Personal measurements

Personal exposure to RF-EMF depends not only on the exposure levels in different environments, but also individual behaviour (Röösli et al. 2010). Personal measurements enable to measure during all everyday activities and at times participants actually spend their time at these locations.
Personal measurements in Europe were mainly conducted in adults (Bolte and Eikelboom 2012; Frei et al. 2009b; Thomas et al. 2008a; Thuróczy et al. 2008; Valic et al. 2009; Viel et al. 2009) whereas personal measurements in children and adolescents are scarce (Thomas et al. 2008b; Valic et al. 2015). In 2006/2007 measurements in 3,022 German children and adolescents were conducted (Thomas et al. 2008b) and in 2010/2011, a small personal measurement study was performed in Slovenia including 18 children and adolescents (Valic et al. 2015). Personal measurements enable to investigate the temporal and spatial variability of personal RF-EMF exposure, but their realization

requires a large organizational effort. Furthermore, participants are additionally asked to fill in a time-activity diary to record their daily life. The quality of the measurements depends highly on the quality of the diary entries, since diaries provide the necessary information to assign the measurements to the corresponding locations.

By means of personal measurements, one is able to capture exposure from several environmental sources. However, the exposure from the use of devices close to the body such as mobile phones, cordless phones, computers, laptops and tablets connected to WLAN is not measured adequately, because the measured exposure depends highly on the distance between the emitting source and the device and that is not necessarily the same as the distance between the source and the body (Inyang et al. 2008; Röösli et al. 2010).

Another challenge for personal measurements is the possible impact of the own mobile phone use on the measurements. A few years ago, Frei et al. (2010) concluded, that personal mobile phone use contributed relatively little to average personal measurements (Frei et al. 2010). However, in a measurement study conducted in 2010, it was observed that even a mobile phone in stand-by mode increased measured exposure in public transport and cars compared to scenarios where the mobile phone was switched off (Urbinello and Röösli 2013). This indicates that the introduction of smartphones and other wireless communication devices such as tablets and the accompanying growing use of these devices may affect nowadays RF-EMF measurements in a non-negligible way.

1.3.3 Dosimetric approach

To combine the exposure from environmental sources (far-field) and wireless device use (near-field), one has to convert these two types of exposures into a common surrogate measure. Such a surrogate measure is the amount of radiation energy absorbed by the body, the RF-EMF dose. The main data sources for dose calculations are the incident fields from far-field sources and the use durations of close-to-body sources. Furthermore, corresponding SAR values are required.

So far, few attempts have been made to calculate the RF-EMF dose from several sources. Lauer et al. (2013) combined realistic data about near-field (mobile and cordless phone calls) and far-field (fixed site transmitters, Digital Enhanced Cordless Telecommunications (DECT), Wireless Local Area Network (WLAN)) exposure (Lauer et al. 2013). This proposed framework was used for instance to compare different base station scenarios and their implications for the downlink and the corresponding uplink exposure from mobile phone calls (Aerts et al. 2015; Aerts et al. 2014; Plets et al. 2014). The estimation of the dose at locations of brain tumours of participants was applied in the Interphone study, a large worldwide study investigating mobile phone use and cancer (Cardis et al. 2007; Cardis et al. 2011). In the framework of a European project called LEXNET aiming to develop mechanisms to reduce public RF-EMF exposure, a population-based exposure metric was developed (Varsier et al. 2015).

1.4 Behaviour and concentration capacity of adolescents

Behavioural problems are common during childhood and adolescence. Swiss paediatricians estimated the percentage of children with attention deficit hyperactivity disorder (ADHD) or conduct problems seen in their practice at 9% (In-Albon et al. 2010). In Germany, parent-rated behavioural problems were found in 7% of 7,000 adolescents aged 11 to 17 years (Hölling et al. 2007). Among the specific problems, most frequent problems were conduct problems (14%), followed by problems with peers (13%) and emotional symptoms (10%). Hyperactivity was reported for 7% of the adolescents and 4% showed antisocial behaviour. In Sweden, concentration difficulties were among the most frequent reported health complaints in adolescents (Söderqvist et al. 2008) and in Germany, 32% of adolescents participating in a measurement study reported to have concentration problems (Heinrich et al. 2010). In Chinese adolescents, prevalence of inattention was reported to be as high as 70% (Zheng et al. 2014).

Since children and adolescents may be more susceptible to RF-EMF (Kheifets et al. 2005) and they are among the heaviest mobile phone users, behaviour or concentration capacity of adolescents may be affected by RF-EMF exposure or mobile phone use. Findings of a Danish and a Dutch study about mobile phone use during pregnancy and childhood and behavioural problems in children are contradictory and highly discussed (Aarstad 2011; Divan et al. 2008; Divan et al. 2012; Guxens et al. 2013a; Guxens et al. 2013b; Sudan et al. 2013). The Danish study found mobile phone use among children associated with behavioural problems and this association was even stronger for additional mobile phone use of the mother during pregnancy (Divan et al. 2008). The same but weaker associations were found in a larger separate sample (Divan et al. 2012). The Dutch study did not find any associations of maternal mobile phone or cordless phone use during pregnancy and behavioural problems in their children (Guxens et al. 2013a).

In a German study, measured exposure to RF-EMF in the highest quartile was found to be significantly associated with overall behavioural problems and conduct problems in adolescents (Thomas et al. 2010b). No associations were found for measured RF-EMF exposure or self-reported mobile phone use and acute concentration problems (Heinrich et al. 2010). A Swedish study found the duration of mobile phone and cordless phone use significantly associated with self-reported concentration difficulties (Söderqvist et al. 2008), whereas mobile phone calls were not associated with ADHD symptoms in 2,422 Korean children (Byun et al. 2013b) or inattention in 7,102 Chinese adolescents (Zheng et al. 2014). But interestingly, they found mobile phone use for playing games (Byun et al. 2013b) and the time spent on the mobile phone for entertainment (Zheng et al. 2014) being associated with ADHD symptoms or inattention, respectively. Note that these are cross-sectional studies and therefore no conclusions about the direction of the effects can be drawn. Results of numerous human experimental studies in adults applying a mobile phone-like exposure set-up reported inconsistent effects on cognitive functions, although mostly absence of an association (Valentini et al. 2010). Studies in children and adolescents using base station-like exposure (Riddervold et al. 2008), or mobile phone handset exposure (Haarala et al. 2005; Preece et al. 2005) did not find effects on attention. In Finland, modulations on the electroencephalogram (EEG) activity reflecting brain activity during cognitive processing were found if adolescents were exposed to mobile phone-like exposure (Krause et al. 2006), whereas a Swiss and an Australian study did not find such effects (Croft et al. 2010; Loughran et al. 2013). However, the sample size of these studies is very small (15 to 40 participants).

Epidemiological studies about mobile phone use and cognitive functions are scarce. A study in students from Hong Kong found better performance of mobile phone users compared to non-users in a trail making test but not in two other cognitive tasks measuring attention (Lee et al. 2001). A cross-sectional study including 317 Australian adolescents found self-reported number of mobile phone calls associated with impaired performance in the Stroop Color-Word test measuring focused attention, but no associations with number of text messages or duration of mobile phone use since start of use were observed (Abramson et al. 2009). In the longitudinal study in the same adolescents, no associations were seen between mobile phone use and focused attention (Thomas et al. 2010a).

2 Main objectives

Objective 1

Investigate problematic mobile phone use of adolescents and its relation to mental health and behavioural problems.

Mobile phone use increased in the last years and adolescents are among the heaviest users. This frequent use may have a negative impact on daily life and thus may be considered problematic. No definition or measure of problematic mobile phone use has been established so far and therefore different measures are used (Billieux 2012). This diversity consequently translates into a wide range of prevalence rates ranging from no occurrence of problematic use to 38% (Pedrero Perez et al. 2012). Thus the first aim was to shorten the widely used 27-item MPPUS (Bianchi and Phillips 2005) validated in adults to obtain a short scale measuring problematic mobile phone use in adolescents. The results are presented and discussed in article 1 (section 4).

Regarding possible effects on health, most of the conducted studies so far used the amount of mobile phone use as proxy for problematic mobile phone use. They found mobile phone use associated with impaired well-being (Byun et al. 2013a; Redmayne et al. 2013) and impaired mental health (Byun et al. 2013b; Ikeda and Nakamura 2014; Sanchez-Martinez and Otero 2009; Thomée et al. 2011; Zheng et al. 2014). Studies investigating problematic mobile phone use applying different scales found also associations with impaired mental health (Augner and Hacker 2012; Bianchi and Phillips 2005; Yang et al. 2010; Yen et al. 2009). However, it remains unclear, if these adverse effects are due to the amount of mobile phone use or the problematic aspects of use. Therefore we aimed secondly at investigating the relationships of problematic mobile phone use and mental health and behavioural problems in adolescents while controlling for amount of mobile phone use. We had self-reported as well as operator-recorded amount of mobile phone use for a subgroup of the study participants available. This analysis will help to better understand if associations are due to problematic aspects of mobile phone use. The results are presented and discussed in article 2 (section 4).

Objective 2

Describe the personal RF-EMF exposure of Swiss adolescents and evaluate exposure relevant factors.

Exposure to RF-EMF is ubiquitous, but little is known about the extent of personal exposure to RF-EMF in daily life, especially in adolescents. We conducted personal measurements in a subgroup of the HERMES study participants. The participants were selected to represent a broad range of the

HERMES cohort according to basic criteria such as gender, age, school level and urbanization of home and school place. The adolescents were instructed to carry the exposimeter for three consecutive days. Additionally, they filled in a time-activity diary installed as an application on a smartphone and GPS coordinates were recorded. The exposure measurements were analysed regarding levels of exposure at different locations and times and potentially exposure relevant factors such as WLAN in school and at home and mobile phone use-related factors were evaluated. Results are presented and discussed in article 3 (section 5).

Objective 3

Development of an RF-EMF exposure surrogate combining various near-field and far-field RF-EMF sources.

Sources emitting RF-EMF are everywhere, in the near-field, close to the body and in the far-field, further away from the body. Since the exposure assessment is a crucial part for studying potential effects of RF-EMF, we aimed at developing a cumulative RF-EMF exposure surrogate combining various sources of RF-EMF to one single brain and whole body measure. Near-field sources included wireless communication devices used close to the body such as mobile phones for calls and data exchange, cordless phones and computers, laptops and tablets connected to WLAN. Far-field sources included environmental sources such as fixed site transmitters (mobile phone base stations and radio and TV broadcast transmitters), DECT and WLAN base stations as well as mobile phones in the surroundings. To combine these different sources, we calculated the daily dose originating from each of these sources. These contributions were then summed up to one cumulative daily dose measure for the brain and the whole body. For the use of devices, reported durations from the questionnaire were combined with SAR values derived from the literature. For the environmental sources, levels of the incident fields were estimated using geospatial propagation modelling for fixed site transmitters and multivariable regression modelling calibrated on personal measurements for DECT and WLAN exposure and exposure from other mobile phones. The RF-EMF exposure surrogate is presented and discussed in article 4 (section 6).

Objective 4

Investigate whether mobile phone use or RF-EMF exposure causes behavioural problems or affects concentration capacity of adolescents.

Adolescents are among the heaviest mobile phone users and behavioural problems (Hölling et al. 2007; In-Albon et al. 2010; Thomas et al. 2015) and concentration problems (Heinrich et al. 2010; Söderqvist et al. 2008; Zheng et al. 2014) are prevalent among adolescents. Thus, the question arose if mobile phone use or RF-EMF exposure causes behavioural problems or affects the concentration capacity of adolescents. For instance, mobile phone use for playing games or entertainment was found to be associated with ADHD symptoms (Byun et al. 2013b) and inattention (Zheng et al. 2014), but no associations were found with mobile phone calls (Byun et al. 2013b; Zheng et al. 2014). Measured RF-EMF exposure in the highest quartile was found to be associated with behavioural problems in German adolescents (Thomas et al. 2010b).

Previous studies used self-reported mobile phone use, what is well known to be difficult to recall and leading to uncertainty in mobile phone use data (Aydin et al. 2011; Inyang et al. 2009). Furthermore, mobile phone use was used as proxy for RF-EMF exposure. But RF-EMF exposure from mobile phones depends for instance also on the network used for calls and the mode of use (calling or data traffic) (Gati et al. 2009; Lauer et al. 2013; Persson et al. 2012) and other RF-EMF sources such as for instance fixed site transmitters should be considered as well. And in addition, most of the previous studies were of cross-sectional design. To overcome these limitations, we used additionally operator-recorded mobile phone use and estimated daily RF-EMF dose for the brain and the whole body developed in the framework of the HERMES study (Article 4) taking into account several RF-EMF sources. Furthermore, we used a cross-sectional as well as a longitudinal approach to be able to draw conclusions about the direction of possible effects. The results are presented and discussed in article 5 (section 7).

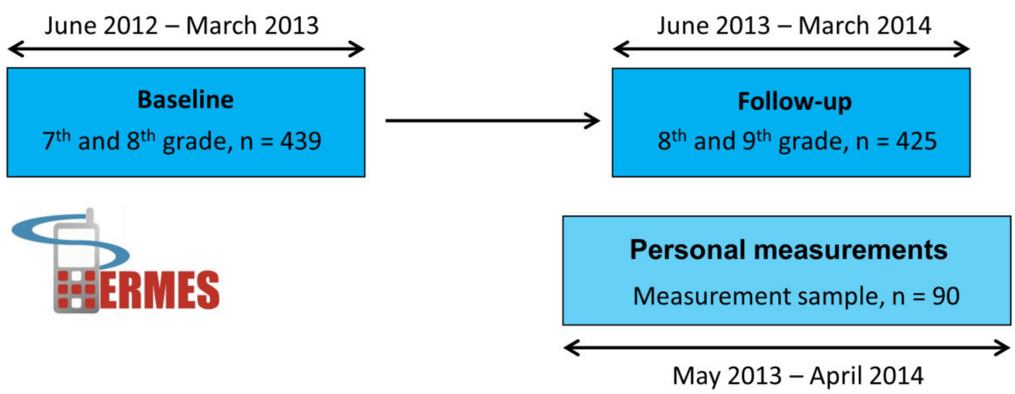
3 Methods

3.1 HERMES study

The HERMES study, a cohort study conducted in Central Switzerland, aimed at prospectively investigate whether mobile phone use or 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 functions in adolescents. The recruitment of the participants was carried out as follows: First, the heads of all schools including 7th grade students in Central Switzerland were contacted by phone and informed about the study. If they were willing to participate in the study, they handed on the information to the teachers. If they decided to participate, the classes were visited for an information presentation lasting about 10 minutes. Finally, the participation of the adolescents was based on their informed consent together with the consent of their parents.

The baseline investigation took place from June 2012 until March 2013; the follow-up investigation was conducted approximately one year later (Figure 3). The study participants filled in a paper and pencil questionnaire and performed two cognitive tests measuring concentration capacity and memory performance using a standardized, computerized cognitive test battery. The investigation took place in school during school time and was supervised by two study managers. Furthermore paper and pencil questionnaires for the parents were distributed and they were asked to return these directly to the study managers.

Figure 3. Structure and chronology of the HERMES study and the measurement study (personal RF-EMF measurements) within the study.



3.2 Amount of mobile phone use

The exposure measures for the amount of mobile phone use included self-reported mobile phone use derived from the questionnaire and objectively recorded mobile phone use for a subsample of the study participants giving informed consent to obtain data from the three mobile phone operators working in Switzerland.

3.3 Problematic mobile phone use

The original English MPPUS by Bianchi and Phillips (2005) was translated into German using a back translation procedure and was included in the questionnaire. Principal component analysis (PCA) was applied to derive a short version of the 27-item MPPUS developed by Bianchi and Phillips (2005) suitable for research in adolescents. The derived short scale was subsequently used to investigate problematic mobile phone use in relation to mental health and behavioural problems of adolescents while controlling for the amount of mobile phone use.

3.4 Personal measurements

The participants of the personal measurements were selected among the HERMES study participants indicating to be willing to participate in the measurement study. The personal measurements were conducted between May 2013 and April 2014. The participants were instructed in school during school time by a study manager. They carried an exposimeter for three consecutive days. The used exposimeter ExpoM-RF (Fields at Work 2015; Lauer 2011) was developed at the ETH Zürich, Switzerland (Figure 4). It is band selective and measures 13 frequency bands ranging from 470 to 3,600 MHz (Table 1). This range includes RF-EMFs from broadcast transmitters, mobile telecommunication (handsets and base stations), WLAN and DECT. The exposure originating from the transmission from a mobile phone handset to a mobile phone base station is called uplink, the exposure from the transmission from a base station to a handset downlink.

Table 1. Frequency bands and corresponding frequency range (MHz) and reporting limit (V/m) of the ExpoM-RF measurement device.

Frequency band	description	frequency range [MHz]	reporting limit [V/m]
TV	Television broadcast transmitter	470 - 790	0.0025
LTE 800 Downlink	Transmission from mobile phone base station to handset	791 - 821	0.0025
LTE 800 Uplink	Transmission from mobile phone handset to base station	832 - 862	0.0025
Uplink 900	Transmission from mobile phone handset to base station	880 - 915	0.0025
Downlink 900	Transmission from mobile phone base station to handset	925 - 960	0.0025
Uplink 1800	Transmission from mobile phone handset to base station	1710 - 1785	0.0025
Downlink 1800	Transmission from mobile phone base station to handset	1805 - 1880	0.0025
DECT	Digital Enhanced Cordless Telecommunications	1880 - 1900	0.0025
Uplink 1900	Transmission from mobile phone handset to base station	1920 - 1980	0.0015
Downlink 2100	Transmission from mobile phone base station to handset	2110 - 2170	0.0015
LTE 2600	Transmission from mobile phone base station to handset and vice versa (combined downlink and uplink)	2500 - 2690	0.0125
WLAN	Wireless Local Area Network	2400 - 2485	0.0025
WiMax *	Worldwide Interoperability for Microwave Access	3400 - 3600	0.0015

* WiMax was excluded from the analysis since it is not used in Switzerland.

The measurement range ranges from the frequency specific reporting limits (Table 1) to 5 V/m. The devices have the size of 16 x 8 x 3 to 5 cm and a weight of 300 g.

Personal RF-EMF measurement devices are designed to measure under far-field conditions. RF-EMFs in the far-field are expressed in electric field strength (unit V/m) or power flux density (unit W/m²). Electric field strength and power flux density are linked via

$$S = \frac{E^2}{Z_0} \Leftrightarrow E = \sqrt{S * Z_0}$$

E represents the electric field strength and S the power flux density. Z_0 is the impedance of free space and equals approximately 376.7 Ω.

During the measurement period, the participants filled in a time-activity diary installed as an application on a smartphone operating in flight mode (no signal transmission) (Figure 5). The diary contained the a priori defined activities *home*, *school*, *outdoors*, *travelling* and *various locations*. *Travelling* was further subdivided into different transport modes (by foot or bike, train, bus, car). *Various locations* contained other locations such as shopping centres or restaurants.

Figure 4. Portable RF-EMF measurement device ExpoM-RF used in the personal measurement study.

Figure 5. Time-activity diary installed as an application on a smartphone operating in flight mode.

Mean and median of the measurements at the different locations and at different times (day and night, workdays and weekend) were calculated. Furthermore, the influence of WLAN in school and at home was investigated. Effects of different aspects of mobile phone use on the measurements were studied by comparing different user groups. Additionally, the measurements were combined with the exposure from the use of wireless communication devices (mobile phones, cordless phones, computers, laptops and tablets connected to WLAN) and thereof, the daily dose for a typical (average) HERMES participant was calculated.

3.5 Dosimetric approach

The dosimetric approach consists of converting the near-field and the far-field exposures to RF-EMF in a common unit and combining them to one exposure surrogate, the cumulative dose. The dose is the amount of radiation energy absorbed by a certain tissue per mass and is measured in J/kg. For the calculation of the dose, basically, three components are needed: the exposure duration, the SAR and the intensity of the incident field for environmental sources and the output power of the device for close-to-body sources. Hence, the dose can be calculated as follows:

$$dose = near\text{-}field\ dose + far\text{-}field\ dose$$

where

$$near\text{-}field\ dose = \sum_i near\text{-}field\ dose_i = \sum_i t_{use_i} * SAR_i^n * p_i$$

and

$$far\text{-}field\ dose = \sum_i far\text{-}field\ dose_i = \sum_i t_{exp_i} * SAR_i^f * S_i$$

- t_{use} is the exposure duration (in s) in terms of duration of device use
- $t_{exp}$is the exposure duration (in s) in terms of duration of being exposed to an environmental source
- SAR^n is the normalized (to an output power of the device of 1 W) specific absorption rate (in W/kg)
- SAR^f is the normalized (to an intensity of the incident field of 1 W/m²) specific absorption rate (in W/kg)
- p is the output power of a device (in W)
- S is the intensity of the incident field (in W/m²) emitted by an environmental source

In the HERMES study, we calculated the daily cumulative dose from environmental sources (far-field exposure; broadcast transmitters, mobile phone base stations, DECT and WLAN base stations and mobile phones in the surroundings and from wireless device use (near-field exposure; mobile phones, cordless phones, computers, laptops and tablets connected to WLAN).

3.6 Measures of health, behavioural problems and concentration capacity

Health related quality of life (HRQOL) and behavioural problems of the adolescents were measured by means of written questionnaires; the concentration capacity was measured using a computerized cognitive test.

Health related quality of life

HRQOL was measured using the KIDSCREEN-52 (Ravens-Sieberer et al. 2008; The KIDSCREEN Group Europe 2006). It measures HRQOL on ten dimensions named Physical well-being (5 items), Psychological well-being (6 items), Moods and emotions (7 items), Self-perception (5 items), Autonomy (5 items), Parent relations and home life (6 items), Social support and peers (6 items), School environment (6 items), Social acceptance (3 items) and Financial resources (3 items) answered on a 5-point Likert scale.

Behavioural problems

The German adaptations of the self-report and parent-rated standardized Strengths and Difficulties Questionnaire (SDQ) (Goodman 1997) measuring behavioural and affective problems of adolescents were used. They consist of five scales assessing Emotional symptoms, Conduct problems, Hyperactivity, Peer problems and Prosocial behaviour on five items each answered on a 3-point Likert scale, respectively.

Concentration capacity

We used a standardized, computerized cognitive test battery named FAKT-II (Frankfurter Adaptiver Konzentrationsleistungs-Test-II, (Moosbrugger and Goldhammer 2007)) to measure the concentration capacity of the adolescents. Concentration capacity measured by the FAKT-II included homogeneity, power and accuracy of concentration.

4 Problematic mobile phone use in adolescents

Article 1: Problematic mobile phone use in adolescents: derivation of a short scale MPPUS-10

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ORIGINAL ARTICLE

Problematic mobile phone use in adolescents: derivation of a short scale MPPUS-10

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Abstract
Objectives Our aim was to derive a short version of the Mobile Phone Problem Use Scale (MPPUS) using data from 412 adolescents of the Swiss HERMES (Health Effects Related to Mobile phonE use in adolescentS) cohort.
Methods A German version of the original MPPUS consisting of 27 items was shortened by principal component analysis (PCA) using baseline data collected in 2012. For confirmation, the PCA was carried out again with follow-up data 1 year later.
Results PCA revealed four factors related to symptoms of addiction (*Loss of Control, Withdrawal, Negative Life Consequences* and *Craving*) and a fifth factor reflecting the social component of mobile phone use (*Peer Dependence*). The shortened scale (MPPUS-10) highly reflects the original MPPUS (Kendalls' Tau: 0.80 with 90% concordant pairs). Internal consistency of MPPUS-10 was good with Cronbach's alpha: 0.85. The results were confirmed using the follow-up data.
Conclusions The MPPUS-10 is a suitable instrument for research in adolescents. It will help to further clarify the definition of problematic mobile phone use in adolescents and explore similarities and differences to other technological addictions.

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Keywords Mobile phone use · Problematic mobile phone use · MPPUS · Technological addictions · Adolescents

Introduction

Since the mid-90s and the public availability of the internet and mobile phones, the use of electronic media devices rapidly increased. According to the International Telecommunication Union (ITU), the amount of mobile phone subscriptions has grown from 2.2 billion in 2005 to 6.9 billion in 2014 (ITU 2014). Despite the facilitating effects of mobile phones like the ease of accessibility or useful applications, for example in health care (Boulos et al. 2011), concerns about adverse effects on social communication patterns and health due to new information technologies have arisen (Kowall et al. 2012; Schreier et al. 2006; Srivastava 2005). In 2014, 98 % of adolescents own a mobile phone in Switzerland (thereof 97 % a smartphone) (Willemse et al. 2014). Problematic mobile phone use (also known as mobile phone addiction, compulsive mobile phone use) has been documented for adolescents and young adults, whereby affected persons experience unpleasant symptoms of withdrawal when switching off their mobile phone or being out of range (Campbell 2005; Walsh et al. 2007). In addition, a variety of adverse health effects such as depression, social anxiety, insomnia, hyperactivity or conduct problems have been associated with different forms of technology overuse (Canan 2013; Cheung and Wong 2011; Jenaro et al. 2007; Morgan and Cotten 2003; Thomée et al. 2011). Behavioural addictions are like drug addictions characterized through maintaining abuse despite of its adverse consequences. While in drug addictions, short-term rewards, the so-called "highs", are gained from and necessarily need chemical substance intake; in behavioural addictions, similar effects, neurologically and emotionally, are reached through engaging in specific behaviours (Clark and Limbrick-Oldfield 2013). The primary diagnostic symptoms of substance abuse include withdrawal, loss of control, tolerance or craving and are featured by behavioural addictions as well. Those symptoms cause major negative life consequences in the affected person like impaired health or deprived social functioning (Park 2005).

One major problem in research on problematic mobile phone use is the inconsistency in its definition and assessment. Bianchi and Phillips have introduced a 27-item Mobile Phone Problem Use Scale (in the following referred to as MPPUS-27) which addresses different aspects of addiction (Bianchi and Phillips 2005). Particularly, the aspects of *Tolerance, Escape from other Problems, Withdrawal, Craving* and *Negative Life Consequences* are emphasized by the authors. The MPPUS-27 is frequently used in research on problematic mobile phone use (Izdebski and Kotyśko 2013; Lopez-Fernandez et al. 2011, 2014; Richardson 2012). The scale shows excellent internal consistency (Cronbach's $\alpha > 0.9$) and is validated in an adult sample through comparison with general mobile phone usage behaviour and the Addiction Potential Scale (APS) of the Minnesota Multiphasic Personality Inventory (MMPI-2). Despite of those strengths, it is long and tends to be somewhat redundant which may be a problem for research in adolescents. This may elevate the risk to upset the study participants and may lead to blindfold answers on similar items. Further, it has not yet been evaluated in adolescent research. For that reason, we aimed at developing a short MPPUS suitable for adolescents using data from the ongoing HERMES (Health Effects Related to Mobile phonE use in adolescentS) study.

Methods

Study population

The HERMES study aims to investigate effects of mobile phone use on health and behaviour of adolescents. The study population consists of 7th, 8th and 9th grade students (12–17 years) attending secondary schools in Central Switzerland. The baseline investigation took place from June 2012 until March 2013, and each school was visited 1 year later for a follow-up investigation with the same study participants. Participating adolescents were recruited through initial phone contact with the head of the school and a subsequent informational visit in the respective classes. Participation was voluntary and had to be preceded by informed consent of the adolescents and a parent. The investigation took place in school during school time and was led by two study managers. It consisted of filling in a paper and pencil questionnaire on various aspects such as mobile phone use, behavioural aspects, health-related quality of life, socio-economic factors and other covariates. Student's mobile phone use was assessed through questionnaire including questions about frequency and duration of calls, frequency of outgoing text messages (text messages sent by mobile phone network referred as SMS as well as other text messages sent by internet-based applications like *WhatsApp*), duration of data traffic on the mobile phone and about the usage of the mobile phone for other purposes. Objective mobile phone use traffic data were provided from the three mobile phone operators in Switzerland for the participants who gave informed consent together with their parents to collect these data. These operator data included the amount of outgoing and incoming calls and SMS, the duration of calls and the amount and the volume of data traffic sessions for up to 6 months prior to the investigation. Only participants reporting to own a mobile phone were included in analysis.

Ethical approval for the conduct of the study was received from the ethical committee of Lucerne, Switzerland on 9 May 2012 (EK 12025).

Mobile phone problem use scale (MPPUS)

The MPPUS-27 consists of 27 items covering the addictive symptoms *Tolerance, Escape from other Problems, Withdrawal, Craving* and *Negative Life Consequences* (Bianchi and Phillips 2005) (see Table 1). The 27 items have to be answered on a 10-point Likert scale ranging from 1 ("not true at all") to 10 ("extremely true") resulting in a final sum score with a theoretical maximum range of 27–270 points. The English version was translated into German by the study managers using a back translation procedure.

Statistical analysis

Principal component analysis

We applied principal component analysis (PCA) to derive a short version of the MPPUS for adolescents. The PCA was conducted with data from participants that had no missing in the MPPUS-27 (35 participants (8.5 %) with at least one missing value; $n = 377$). Prior to the analysis, we tested the data to be suitable assessing the Kaiser–Meyer–Olkin measure and Bartlett's test for sphericity. Furthermore, an item analysis of the MPPUS-27 items was executed including item-test correlations, item-rest correlations and average inter-item correlations. Additionally the mean and the standard deviation of each item were calculated to evaluate the discriminatory power of the items. Based on those results, the less conservative Kaiser-Criterion was chosen for factor

Table 1 The 27-item Mobile Phone Problem Use Scale (MPPUS-27)

For each item, please mark the box which fits best for you from 1 "Not true at all" to 10 "Extremely true"	
1	I can never spend enough time on my mobile phone
2	I have used my mobile phone to make myself feel better when I was feeling down
3	I find myself occupied on my mobile phone when I should be doing other things, and it causes problems
4	All my friends own a mobile phone
5	I have tried to hide from others how much time I spend on my mobile phone
6	I lose sleep due to the time I spend on my mobile phone
7	I have received mobile phone bills I could not afford to pay
8	When out of range for some time, I become preoccupied with the thought of missing a call
9	Sometimes, when I am on the mobile phone and I am doing other things, I get carried away with the conversation and I don't pay attention to what I am doing
10	The time I spend on the mobile phone has increased over the last 12 months
11	I have used my mobile phone to talk to others when I was feeling isolated
12	I have attempted to spend less time on my mobile phone but am unable to
13	I find it difficult to switch off my mobile phone
14	I feel anxious if I have not checked for messages or switched on my mobile phone for some time
15	I have frequent dreams about the mobile phone
16	My friends and family complain about my use of the mobile phone
17	If I do not have a mobile phone, my friends would find it hard to get in touch with me
18	My productivity has decreased as a direct result of the time I spend on the mobile phone
19	I have aches and pains that are associated with my mobile phone use
20	I find myself engaged on the mobile phone for longer periods of time than intended
21	There are times when I would rather use the mobile phone than deal with other more pressing issues
22	I am often late for appointments because I am engaged on the mobile phone when I should not be
23	I become irritable if I have to switch off my mobile phone for meetings, dinner engagements, or at the movies
24	I have been told that I spend too much time on my mobile phone
25	More than once I have been in trouble because my mobile phone has gone off during a meeting, lecture, or in a theatre
26	My friends do not like it when my mobile phone is switched off
27	I feel lost without my mobile phone

extraction which allows factors with eigenvalues above one to be included. Varimax rotation was used to maximize factor loadings. The number of items per factor included in the shortened questionnaire was decided based on the explained variance of each factor. A main criterion for choosing a specific item was its load on the corresponding factor. Further, we preferred items which tend to have stronger discriminatory power. And additionally, we wanted items with face validity for adolescents. Since this cannot be guaranteed by looking at the factor loadings and item analysis only, we did the final item selection manually. PCA was executed again with the follow-up data 1 year later.

Missing items

To do all further reliability analyses and comparisons with the full sample, missing items of the shortened MPPUS-scale (referred to as MPPUS-10) were imputed using a linear regression imputation taking into account the remaining items of the MPPUS-10. From the 35 participants with missing values in the MPPUS-27 only 13 participants had at least one to maximum four missing values in the MPPUS-10 items. The same computations were executed with the follow-up data one year later (10 participants with one missing item each in the follow-up MPPUS-10 score).

Reliability measures

To test the internal consistency of the questionnaire, Cronbach's alpha was assessed for the derived shortened MPPUS-10 as well as for the MPPUS-27. The retest reliability for the MPPUS-10 between the baseline and follow-up measures was calculated using Pearson's correlation for continual variables.

MPPUS-27 vs. MPPUS-10 relations

To investigate how well the sum score of the MPPUS-10 reflects the original score, the Pearson's correlation between the MPPUS-27 and the MPPUS-10 was calculated. Since this approach overestimates the correlation because the MPPUS-10 score is part of the MPPUS-27 score, we also calculated the correlation between the MPPUS-10 and the 17 remaining items of the MPPUS-27. This shows to what extent the 10 final items are reflected by the remaining 17 items only. In addition, to test the concordance of both scales Kendall's Tau was calculated. The proportion of persons assigned to the same rank amongst all participants according to both questionnaire scores was obtained by the following formula: Percentage of concordant pairs $= 0.5 \times (\tau + 1) \times 100$.

Subjective and objective mobile phone use data

Pearson's correlations were calculated for the MPPUS-10 versus subjectively (questionnaire data) and objectively recorded (operator data) quantitative mobile phone use data including frequency of calls per day, outgoing text messages/SMS per day and daily duration of internet use/data traffic volume.

Statistical analyses were carried out using STATA version 12.1 (StataCorp, College Station, TX, USA).

Results

In total, 439 adolescents participated in the baseline investigation of the HERMES study. Thereof, 27 (6.2 %) reported not to own a mobile phone and were therefore excluded from the data analysis. Thus, data from 412 (93.8 %) participants owning a mobile phone were included in the baseline data analysis. Of the mobile phone users, 319 (77.4 %) were smartphone users.

253 (61.4 %) of the 412 participants were female and 159 (38.6 %) male with a mean age of 14.0 years (min = 12.1 years, max = 17.0 years). A majority (67.6 %) were 8th grade students, and 317 participants (76.9 %) went to secondary school and 95 participants (23.1 %) attended a gymnasium. 79.6 % of the participants were Swiss.

The study participants reported to use their mobile phone on average for 1.3 calls (standard deviation: 1.5; maximum: 8.6) and for 44.9 min of data traffic (SD 41.4; 103.6) per day. 151 participants (36.7 %) reported to send up to 5 messages per day, 50 (12.1 %) 6–15 messages per day, 90 (21.8 %) 16–40 messages per day and 121 participants (29.4 %) reported to send more than 40 messages per day. According to objectively recorded operator data available from 234 (56.8 %) participants, they used their mobile phone for 0.8 calls (SD 1.7; maximum: 8.5), sending 2.8 short text messages (SMS) (SD 5.0; 40.2) per day, and the daily data traffic volume exchanged was 3.9 MB (SD 9.3; 50.5). Note that operator data include only messages sent by short message services (SMS) but not by internet-based applications, whereas self-reported messages refer to both type of messages.

Principal component analysis

PCA was performed using complete MPPUS-27 questionnaires of 377 (91.5 %) participants. Because test scores were left skewed data were z-standardized prior to analysis. In order to test the data to be suitable for PCA, we assessed the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy which was 0.909 (rejection if KMO <0.5). We tested the data for multicollinearity using Bartlett's test for sphericity which tests the null hypothesis if the correlation matrix is an identity matrix. With suitable data, this test should be significant, and we obtained $\chi = 4{,}317.3$, $df = 351$; $p < 0.001$. The PCA revealed five factors with eigenvalues above one (see Table 2). Factor interpretation was based on the clinical diagnostic symptoms of addiction and the theoretical considerations of the authors of the MPPUS-27 (Bianchi and Phillips 2005). The factors extracted were named *Loss of Control* (explanation of 15.9 % of total variance), *Withdrawal* (12.5 %), *Negative Life Consequences* (11.8 %), *Craving* (8.8 %) and *Peer Dependence* (7.1 %). After factor rotation, the five factors explained 56.1 % of the total variance. Although the eigenvalues of factor 4 (subsequently named *Craving*) and factor 5 (*Peer Dependence*) were close to one, we decided to keep them as single factors because our major consideration was to keep as much content as possible of the original MPPUS. Eigenvalues, the proportion of explained variance as well as the cumulative proportion of explained variance of the factors, are displayed in Table 2.

Item selection

The higher the variance explained by a factor, the more items were included in the MPPUS-10. Three items loading on the factors *Loss of Control* and *Withdrawal* and two from the factor *Negative Life Consequences* were chosen, respectively. One single item was chosen loading on the factors *Craving* and *Peer Dependence* since the variance explained by these factors and their eigenvalues were considerably lower compared to the others (see Table 3).

We preferred items with a mean value close to the average of the item scores with additionally high standard deviations since they tend to have stronger discriminatory power (see Table 4).

After all we wanted items to be suitable for adolescents thus to be short, easy to understand, unambiguous and nonredundant in their content. Thus, despite high factor load item 11, item 15, item 23 and item 26 were not considered

Table 2 Eigenvalues, proportion of explained variance (%) and the cumulative proportion of explained variance (%) after factor rotation of the factors

Factor	Eigenvalue	Proportion of explained variance (%)	Cumulative proportion of explained variance (%)
Factor 1 (subsequently named *Loss of Control*)	8.91	15.90	15.90
Factor 2 (*Withdrawal*)	2.38	12.47	28.37
Factor 3 (*Negative Life Consequences*)	1.63	11.81	40.18
Factor 4 (*Craving*)	1.15	8.83	49.01
Factor 5 (*Peer Dependence*)	1.07	7.07	56.08

Subsequently chosen names in italic brackets. Factors with eigenvalues below one are omitted

Table 3 Factor loadings of the 27 items of the original Mobile Phone Problem Use Scale (MPPUS-27) on each factor after factor rotation

Factor	Loss of Control	Withdrawal	Negative Life Consequences	Craving	Peer Dependence
Item					
Item 1	0.10	0.18	−0.08	0.24	0.03
Item 2	*0.01*	*−0.02*	*0.03*	***0.49***	*0.05*
Item 3	0.26	0.05	−0.01	0.07	0.10
Item 4	0.01	0.24	−0.29	−0.27	0.28
Item 5	0.00	0.01	0.19	0.28	−0.04
Item 6	0.16	0.09	0.02	0.21	−0.09
Item 7	*0.09*	*−0.04*	***0.33***	*−0.07*	*0.12*
Item 8	*−0.02*	***0.45***	*0.00*	*0.06*	*−0.13*
Item 9	0.10	0.33	0.01	−0.08	−0.03
Item 10	0.26	0.07	−0.14	0.00	0.13
Item 11	−0.09	0.01	−0.04	0.52	0.14
Item 12	0.26	0.07	0.08	0.07	−0.07
Item 13	*0.07*	***0.35***	*−0.02*	*0.00*	*0.02*
Item 14	*0.05*	***0.32***	*−0.07*	*0.18*	*−0.02*
Item 15	−0.16	0.10	0.43	0.00	0.02
Item 16	***0.48***	*−0.12*	*0.02*	*−0.03*	*−0.07*
Item 17	*0.06*	*−0.03*	*0.03*	*0.01*	***0.57***
Item 18	0.13	−0.10	0.27	0.07	0.12
Item 19	0.04	0.05	0.38	−0.01	−0.16
Item 20	***0.38***	*0.06*	*−0.01*	*−0.03*	*−0.02*
Item 21	0.27	0.07	−0.01	−0.01	0.10
Item 22	*−0.01*	*−0.02*	***0.46***	*0.03*	*0.01*
Item 23	−0.08	0.40	0.18	−0.11	−0.02
Item 24	***0.47***	*−0.12*	*0.06*	*−0.03*	*−0.09*
Item 25	0.01	0.18	0.26	−0.34	0.20
Item 26	−0.03	−0.11	0.07	0.05	0.60
Item 27	−0.05	0.28	−0.01	0.17	0.18

Item numbers relate to the MPPUS-27 questionnaire displayed in Table 1. The chosen items for the short version Mobile Phone Problem Use Scale-10 (MPPUS-10) are marked in italics. The factor loadings of the chosen items for the particular factor are marked in bold

for the factors *Craving, Negative Life Consequences, Withdrawal* and *Peer Dependence*, respectively. The final short version MPPUS-10 with the chosen items is displayed in Table 5.

The PCA was executed again with the follow-up data including data from 378 adolescents owning a mobile phone and filled in all MPPUS-27 items at follow-up to replicate the extracted five factor structure found through the PCA with the baseline data. The analysis with the follow-up data (Table 6) did not noticeably differ from the baseline analysis (Table 3).

Reliability of the MPPUS-10

The mean of the MPPUS-27 was $m = 80.5$ (SD 34.5; min $= 32$, max $= 239$) with a theoretical achievable

Table 4 Number of observations (*N*), results of item analysis (item-test, item-rest and average inter-item correlation coefficients), means and standard deviations (SD) for each item of the Mobile Phone Problem Use Scale prior to shortening (MPPUS-27)

	N	Item-test correlation[a]	Item-rest correlation[b]	Average inter-item correlation[c]	Mean[d]	SD[e]
Item 1	410	0.66	0.63	0.29	3.46	2.53
Item 2	*410*	*0.65*	*0.60*	*0.29*	*3.84*	*2.88*
Item 3	409	0.67	0.63	0.29	3.71	2.68
Item 4	409	0.12	0.06	0.32	8.68	2.20
Item 5	409	0.55	0.50	0.30	1.95	1.97
Item 6	410	0.64	0.60	0.29	2.47	2.23
Item 7	*411*	*0.53*	*0.48*	*0.30*	*1.37*	*1.40*
Item 8	*410*	*0.64*	*0.60*	*0.29*	*2.20*	*2.07*
Item 9	410	0.58	0.53	0.29	2.69	2.21
Item 10	409	0.52	0.47	0.30	4.90	3.23
Item 11	412	0.53	0.48	0.30	3.95	3.03
Item 12	412	0.67	0.63	0.29	2.38	2.16
Item 13	*411*	*0.67*	*0.63*	*0.29*	*2.56*	*2.58*
Item 14	*412*	*0.69*	*0.65*	*0.29*	*2.74*	*2.47*
Item 15	412	0.41	0.36	0.30	1.25	1.10
Item 16	*412*	*0.62*	*0.57*	*0.29*	*2.98*	*2.62*
Item 17	*407*	*0.54*	*0.49*	*0.30*	*4.94*	*3.13*
Item 18	411	0.59	0.54	0.29	2.09	1.65
Item 19	409	0.47	0.42	0.30	1.43	1.30
Item 20	*409*	*0.70*	*0.66*	*0.29*	*3.30*	*2.53*
Item 21	405	0.63	0.58	0.29	4.14	2.84
Item 22	*410*	*0.56*	*0.52*	*0.30*	*1.45*	*1.14*
Item 23	409	0.59	0.54	0.29	1.62	1.42
Item 24	*410*	*0.64*	*0.59*	*0.29*	*2.86*	*2.68*
Item 25	408	0.38	0.32	0.30	1.90	1.93
Item 26	401	0.40	0.34	0.30	3.02	2.60
Item 27	407	0.69	0.65	0.29	2.95	2.63
Mean	409	0.57	0.52	0.30	2.98	2.26

Item numbers relate to the MPPUS-27 displayed in Table 1. Chosen items are in italics

[a] Item-test correlation: correlation between the item score *i* and the total test score

[b] Item-rest correlation: correlation between the item score *i* and the sum of the other item scores excluding item score *i*

[c] Average inter-item correlation: average of the correlation between the item score *i* and the other item scores

[d] Mean: mean of the item score *i*

[e] SD: standard deviation of the item score *i*

maximum range of 27–270. The MPPUS-10 had a mean of $m = 28.2$ (SD 15.6; min = 10, max = 96) with a theoretic maximum range of 10–100. Cronbach's alpha measuring the internal consistence was good with alpha = 0.85 for the MPPUS-10 (Nunnally et al. 1967). In our adolescent sample for the MPPUS-27, alpha was 0.92 which is similar to the internal consistency assessed by Bianchi et al. in an adult sample (0.93). The retest reliability of the MPPUS-10 after 1 year assessed through Pearson's correlation between baseline and follow-up data was relatively low ($r = 0.40$, $p < 0.001$).

MPPUS-27 vs. MPPUS-10 relations

The Pearson's correlation between the MPPUS-10 and the MPPUS-27 was $r = 0.95$, $p < 0.001$ (Fig. 1), and the Pearson's correlation between the MPPUS-10 and the remaining 17 items of the MPPUS-27 was $r = 0.86$, $p < 0.001$. Assuming that the first measure overestimates the correlation and the second should rather underestimate it, the true correlation is still quite high. Kendall's Tau for the MPPUS-10 vs. MPPUS-27 was 0.80, $p < 0.001$ with a corresponding proportion of concordant ranks among the participants of 90 %.

MPPUS-10 vs. quantitative mobile phone use

The Pearson's correlation between the MPPUS-10 and the self-reported frequency of phone calls was $r = 0.31$ ($p < 0.001$). The correlation of the MPPUS-10 with self-reported number of outgoing messages was $r = 0.53$ ($p < 0.001$), and for self-reported duration of mobile internet use, we found $r = 0.41$ ($p < 0.001$). For objectively recorded operator data, the Pearson's correlation with the MPPUS-10 score was $r = 0.30$ ($p < 0.001$) for phone calls, $r = 0.34$ ($p < 0.001$) for frequency of SMS and $r = 0.42$ ($p < 0.001$) for the data traffic volume.

Table 5 The Mobile Phone Problem Use Scale-10 (MPPUS-10) items with the original item number of the original scale, the number of observations (*N*), factor loadings after rotation, means and standard deviations (SD)

Item	Original item	*N*	Factor loading	Mean	SD
For each item, please mark the box which fits best for you from 1 "Not true at all" to 10 "Extremely true"					
I have used my mobile phone to make myself feel better when I was feeling down. (*Craving*)	2	410	0.49	3.84	2.89
When out of range for some time, I become preoccupied with the thought of missing a call. (*Withdrawal*)	8	410	0.45	2.20	2.07
If I don't have a mobile phone, my friends would find it hard to get in touch with me. (*Peer Dependence*)	17	407	0.57	4.94	3.13
I feel anxious if I have not checked for messages or switched on my mobile phone for some time. (*Withdrawal*)	14	412	0.32	2.74	2.47
My friends and family complain about my use of the mobile phone. (*Loss of Control*)	16	412	0.48	2.98	2.62
I find myself engaged on the mobile phone for longer periods of time than intended. (*Loss of Control*)	20	409	0.38	3.30	2.53
I am often late for appointments because I'm engaged on the mobile phone when I shouldn't be. (*Negative Life Consequences*)	22	410	0.46	1.45	1.14
I find it difficult to switch off my mobile phone. (*Withdrawal*)	13	411	0.36	2.56	2.58
I have been told that I spend too much time on my mobile phone. (*Loss of Control*)	24	410	0.47	2.86	2.68
I have received mobile phone bills I could not afford to pay. (*Negative Life Consequences*)	7	411	0.33	1.37	1.40

Respective factor classification can be found in italic brackets after each item

Discussion

The derived short scale using 10 items to measure problematic mobile phone use among adolescents showed a good internal consistency and was highly correlated with the original 27-item scale. A large majority of 90 % of participants had the same rank measured by both scores.

Assessment of problematic mobile phone use

The assessment and definition of problematic mobile phone use differs in studies on this topic resulting in inconsistency in prevalence rates and cut-off scores. In an Italian study using the Mobile Addiction Test (MAT), 6.3 % of adolescents were classified as dependent from their mobile phones (Martinotti et al. 2011). In another study on British adolescents using the MPPUS, the 90th percentile was chosen to classify at-risk use according to a statistical classification they prompted to have found in pathological gambling assessment (Lopez-Fernandez et al. 2014). High prevalence rates of about 30 % were reported in studies assessing addictive behaviour through a single questionnaire item ("perceived dependence") (Billieux et al. 2007) or through choosing the 70th percentile as arbitrary questionnaire cut-off value (Ha et al. 2008). In our study, we did not find an obvious threshold for differentiating between problematic and non-problematic mobile phone uses, which supports the idea that problematic mobile phone use is a continuum, and the higher the score on the MPPUS-10, the more likely mobile phone use is problematic in adolescent. A linear association without a threshold for detrimental effects is also supported by our analysis on behavioural and personal factors as well as health symptoms in relation to problematic mobile phone use as measured by the MPPUS-10 (Roser et al., submitted).

Problematic mobile phone use in the context of behavioural addictions

The PCA of the MPPUS revealed five factors. In line with the theoretical construction of the MPPUS, four of them were strongly related to addiction theory and thus were named *Loss of Control, Withdrawal, Negative Life Consequences* and *Craving*. The factors show considerable overlap with the symptoms that have been proposed from the authors of the original MPPUS-27 (including also *Withdrawal, Negative Life Consequences* and *Craving*). *Loss of control*, which was described as *Tolerance* by Bianchi and Phillips (Bianchi and Phillips 2005), deals with the growing time spent with the mobile phone even if not intended. The importance of this factor is also displayed in the correlation between the MPPUS score and quantitative mobile phone use. *Withdrawal* refers to the mental occupation with the device, i.e. anxious or stressful feelings if being out of range. *Negative Life Consequences* due to a mobile phone might either directly result from the first and second factor or may be due to financial, occupational or school issues. *Craving* gets obvious if one needs his mobile phone to relieve himself from negative feelings.

Table 6 Replication of the principal component analysis with the follow-up data: factor loadings of the 27 items of the original Mobile Phone Problem Use Scale (MPPUS-27) on each factor after factor rotation

Factor	Loss of Control	Withdrawal	Negative Life Consequences	Craving	Peer Dependence
Item					
Item 1	0.14	0.23	−0.08	0.12	−0.06
Item 2	*0.06*	*0.04*	*−0.02*	***0.51***	*−0.02*
Item 3	0.30	0.06	−0.03	0.07	−0.01
Item 4	0.17	0.07	−0.37	−0.12	0.03
Item 5	−0.01	−0.09	0.31	0.33	−0.06
Item 6	0.16	0.10	0.16	0.00	−0.06
Item 7	*0.00*	*−0.01*	***0.32***	*0.03*	*0.08*
Item 8	*−0.07*	***0.42***	*0.03*	*−0.03*	*0.10*
Item 9	−0.02	0.20	0.13	0.19	−0.06
Item 10	0.18	0.13	−0.10	0.09	−0.21
Item 11	0.05	−0.05	−0.03	0.56	0.08
Item 12	0.22	0.14	0.04	0.04	−0.20
Item 13	*0.13*	***0.36***	*−0.02*	*−0.14*	*−0.04*
Item 14	*0.00*	***0.47***	*−0.12*	*−0.02*	*−0.05*
Item 15	−0.09	0.06	0.40	0.00	0.03
Item 16	***0.48***	*−0.13*	*0.06*	*−0.21*	*0.03*
Item 17	*0.14*	*−0.03*	*−0.12*	*0.14*	***0.53***
Item 18	0.21	0.02	0.23	−0.01	−0.11
Item 19	0.06	0.02	0.39	−0.08	−0.04
Item 20	0.31	−0.01	−0.03	0.19	−0.01
Item 21	0.34	−0.03	−0.04	0.06	0.08
Item 22	*0.09*	*−0.05*	***0.37***	*−0.05*	*0.04*
Item 23	−0.07	0.37	0.19	−0.11	−0.02
Item 24	***0.43***	*−0.06*	*0.05*	*−0.11*	*0.04*
Item 25	0.07	0.05	0.16	−0.24	0.41
Item 26	−0.03	0.10	0.02	0.06	0.63
Item 27	−0.05	0.36	−0.01	0.14	0.09

Item numbers relate to the MPPUS-27 questionnaire displayed in Table 1. The chosen items for the short version Mobile Phone Problem Use Scale-10 (MPPUS-10) are marked in italics. The factor loadings of the chosen items for the particular factor are marked in bold

As a fifth factor, *Peer Dependence* was identified. This factor was not described by the authors of the original MPPUS-27. Although peer dependence is not a primary symptom of addictive behaviour, it might be important in the development of problematic mobile phone use in adolescents since the mobile phone is mostly used for social communication purposes, and peer influence is particularly prevalent in adolescent years (Steinberg and Monahan 2007; Steinberg and Silverberg 1986).

Although these symptoms suit the concept of behavioural addictions, it is important to critically reflect, if problematic mobile phone use may be considered a nosological entity. Whereas few years ago mobile phones were solely used for calling and somewhat later for texting, nowadays with the rapid spreading of smartphones, the boundaries between problematic mobile phone use and other technological addictions get blurred due to the various purposes a smartphone may be used for. Problematic mobile phone use may thus involve a combination of various known reinforcing mechanisms of technological addictions such as Online Gaming Disorder (OGD) and Internet-Addiction (IA).

In online gaming, reinforcement is gained through in-game rewards and the ease to escape daily life (Hilgard et al. 2013), and similarly, a prominent motive for excessive internet use is diversion (Song et al. 2004). Both gaming and surfing the web are possible with smartphone use, and in our study a higher MPPUS-10 score is correlated with more time spend online and a higher amount of data traffic via mobile phone. Using various applications as well as the perceived satisfaction involved was found to predict compulsive smartphone use (Park and Lee 2011; Salehan and Negahban 2013) and leisure boredom as well as sensation seeking were found as motives in adolescents with higher addictive mobile phone use tendencies (Leung 2008). Distraction through technology may be a mechanism which is common for compulsive gaming, surfing or smartphone use.

A different and more distinct motive for problematic mobile phone use might be the need for social

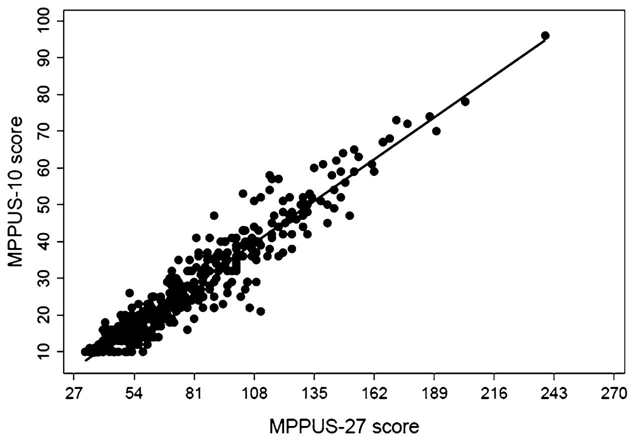

Fig. 1 Correlation of the original 27-item Mobile Phone Problem Use Scale (MPPUS-27) score and the shortened 10-item Mobile Phone Problem Use Scale (MPPUS-10) score. Pearson's correlation was r 0.95, $p < 0.001$. Each *dot* displays a single participants MPPUS-27 score on the x axis (range from 27 to 270) and the corresponding MPPUS-10 score on the y axis (range from 10 to 100 units)

communication, which in our results is underlined by the high quantity of outgoing text messages per day and the highest correlations of the MPPUS-10 with this kind of self-reported mobile phone use (0.53 vs. ≤0.41 for calling and data exchange). Peer influence, social relationships and the need for belongingness are important factors in adolescents life and to interconnect via mobile phones helps adolescents to satisfy their needs (Gardner and Steinberg 2005; Walsh et al. 2009). The urge to be accessible all the time and feelings of fear and loneliness, if they are out of range have been reported by adolescent heavy users being asked about their mobile phones (Campbell 2005). Studies focussing on personality and emotional impact factors on problematic mobile phone use (messaging and phone calls) emphasize high feelings of loneliness, low self-esteem as well as extraversion being prevalent in high users (Augner and Hacker 2012; Butt and Phillips 2008; Reid and Reid 2007; Roser et al., submitted).

Thus, we suggest two different patterns of problematic mobile phone use. One relates to media entertainment which a few years before required being at home. Nowadays, smartphones enable a person to surf the internet and playing online games everywhere, and the use of various applications provides even more possibilities of distraction. This form of problematic mobile phone use may be rather seen as media addiction with the portable smartphone providing the highest accessibility to entertainment. The other form of problematic mobile phone use emphasizes the need for social interconnectivity and relates to the mobile phone used as a communication device. Since the underlying motives and personality factors leading to both forms of problematic mobile phone use differ, it is thinkable that they also lead to distinct health effects.

Strengths and limitations

A particular strength of the HERMES study is the objective data on quantitative mobile phone use provided by the Swiss network operators that minimizes recall bias and allows a more robust evaluation between MPPUS-10 and actual mobile phone use. As a limitation, we did not have data from a second-independent sample, and we did not perform a confirmatory factor analysis with the MPPUS-10. However, at least we conducted the PCA again with the follow-up data to replicate its factorial structure. Of note, the relatively low retest coefficient ($r = 0.40$) may indicate that problematic mobile phone use is not a stable attribute in adolescence, at least during the years of uptake of mobile phone use. The test–retest period of 1 year is long considering the developmental changes which study participants might have undergone in this timespan. Furthermore, a part of the mobile phone users (17.7 %) in our sample switched to using smartphones during this period, which is likely to have a major impact on the usage pattern.

Another limitation is that the MPPUS-10 score was calculated after PCA by summing up the 10 corresponding items of the MPPUS-27. That means, in our study, the MPPUS-10 was an artificial questionnaire that was not filled in by the participants. This procedure might have led to overestimations in correlations between the MPPUS-10 and MPPUS-27. To deal with this shortcoming, the MPPUS-10 is currently distributed in a second sample of adolescents.

Conclusion

The MPPUS-10 showed considerable overlap with the original MPPUS-27. Thus, we suggest using the shorter MPPUS-10 in future research. It is clearly more convenient since it consists only of 10 items which saves time and is likely to reduce the number of missing items. Our item selection criteria focussed particularly on creating a questionnaire suitable for research in adolescents, which is important considering the high amount of mobile phone use stated for this age group in different studies using different methods for assessment (Ha et al. 2008; Lopez-Fernandez et al. 2014; Martinotti et al. 2011).

Future research in adolescents should focus on disentangling two different patterns of problematic mobile phone use. On the one hand, a smartphone may be excessively used for personal entertainment, which may be similar to other technological addictions (e.g. internet use).

On the other hand, a strong need for social interconnectivity may result in problematic mobile phone use as well.

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References

Augner C, Hacker GW (2012) Associations between problematic mobile phone use and psychological parameters in young adults. Int J Public Health 57:437–441

Bianchi A, Phillips JG (2005) Psychological predictors of problem mobile phone use. CyberPsychol Behav 8:39–51

Billieux J, Van der Linden M, d'Acremont M, Ceschi G, Zermatten A (2007) Does impulsivity relate to perceived dependence on and actual use of the mobile phone? Appl Cogn Psychol 21:527–537

Boulos MN, Wheeler S, Tavares C, Jones R (2011) How smartphones are changing the face of mobile and participatory healthcare: an overview, with example from eCAALYX. Biomed Eng Online 10:24

Butt S, Phillips JG (2008) Personality and self reported mobile phone use. Comput Hum Behav 24:346–360

Campbell MA (2005) The impact of the mobile phone on young people's social life. Paper presented at the Social Change in the 21st Century Conference, Brisbane

Canan F (2013) The relationship of affective temperament and emotional-behavioral difficulties to internet addiction in turkish teenagers. ISRN psychiatry. doi:10.1155/2013/961734

Cheung LM, Wong WS (2011) The effects of insomnia and internet addiction on depression in Hong Kong Chinese adolescents: an exploratory cross-sectional analysis. J Sleep Res 20:311–317

Clark L, Limbrick-Oldfield EH (2013) Disordered gambling: a behavioral addiction. Curr Opin Neurobiol 23:655–659. doi:10.1016/j.conb.2013.01.004

Gardner M, Steinberg L (2005) Peer influence on risk taking, risk preference, and risky decision making in adolescence and adulthood: an experimental study. Dev Psychol 41:625–635

Ha JH, Chin B, Park D-H, Ryu S-H, Yu J (2008) Characteristics of excessive cellular phone use in Korean adolescents. CyberPsychol Behav 11:783–784

Hilgard J, Engelhardt CR, Bartholow BD (2013) Individual differences in motives, preferences, and pathology in video games: the gaming attitudes, motives, and experiences scales (GAMES). Frontiers in psychology 4. doi:10.3389/fpsyg.2013.00608

ITU (2014) The World in 2014: ICT Facts and Figures. International Telecommunication Union, Geneva

Izdebski P, Kotyśko M (2013) Personality variables and depression as determinants of problematic use of mobile phones in Poland. Polish J Appl Psychol 11:111–126

Jenaro C, Flores N, Gómez-Vela M, González-Gil F, Caballo C (2007) Problematic internet and cell-phone use: Psychological, behavioral, and health correlates. Addict Res Theory 15:309–320

Kowall B, Breckenkamp J, Blettner M, Schlehofer B, Schüz J, Berg-Beckhoff G (2012) Determinants and stability over time of perception of health risks related to mobile phone base stations. Int J Public Health 57:735–743

Leung L (2008) Linking psychological attributes to addiction and improper use of the mobile phone among adolescents in Hong Kong. J Child Media 2:93–113

Lopez-Fernandez O, Honrubia-Serrano M, Freixa-Blanxart M (2011) Spanish adaptation of the "Mobile Phone Problem Use Scale" for adolescent population. Adicciones 24:123–130

Lopez-Fernandez O, Honrubia-Serrano L, Freixa-Blanxart M, Gibson W (2014) Prevalence of Problematic Mobile Phone Use in British Adolescents. Cyberpsychol Behav Social Netw 17:91–98

Martinotti G et al (2011) Problematic mobile phone use in adolescence: a cross-sectional study. J Public Health 19:545–551

Morgan C, Cotten SR (2003) The relationship between internet activities and depressive symptoms in a sample of college freshmen. CyberPsychol Behav 6:133–142

Nunnally JC, Bernstein IH, Berge JMt (1967) Psychometric theory vol 226. McGraw-Hill, New York

Park WK (2005) Mobile phone addiction. In: Mobile Communications. Springer, pp 253-272

Park B-W, Lee KC (2011) The effect of users' characteristics and experiential factors on the compulsive usage of the smartphone. In: Ubiquitous computing and multimedia applications. Springer, Heidelberg, pp 438–446

Reid DJ, Reid FJ (2007) Text or talk? Social anxiety, loneliness, and divergent preferences for cell phone use. CyberPsychol Behav 10:424–435

Richardson MH (2012) Increased levels of anxiety revealing characteristics of social phobia elucidated by smartphone use. University of Central Florida Orlando, Florida

Roser K, Schoeni A, Foerster M, Röösli M, Problematic mobile phone use: associations with personal factors, health and behaviour in Swiss adolescents (submitted)

Salehan M, Negahban A (2013) Social networking on smartphones: When mobile phones become addictive. Comput Hum Behav 29:2632–2639

Schreier N, Huss A, Röösli M (2006) The prevalence of symptoms attributed to electromagnetic field exposure: a cross-sectional representative survey in Switzerland. Sozial-und Präventivmedizin 51:202–209

Song I, Larose R, Eastin MS, Lin CA (2004) Internet gratifications and Internet addiction: on the uses and abuses of new media. CyberPsychol Behav 7:384–394

Srivastava L (2005) Mobile phones and the evolution of social behaviour. Behavi Inf Technol 24:111–129

Steinberg L, Monahan KC (2007) Age differences in resistance to peer influence. Dev Psychol 43:1531

Steinberg L, Silverberg SB (1986) The vicissitudes of autonomy in early adolescence. Child Dev 57:841–851

Thomée S, Härenstam A, Hagberg M (2011) Mobile phone use and stress, sleep disturbances, and symptoms of depression among young adults-a prospective cohort study. BMC Public Health 11:66

Walsh SP, White KM, Young RM (2007) Young and connected: Psychological influences of mobile phone use amongst Australian youth. In: Goggin G, Hjorth L (eds) Proceedings Mobile Media 2007. University of Sydney, Sydney, pp 125–134

Walsh SP, White KM, Young RM (2009) The phone connection: A qualitative exploration of how belongingness and social identification relate to mobile phone use amongst Australian youth. J Commun Appl Social Psychol 19:225–240

Willemse I, Suess D, Waller G (2014) JAMES-Studie. Jugend, Aktivität, Medien—Erhebung Schweiz. Factsheet Befunde 2014. Zürcher Hochschule für angewandte Wissenschaft, Zürich

Article 2: Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour?

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ORIGINAL ARTICLE

Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour?

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Abstract
Objectives To investigate the associations between problematic mobile phone use and mental health and behavioural problems in 412 Swiss adolescents owning a mobile phone while controlling for amount of mobile phone use.
Methods Problematic mobile phone use was determined by the MPPUS-10 (Mobile Phone Problem Use Scale) and related to health and behavioural problems by means of multivariable regression modelling.
Results MPPUS-10 was 4.7 (95 % CI 1.8, 7.6) units higher in girls than in boys, increased significantly with age and was significantly decreased with increasing educational level of the parents. Furthermore, problematic mobile phone use was associated with impaired psychological well-being, impaired parent and school relationships and more behavioural problems but was not related to peer support and social acceptance.
Conclusions Our study indicates that problematic mobile phone use is associated with external factors such as worse home and school environment and internal factors such as impaired mental health and behavioural problems of the adolescents and thus problematic mobile phone use should be addressed, in particular when dealing with adolescents showing behavioural or emotional problems.

Keywords Mobile phone use · Problematic mobile phone use · MPPUS · Health · Behaviour · Adolescents · Addiction

Introduction

Nowadays mobile phones are omnipresent in everyday life and adolescents are among the heaviest mobile phone users. A recent representative survey in more than 1000 adolescents aged 12–19 years in Switzerland revealed that 98 % of the adolescents own a mobile phone and 97 % of these devices are smartphones (Willemse et al. 2014). Smartphones are multifunctional devices often used by adolescents for gaming, browsing the internet and exchanging text messages. For instance, 94 % of the Swiss adolescents surveyed used their mobile phone daily or several times per week for exchanging text messages via internet-based applications, 87 % for browsing the internet, 53 % for gaming and 61 % for checking their e-mails (Willemse et al. 2014). This frequent use may have a negative impact on daily life and thus may be problematic. However, to date it is not clear what aspects of mobile phone use, if any, are problematic and what this means for mental health and behaviour of adolescents.

On the basis of the lack of a theoretical framework for problematic mobile phone use, Billieux (2012) proposed an integrative model describing four pathways leading to problematic mobile phone use (Billieux 2012), an impulsive pathway, a relationship maintenance pathway, an extraversion pathway and a cyber-addiction pathway. The first three pathways describe a link of problematic mobile

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phone use and personality traits found in previous studies (Augner and Hacker 2012; Bianchi and Phillips 2005; Takao et al. 2009). The cyber-addiction pathway is related to and inspired by research about problematic internet use, since nowadays most adolescents own a smartphone and, therefore, have internet access on their mobile phone. Along that line, Bianchi and Phillips (2005) have introduced a 27-item Mobile Phone Problem Use Scale (MPPUS) to measure problematic use. The scale addresses different aspects of addiction such as tolerance, escape from other problems, withdrawal, craving and negative life consequences.

Strikingly, little research has quantified the impact of problematic mobile phone use on mental health and behaviour of adolescents. A cross-sectional survey in 196 young adults living in Austria observed increased chronic stress, increased extraversion, increased depression and decreased emotional stability to be related to problematic mobile phone use (Augner and Hacker 2012). In this study, problematic mobile phone use was more common among women than men. In an Australian survey of 195 adults, prevalence of problematic mobile phone use was not different between men and women, but also related to increased extraversion and low self-esteem (Bianchi and Phillips 2005). In a cross-sectional study including more than 10,000 Taiwanese adolescents, depressive symptoms were related to problematic mobile phone use (Yen et al. 2009). Additionally, adolescents showing symptoms of problematic use showed impairment in daily life such as poor relationship with friends and family, problems in financial affairs or poor academic performance. Another study in the same adolescents observed that those adolescents with problematic use were more likely to be aggressive, be victims of aggression and to have low self-esteem (Yang et al. 2010). Furthermore, they found higher prevalence of problematic mobile phone use in girls and in older adolescents. A South Korean study dividing mostly male adolescents in an excessive user group and a comparison group found more depressive symptoms, more difficulty in expression of emotions, higher anxiety and lower self-esteem in the excessive mobile phone users (Ha et al. 2008).

To better understand the consequences of problematic mobile phone use for the life of adolescents, potential associations with physical well-being and behaviour need to be evaluated. However, this was not done so far, although impaired well-being (Byun et al. 2013a; Redmayne et al. 2013) and attention deficit hyperactivity disorder (ADHD) symptoms (Byun et al. 2013b) were linked to amount of mobile phone use in children and adolescents. Thus, it remains unclear, if these adverse effects in adolescents may be attributed to problematic use of the mobile phone or amount of mobile phone use.

In this explorative study, we aim at obtaining a better understanding on how problematic mobile phone use is related to health-related quality of life (HRQOL) including mental health and behavioural problems in adolescents while controlling for amount of mobile phone use. These findings are relevant to assess the impact of problematic mobile phone use for adolescents and to contribute to a better understanding of behavioural and emotional problems in adolescents.

Methods

Study population

The Health Effects Related to Mobile PhonE use in adolescentS study (HERMES) population consists of 7th, 8th and 9th grade students attending secondary schools in Central Switzerland. The baseline investigation took place from June 2012 until March 2013. Participating adolescents were recruited through initial phone contact with the head of the school and a subsequent informational visit in the respective class. Participation was voluntary and had to be preceded by informed consent of the adolescents and a parent. The investigation took place in school during school time and was led by two study managers. It consisted of filling in a paper and pencil questionnaire. An additional paper and pencil questionnaire for the parents was distributed, filled in at home and sent back to the study managers.

Questionnaire

The adolescents' questionnaire included questions about mobile phone use, age, sex, nationality, school level, the German adaptation of the self-report version of the standardized Strengths and Difficulties Questionnaire (SDQ) (Goodman 1997) (referred to as *Adolescents SDQ*) measuring behavioural and affective problems of adolescents and the KIDSCREEN-52 (Ravens-Sieberer et al. 2008; The KIDSCREEN Group Europe 2006) measuring HRQOL. The parents' questionnaire included a question about the educational level of the parents and the German adaptation of the informant-rated version of the SDQ (referred to as *Parents SDQ*) measuring adolescents' behavioural and affective problems.

Problematic mobile phone use measured by the MPPUS-10

We used a shortened 10-item version (MPPUS-10 (Foerster et al. 2015); Table S1 in Electronic Supplementary Material) of the MPPUS, which addresses different issues of problematic mobile phone use by means of a 27-item questionnaire (Bianchi and Phillips 2005). The five factors covered by the MPPUS-10 are loss of control, withdrawal, negative life consequences, craving and peer dependence. The first four factors are strongly related to addiction theory, the fifth factor *peer dependence* was considered important especially in adolescents (Foerster et al. 2015). The items have to be answered on a 10-point Likert scale ranging from 1 ("not true at all") to 10 ("extremely true"). Internal consistency of the MPPUS-10 measured by Cronbach's alpha was 0.84 in our study sample.

Amount of mobile phone use

To capture various aspects of mobile phone use, we collected different usage measures which were either self-reported or recorded by the mobile phone operators. Adolescents' self-reported mobile phone use included frequency of outgoing and incoming calls, frequency of outgoing text messages [text messages sent by mobile phone network (SMS) as well as text messages sent by internet-based applications] and duration of data traffic on the mobile phone. Objective mobile phone use data were provided from the three mobile phone operators in Switzerland for the participants who gave informed consent together with their parents to collect these data. These operator data included frequency of outgoing and incoming calls and outgoing SMS and the volume of data traffic for up to 6 months prior to the investigation.

Behaviour measured by the SDQ

The *Adolescents SDQ* in the questionnaire of the adolescents and the *Parents SDQ* in the parents' questionnaire score self-reported and parent-rated behavioural and affective problems of adolescents, respectively. They consist of five scales assessing *Emotional symptoms*, *Conduct problems*, *Hyperactivity*, *Peer problems* and *Prosocial behaviour* on five items answered on a 3-point Likert scale, respectively. A *Total Difficulties Score* can be calculated by summing up the scores for *Emotional symptoms*, *Conduct problems*, *Hyperactivity* and *Peer problems*. Internal consistency of the five scales measured by Cronbach's alpha ranged from 0.51 to 0.74 in our study sample and was comparable to a nationwide British study sample of children and adolescents (0.41–0.77) (Goodman 2001). Furthermore, the scales of the SDQ were associated with relevant diagnoses (Goodman 2001). An overview from Klasen et al. (2003) concluded that the German SDQ is just as useful and valid as the English original scale in terms of similar factorial structure, reliability and validation of the scales (Klasen et al. 2003).

HRQOL measured by the KIDSCREEN

The KIDSCREEN-52 (Ravens-Sieberer et al. 2008; The KIDSCREEN Group Europe 2006) is a standardized questionnaire measuring health-related quality of adolescents' life on ten dimensions named *Physical well-being* (5 items), *Psychological well-being* (6 items), *Moods and emotions* (7 items), *Self-perception* (5 items), *Autonomy* (5 items), *Parent relations and home life* (6 items), *Social support and peers* (6 items), *School environment* (6 items), *Social acceptance* (3 items) and *Financial resources* (3 items) answered on a 5-point Likert scale. Internal consistency of the ten dimensions ranged from 0.77 to 0.88 in our study sample and was comparable to a representative sample of children and adolescents from 13 European countries (0.77–0.89) (Ravens-Sieberer et al. 2008).

Statistical analyses

The associations of problematic mobile phone use (MPPUS-10) with behaviour (Adolescents SDQ, Parents SDQ) and HRQOL (KIDSCREEN) of the adolescents were investigated by multivariable linear regression models. Nonparametric bootstrapping was used to estimate the coefficients to account for non-normal data distribution. MPPUS-10 was included either as continuous score or as categorical variable since no cutoff point dividing mobile phone use into non-problematic and problematic is proposed. The four categories of MPPUS-10 were defined a priori using the 30th, the 60th and the 90th percentile of the distribution of the MPPUS-10 as cutoff points. All models were adjusted for age, sex, nationality (Swiss, mixed or foreign), school level (college preparatory high school or high school), educational level of the parents (six categories: no education, mandatory school, training school, college preparatory high school, college of higher education, university) and self-reported frequency of outgoing text messages as a proxy for amount of mobile phone use. Sensitivity analyses were conducted with operator-recorded frequency of outgoing text messages instead of self-reported frequency of text messages as well as without any adjustment for amount of mobile phone use. Missing items in the MPPUS-10 were imputed using a linear regression imputation taking into account the available items of the MPPUS-10 (13 participants with four or less missing values in the MPPUS-10 items). Missing values in the confounder variables were imputed using imputation of the most common category "training school" for education of the parents (71 missing values) and mean of the available answers for self-reported frequency of outgoing text messages (1 missing value).

Statistical analyses were carried out using STATA version 12.1 (StataCorp, College Station, TX, USA).

Figures were made with the software R using version R for Windows 3.0.1.

Results

HERMES study

In total, 439 adolescents participated in the HERMES study. Participation rate for adolescents was 36.8 % and 89.5 % of their parents returned the questionnaire. 27 (6.2 %) of the adolescents reported not to own a mobile phone and were, therefore, excluded for this analysis. Out of the remaining 412 participants, 319 (77.4 %) indicated to own a smartphone. Participants had a mean age of 14.0 years (ranging from 12.1 to 17.0 years) and 253 (61.4 %) of the participants were female (Table 1). The majority of the adolescents (66.8 %) were 8th grade students.

The average MPPUS-10 score was 28.2 (SD 15.6). Score was higher in smartphone users than in non-smartphone users (mean of 30.6 (SD 16.1) vs. 20.0 (SD 10.0)). The 30th, 60th and 90th percentile of the MPPUS-10 corresponded to MPPUS-10 scores of 17, 29 and 51 units, respectively. All participants in the highest MPPUS-10 category reported to own a smartphone.

According to multivariable regression modelling, problematic mobile phone use score was 4.7 (95 % CI 1.8, 7.6) units higher in girls than in boys and increased significantly with age (2.1 units increase per 1 year ageing, $p = 0.031$) (Table 1). Problematic mobile phone use score was significantly decreased with increasing educational level of the parents ($p = 0.004$). Problematic mobile phone use score tended to be higher in adolescents with mixed nationality compared to Swiss nationality ($p = 0.107$) and tended to be lower for participants attending college preparatory high school compared to participants from high schools ($p = 0.222$).

Amount of mobile phone use

Self-reported mobile phone use data were available for all 412 participating mobile phone users (1 missing value each for frequency of outgoing text messages and duration of data traffic), operator-recorded data were available for a subsample of 233 (56.6 %) participants. Spearman correlation coefficients of self-reported and operator-recorded mobile phone use were 0.48 ($p < 0.001$) for frequency of calls, 0.56 ($p < 0.001$) for frequency of outgoing text messages and 0.50 ($p < 0.001$) for data traffic on the mobile phone.

There was a clear trend of increasing mobile phone use across the four MPPUS-10 categories (Table S2 and Figure S1 in Electronic Supplementary Material). The participants in the highest MPPUS-10 category reported to use their mobile phone on average for 2.7 calls, for sending 44.8 text messages (SMS and text messages sent by internet-based applications) and for 84.3 min of data traffic per day. According to objectively recorded operator data they used their mobile phone for 1.8 calls, sending 6.8 SMS (only SMS were recorded but not text messages sent by internet-based applications) and their mobile phone transmitted 13.9 MB data traffic volume per day.

Table 1 Personal and social factors of the HERMES study participants and change in the Mobile Phone Problem Use Scale-10 score per unit increase in factors, the corresponding 95 % confidence intervals and *p* values, HERMES study, Switzerland, 2012

Personal and social factors		MPPUS-10 score			
		Coefficient		95 % CI	*p* value
Age (in years)	14.0 (12.1–17.0)	Per year	2.09	(0.19, 4.00)	0.031
Sex: female	253 (61.4 %)	Compared to male	4.71	(1.78, 7.64)	0.002
Nationality					
Swiss	328 (79.6 %)				
Mixed	56 (13.6 %)	Compared to Swiss	4.10	(−0.89, 9.10)	0.107
Foreign	28 (6.8 %)	Compared to Swiss	−0.76	(−6.98, 5.47)	0.811
School level: college preparatory high school	95 (23.1 %)	Compared to high school	−2.12	(−5.52, 1.28)	0.222
Highest educational level parents		Per category	−1.80	(−3.05, −0.56)	0.004
No education	3 (0.7 %)				
Mandatory school	12 (2.9 %)				
Training school	212 (51.5 %)				
College preparatory high school	30 (7.3 %)				
College of higher education	122 (29.6 %)				
University	33 (8.0 %)				

The strongest Spearman correlation of problematic mobile phone use score with amount of mobile phone use was observed for self-reported frequency of outgoing text messages with $\rho = 0.59$ ($p < 0.001$). Other types of use were only fairly to moderately correlated [self-reported frequency of calls: 0.32 ($p < 0.001$), self-reported duration of data traffic: 0.42 ($p < 0.001$), objectively recorded frequency of calls: 0.35 ($p < 0.001$), objectively recorded frequency of outgoing SMS: 0.41 ($p < 0.001$), objectively recorded volume of data traffic: 0.39 ($p < 0.001$)].

Behaviour

Problematic mobile phone use was significantly positively associated with overall behavioural problems [adjusted coefficient 0.96 (95 % CI 0.58, 1.35) units increase in the *Total Difficulties Score* per 10 units increase in the MPPUS-10 score] (Table 2). Among the specific behavioural problems, most pronounced association was observed for *Hyperactivity* [0.42 (0.26, 0.57)], followed by *Conduct problems* [0.30 (0.19, 0.41)] and *Emotional symptoms* [0.17 (0.02, 0.32)]. *Prosocial behaviour* was significantly negatively associated with problematic mobile phone use [−0.14 (−0.25, −0.04)], whereas *Peer problems* was not related to problematic mobile phone use. Results were similar for continuous and categorical analysis. Behavioural problems rated by the parents based on 344 questionnaires showed a similar pattern although coefficients were lower and associations with *Emotional symptoms* and *Prosocial behaviour* did not reach statistical significance (Table S3 in Electronic Supplementary Material).

Estimated coefficients and the corresponding 95 % confidence intervals did not much change if adjustment for self-reported or operator-recorded frequency of outgoing text messages was dropped (Tables S4 and S5 in Electronic Supplementary Material).

HRQOL

Six out of the ten HRQOL dimensions were significantly decreased (*Moods and emotions*, *Self-perception*, *Autonomy*, *Parent relations and home life*, *Financial resources* and *School environment*) for increasing problematic mobile phone use score (Table 2). Not related to problematic mobile phone use were the dimensions *Social support and Peers* and *Social acceptance*. *Physical well-being* and *Psychological well-being* were significantly decreased in the 10 % of adolescents in the highest MPPUS-10 category, but the associations were only borderline or not significant according to the test for trend and the continuous analysis. Again, results were similar for continuous and categorical analysis. Adjustment for self-reported or operator-recorded frequency of outgoing text messages as a proxy for amount of mobile phone use had little impact on the results (Tables S4 and S5 in Electronic Supplementary Material).

Discussion

Overall, problematic mobile phone use, expressed by a higher MPPUS-10 score, was associated with increased amount of mobile phone use, impaired psychological well-being, decreased mood and more behavioural problems whereas no association with social relationships with peers was observed. Our categorical analysis indicates that there is no common threshold above which mobile phone use becomes problematic for mental health, instead we observed a fairly linear relation between the problematic mobile phone use score and various mental health outcomes.

Problematic mobile phone use and amount of mobile phone use

Problematic mobile phone use score was associated with amount of calls, text messages and data traffic. Nevertheless, Spearman correlations were modest indicating that problematic mobile phone use as measured by the MPPUS-10 does not only reflect amount of mobile phone use but also other aspects such as loss of control, withdrawal symptoms, craving and peer dependence which are problematic. As a consequence even extensive amount of mobile phone use did not result in a high problematic mobile phone use score in some study participants and vice versa high problematic mobile phone use score occurred in participants with low to modest amount of mobile phone use. Strikingly, the coefficients of all models with mental health outcomes did not change noticeably if models were not adjusted for amount of mobile phone use. This indicates that the observed associations are independently related to problematic aspects of use and not to the amount of mobile phone use itself. Thus, amount and problematic aspects of mobile phone use should be considered separately in future studies in adolescents.

Personal and social factors related to problematic mobile phone use

Significant increases of problematic mobile phone use score were found for being female, age and low educational level of the parents. These findings are in line with other studies (Augner and Hacker 2012; Bianchi and Phillips 2005; Byun et al. 2013a; Sanchez-Martinez and Otero 2009; Yang et al. 2010) although, to the best of our

Table 2 Change in the Adolescents Strengths and Difficulties Questionnaire scores and KIDSCREEN dimensions per 10 unit increase in the Mobile Phone Problem Use Scale-10 score and per Mobile Phone Problem Use Scale-10 category and the corresponding 95 % confidence intervals and *p* values for the test for trend in the Mobile Phone Problem Use Scale-10 categories, HERMES study, Switzerland, 2012

Adolescents SDQ	*n*	MPPUS-10 score				MPPUS-10 categories**								Test for trend***
		Crude		Adjusted*		<30th (*n* = 125)		30th–60th (n = 120)		60th–90th (*n* = 125)		≥90th (*n* = 42)		
		Coefficient	95 % CI	Coefficient	95 % CI			Coefficient	95 % CI	Coefficient	95 % CI	Coefficient	95 % CI	*p* value
Total Difficulties Score	412	0.80	(0.48, 1.12)	0.96	(0.58, 1.35)	0	(reference)	1.17	(0.07, 2.27)	2.36	(1.22, 3.49)	4.99	(2.94, 7.03)	<0.001
Emotional symptoms	412	0.20	(0.07, 0.34)	0.17	(0.02, 0.32)	0	(reference)	0.04	(−0.46, 0.53)	0.26	(−0.24, 0.76)	0.73	(−0.12, 1.57)	0.075
Conduct problems	412	0.26	(0.17, 0.35)	0.30	(0.19, 0.41)	0	(reference)	0.52	(0.17, 0.86)	0.88	(0.5, 1.25)	1.52	(0.89, 2.14)	<0.001
Hyperactivity	412	0.38	(0.24, 0.51)	0.42	(0.26, 0.57)	0	(reference)	0.55	(0.04, 1.05)	1.13	(0.63, 1.63)	2.33	(1.52, 3.15)	<0.001
Peer problems	412	−0.05	(−0.15, 0.05)	0.08	(−0.05, 0.21)	0	(reference)	0.07	(−0.39, 0.53)	0.09	(−0.38, 0.56)	0.41	(−0.34, 1.16)	0.371
Prosocial behaviour	412	−0.05	(−0.15, 0.05)	−0.14	(−0.25, −0.04)	0	(reference)	−0.38	(−0.81, 0.05)	−0.25	(−0.69, 0.2)	−0.88	(−1.48, −0.28)	0.039
KIDSCREEN														
Physical well-being	411	−0.44	(−1.02, 0.14)	−0.66	(−1.53, 0.21)	0	(reference)	−0.02	(−2.28, 2.23)	−1.24	(−3.91, 1.44)	−5.07	(−9.02, −1.13)	0.036
Psychological well-being	412	−0.74	(−1.33, −0.16)	−0.62	(−1.39, 0.14)	0	(reference)	−0.90	(−3.22, 1.41)	−0.80	(−3.22, 1.62)	−5.00	(−9.23, −0.78)	0.063
Moods and emotions	412	−2.00	(−2.70, −1.30)	−1.73	(−2.64, −0.82)	0	(reference)	−2.25	(−4.98, 0.48)	−5.87	(−8.59, −3.14)	−8.65	(−12.94, −4.36)	<0.001
Self-perception	412	−1.12	(−1.68, −0.57)	−0.90	(−1.66, −0.15)	0	(reference)	−1.41	(−3.8, 0.98)	−4.23	(−6.61, −1.84)	−3.90	(−7.46, −0.33)	0.001
Autonomy	409	−0.62	(−1.12, −0.12)	−0.67	(−1.28, −0.06)	0	(reference)	−2.05	(−4.17, 0.07)	−1.62	(−3.94, 0.7)	−4.61	(−7.87, −1.34)	0.026
Parent relations and home life	408	−1.39	(−1.87, −0.90)	−1.50	(−2.09, −0.91)	0	(reference)	−2.58	(−4.92, −0.23)	−5.15	(−7.52, −2.77)	−5.82	(−9.36, −2.28)	<0.001
Financial resources	405	−1.15	(−1.63, −0.68)	−1.51	(−2.03, −0.99)	0	(reference)	−1.85	(−3.78, 0.08)	−4.47	(−6.46, −2.47)	−6.15	(−9.1, −3.21)	<0.001
Social support and peers	412	0.46	(−0.03, 0.94)	−0.11	(−0.72, 0.50)	0	(reference)	−1.95	(−4.09, 0.2)	−0.38	(−2.84, 2.09)	−2.08	(−5.34, 1.17)	0.551
School environment	407	−1.08	(−1.51, −0.65)	−0.97	(−1.54, −0.41)	0	(reference)	−2.62	(−4.66, −0.59)	−3.51	(−5.58, −1.44)	−5.34	(−8.1, −2.58)	<0.001
Social acceptance	409	−0.04	(−0.66, 0.57)	−0.60	(−1.36, 0.16)	0	(reference)	−0.09	(−2.72, 2.53)	−1.07	(−3.87, 1.73)	−2.19	(−6.38, 2.00)	0.266

* Models adjusted for age, sex, nationality, school level, education of the parents and self-reported frequency of outgoing text messages

** MPPUS-10 categories correspond to MPPUS-10 scores of 10–17 (<30th percentile), 18–28 (30th–60th percentile), 29–50 (60th–90th percentile) and 51–100 (≥90th percentile), respectively

*** *p* value of the ordinal variable of the four MPPUS-10 categories <30th percentile, 30th–60th percentile, 60th–90th percentile and ≥90th percentile ranging from 1 to 4 in adjusted regression models knowledge, parents' education was not reported to be associated with problematic mobile phone use before. It is conceivable that parents with higher educational background are more aware of problematic aspects of their children's mobile phone use and thus consider these aspects in their education. Furthermore, the school environment also plays an important role, as indicated by our results on the corresponding KIDSCREEN dimensions (*Parent relations and home life* and *School environment*). These findings also support the relevance of the social background for developing addictive behaviours. Particularly, good family functioning and good communication between parents and adolescents may help prevent problematic mobile phone use in adolescents as it was observed for pathological internet use (Wartberg et al. 2015). A possible explanation could be that rules for media use controlled by parents prevent problematic use. Education of media use in school in combination with adolescents feeling comfortable in school may play a similar role.

HRQOL and problematic mobile phone use

Our results indicate decreased mood and psychological well-being to be associated with problematic mobile phone use. Similar findings come from recent studies linking symptoms of mental ill health, depression and anxiety to problematic mobile phone use (Augner and Hacker 2012; Ha et al. 2008; Yen et al. 2009), to problematic internet use (Kaess et al. 2014; Ko et al. 2012) and to amount of mobile phone use which is expected to partly reflect problematic use (Ikeda and Nakamura 2014; Thomée et al. 2011). Similar to these studies, our cross-sectional study cannot clarify the direction of these associations. Either problematic mobile phone use could be the consequence of decreased mood, psychological well-being and negative self-perception or the other way around. For both pathways there are plausible arguments. Negative self-perception is linked to depression (Lewinsohn et al. 1980) and individuals with negative self-perception may use the mobile phone to elevate their self-perception by spending time on social networks (Steinfield et al. 2008). Mobile phones might thus be used to escape from negative feelings, which in the long run may act as an amplifier of such feelings because the underlying problems are not approached. Or mobile phones may be used to seek for social support in times of depressed feeling. In line of the latter hypothesis, decreased depressive symptoms have been observed for increased instant messenger and social network use (Morgan and Cotten 2003). On the other hand, decreased mood and psychological well-being may be a consequence of problematic mobile phone use thinking of the overwhelming possibilities the mobile phone and the internet provide nowadays and the accompanying stress of being accessible all the time. This hypothesis is in agreement with the finding of Thomée et al. (2011) of high mobile phone use being a risk factor for reporting symptoms for depression 1 year later with the risk being greatest among those participants who reported to perceive stress because of the high accessibility via mobile phone (Thomée et al. 2011). Another possibility is that there is not a pathway pointing in one direction but a reinforcing spiral leading to the associations between problematic mobile phone use and health and behavioural factors as it is proposed for media effects in general (Slater 2007).

Behaviour and problematic mobile phone use

We found a strong association between *Hyperactivity* and problematic mobile phone use, which, to the best of our knowledge, has not been examined so far. Previous studies found hyperactivity and ADHD associated with problematic internet use (Kaess et al. 2014; Ko et al. 2012; Kormas et al. 2011; Ozturk et al. 2013) and using the mobile phone for entertainment (playing games, internet) (Byun et al. 2013b; Zheng et al. 2014). Hyperactive adolescents are easily distracted, show problems in sustaining attention and are less capable of impulse control (Douglas 1972). Thus, hyperactive adolescents may be prone to develop problematic mobile phone use through the countless possibilities of a mobile phone to drift away, find excitement and escape from boredom. At the same time, we found *Conduct problems* to be associated with problematic mobile phone use, which is in line with the finding of Kaess et al. (2014) of problematic internet use being related to conduct problems in adolescents. Adolescents with conduct problems are often impulsive and pathological internet use is considered to be an impulse-control disorder.

Strengths and limitations

A particular strength of this study is that we could rely on both self-reported and objectively recorded mobile phone use data from mobile phone operators. It is well established that adolescents tend to overestimate their mobile phone use (Aydin et al. 2011; Inyang et al. 2009). This especially holds for duration of mobile phone calls and less pronounced for frequency of calls. However, since results were similar for self-reported and operator-recorded amount of mobile phone use, recall or reporting bias is not expected to affect our study results. We adjusted our analyses for self-reported and operator-recorded frequency of outgoing text messages. We think that daily frequency of outgoing text messages is a valuable proxy for all types of activity on the mobile phone. Note that analyses with adjustment for data traffic or call frequency yielded similar results.

We were able to investigate a variety of external as well as internal factors found in the literature and possibly related to problematic mobile phone use in one study sample at the same time. An inherent limitation of our study is that problematic mobile phone use, HRQOL and behaviour are self-reported. However, we had additionally parent-rated behaviour available and SDQ and KIDSCREEN are widely used and validated scales.

Conclusion

Our study indicates that problematic mobile phone use in adolescents is associated with external factors such as worse home and school environment, and internal factors such as impaired HRQOL and behavioural problems. Future longitudinal studies should clarify whether problematic mobile phone use is the consequence of unfavourable conditions or whether and to what extent problematic mobile phone use reinforces behavioural problems as well as decreased mood and psychological well-being. In the meantime, problematic mobile phone use in adolescents should be addressed, in particular when dealing with adolescents showing behavioural or emotional problems.

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Compliance with ethical standards

Ethical standard Ethical approval for the conduct of the study was received from the ethical committee of Lucerne, Switzerland on May 9, 2012 (Ref. Nr. EK 12025).

Conflict of interest The authors declare that they have no conflict of interest.

References

Augner C, Hacker GW (2012) Associations between problematic mobile phone use and psychological parameters in young adults. Int J Public Health 57:437–441

Aydin D, Feychting M, Schuz J et al (2011) Predictors and overestimation of recalled mobile phone use among children and adolescents. Prog Biophys Mol Biol 107:356–361. doi:10.1016/j.pbiomolbio.2011.08.013

Bianchi A, Phillips JG (2005) Psychological predictors of problem mobile phone use. Cyberpsychol Behav 8:39–51

Billieux J (2012) Problematic use of the mobile phone: a literature review and a pathways model. Curr Psychiatry Rev 8:299–307

Byun YH, Ha M, Kwon HJ et al (2013a) Epidemiological characteristics of mobile phone ownership and use in Korean children and adolescents. Environ Health Toxicol 28:e2013018. doi:10.5620/eht.2013.28.e2013018

Byun YH, Ha M, Kwon HJ et al (2013b) Mobile phone use, blood lead levels, and attention deficit hyperactivity symptoms in children: a longitudinal study. PLoS ONE 8:e59742. doi:10.1371/journal.pone.0059742

Douglas VI (1972) Stop, look and listen: the problem of sustained attention and impulse control in hyperactive and normal children. Can J Behav Sci 4:259

Foerster M, Roser K, Schoeni A, Röösli M (2015) Problematic mobile phone use in adolescents: derivation of a short scale MPPUS-10. Int J Public Health 60:277–286. doi:10.1007/s00038-015-0660-4

Goodman R (1997) The Strengths and Difficulties Questionnaire: a research note. J Child Psychol Psyc 38:581–586

Goodman R (2001) Psychometric properties of the strengths and difficulties questionnaire. J Am Acad Child Adolesc Psychiatry 40:1337–1345. doi:10.1097/00004583-200111000-00015

Ha JH, Chin B, Park D-H, Ryu S-H, Yu J (2008) Characteristics of excessive cellular phone use in Korean adolescents. Cyberpsychol Behav 11:783–784

Ikeda K, Nakamura K (2014) Association between mobile phone use and depressed mood in Japanese adolescents: a cross-sectional study. Environ Health Prev Med 19:187–193. doi:10.1007/s12199-013-0373-3

Inyang I, Benke G, Morrissey J, McKenzie R, Abramson M (2009) How well do adolescents recall use of mobile telephones? Results of a validation study. BMC Med Res Methodol 9:36. doi:10.1186/1471-2288-9-36

Kaess M, Durkee T, Brunner R et al (2014) Pathological Internet use among European adolescents: psychopathology and self-destructive behaviours. Eur Child Adolesc Psychiatry 23:1093–1102. doi:10.1007/s00787-014-0562-7

Klasen H, Woerner W, Rothenberger A, Goodman R (2003) The German version of the Strengths and Difficulties Questionnaire (SDQ-Deu)—overview over first validation and normative studies. Prax Kinderpsychol Kinderpsychiatr 52:491–502

Ko CH, Yen JY, Yen CF, Chen CS, Chen CC (2012) The association between Internet addiction and psychiatric disorder: a review of the literature. Eur Psychiatry 27:1–8. doi:10.1016/j.eurpsy.2010.04.011

Kormas G, Critselis E, Janikian M, Kafetzis D, Tsitsika A (2011) Risk factors and psychosocial characteristics of potential problematic and problematic internet use among adolescents: a cross-sectional study. BMC Public Health 11:595

Lewinsohn PM, Mischel W, Chaplin W, Barton R (1980) Social competence and depression: the role of illusory self-perceptions. J Abnorm Psychol 89:203

Morgan C, Cotten SR (2003) The relationship between Internet activities and depressive symptoms in a sample of college freshmen. Cyberpsychol Behav 6:133–142

Ozturk FO, Ekinci M, Ozturk O, Canan F (2013) The Relationship of Affective Temperament and Emotional-Behavioral Difficulties to Internet Addiction in Turkish Teenagers. Int Sch Res Not 2013

Ravens-Sieberer U, Gosch A, Rajmil L et al (2008) The KIDSCREEN-52 quality of life measure for children and adolescents: psychometric results from a cross-cultural survey in 13 European countries. Value Health 11:645–658. doi:10.1111/j.1524-4733.2007.00291.x

Redmayne M, Smith E, Abramson MJ (2013) The relationship between adolescents' well-being and their wireless phone use: a cross-sectional study. Environ Health 12:90. doi:10.1186/1476-069x-12-90

Sanchez-Martinez M, Otero A (2009) Factors associated with cell phone use in adolescents in the community of Madrid (Spain). Cyberpsychol Behav 12:131–137

Slater MD (2007) Reinforcing spirals: the mutual influence of media selectivity and media effects and their impact on individual behavior and social identity. Commun Theory 17:281–303. doi:10.1111/j.1468-2885.2007.00296.x

Steinfield C, Ellison NB, Lampe C (2008) Social capital, self-esteem, and use of online social network sites: a longitudinal analysis. J Appl Dev Psychol 29:434–445

Takao M, Takahashi S, Kitamura M (2009) Addictive personality and problematic mobile phone use. Cyberpsychol Behav 12:501–507

The KIDSCREEN Group Europe (2006) The KIDSCREEN Questionnaires—quality of life questionnaires for children and adolescents. In: Handbook Lengerich. Pabst Science Publishers, Germany

Thomée S, Härenstam A, Hagberg M (2011) Mobile phone use and stress, sleep disturbances, and symptoms of depression among young adults-a prospective cohort study. BMC Public Health 11:66

Wartberg L, Aden A, Thomsen M, Thomasius R (2015) Relationships between family interactions and pathological internet use in adolescents: an review. Z Kinder Jugendpsychiatr Psychother 43:9–17. doi:10.1024/1422-4917/a000328 **(quiz 18–19)**

Willemse I, Waller G, Süss D (2014) JAMES Jugend, Aktivitäten, Medien - Erhebung Schweiz, Factsheet Befunde 2014. Zurich University of Applied Sciences

Yang YS, Yen JY, Ko CH, Cheng CP, Yen CF (2010) The association between problematic cellular phone use and risky behaviors and low self-esteem among Taiwanese adolescents. BMC Public Health 10:217. doi:10.1186/1471-2458-10-217

Yen CF, Tang TC, Yen JY, Lin HC, Huang CF, Liu SC, Ko CH (2009) Symptoms of problematic cellular phone use, functional impairment and its association with depression among adolescents in Southern Taiwan. J Adolesc 32:863–873. doi:10.1016/j.adolescence.2008.10.006

Zheng F, Gao P, He M, Li M, Wang C, Zeng Q, Zhou Z, Yu Z, Zhang L (2014) Association between mobile phone use and inattention in 7102 Chinese adolescents: a population-based cross-sectional study. BMC Public Health 14:1022. doi:10.1186/1471-2458-14-1022

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Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour?

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German version of the MPPUS-10

Table S1. German version of the 10-item Mobile Phone Problem Use Scale-10, HERMES study, Switzerland, 2012

Bitte markiere jeweils auf der Skala von 1 = „überhaupt nicht wahr" bis 10 = „sehr wahr", wie sehr die Aussage auf dich zutrifft.
Ich habe mein Mobiltelefon schon benutzt, um mich besser zu fühlen, als ich mich niedergeschlagen fühlte.
Wenn ich eine Zeit lang keinen Empfang habe, komme ich vom Gedanken nicht los, einen Anruf zu verpassen.
Meine Freunde fänden es mühsam, mich zu kontaktieren, wenn ich kein Mobiltelefon hätte.
Ich werde unruhig, wenn mein Mobiltelefon eine Zeit lang ausgeschaltet ist oder ich mein Mobiltelefon nicht auf neue Nachrichten überprüfen kann.
Meine Freunde und meine Familie beschweren sich über meinen Mobiltelefongebrauch.
Ich beschäftige mich länger als beabsichtigt mit meinem Mobiltelefon.
Ich komme häufig zu spät zu Terminen, weil ich mich mit meinem Mobiltelefon beschäftige, obwohl ich nicht sollte.
Ich finde es schwierig, mein Mobiltelefon auszuschalten.
Mir wurde gesagt, dass ich zu viel Zeit mit meinem Mobiltelefon verbringe.
Ich habe schon Mobiltelefonrechnungen erhalten, die ich nicht bezahlen konnte.

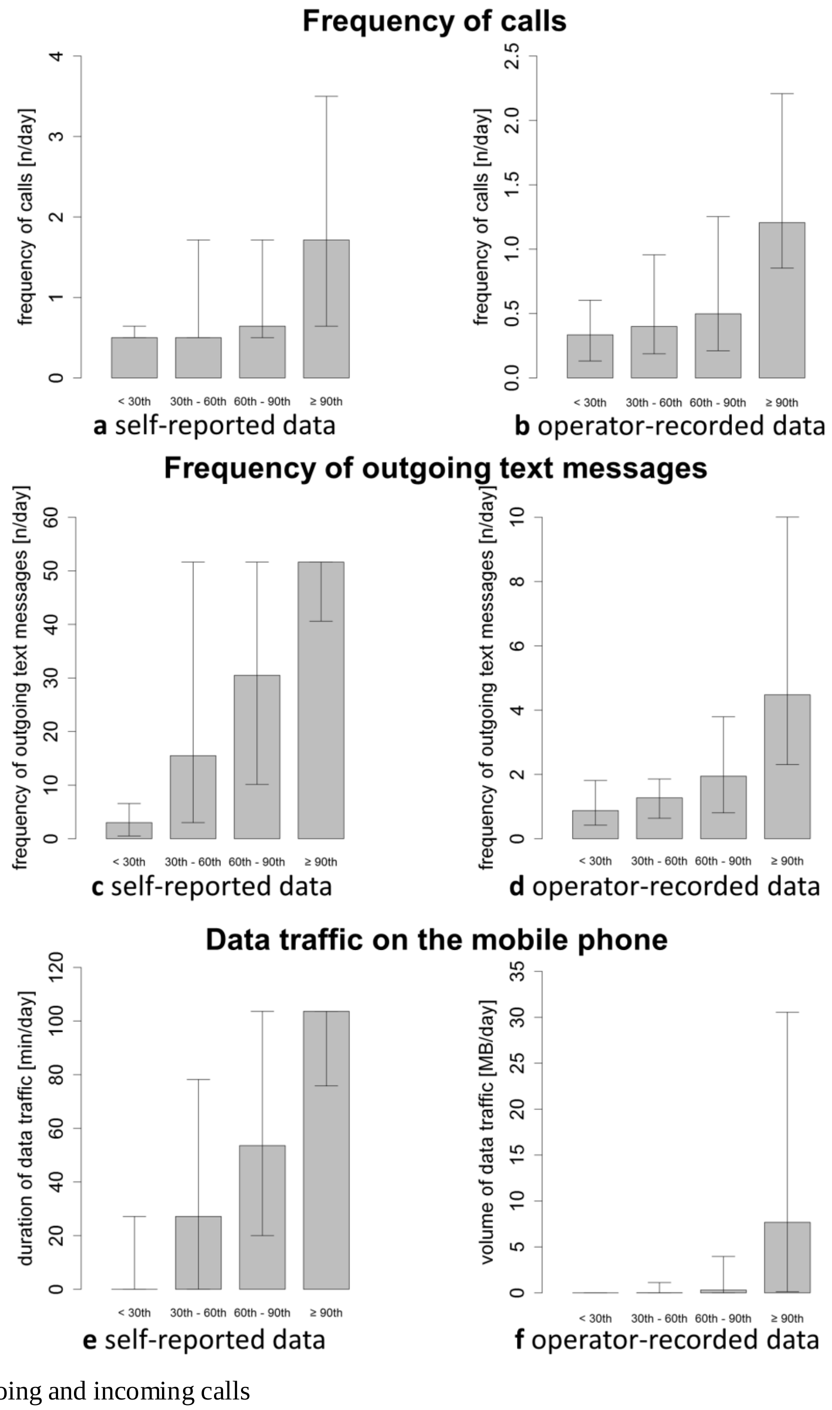
Amount of mobile phone use

Table S2. Mean and standard deviation (SD) of self-reported and operator-recorded mobile phone use measures for the four Mobile Phone Problem Use Scale-10 categories and the whole sample, HERMES study, Switzerland, 2012

	mean (SD)				
	< 30th (n = 125)	30th - 60th (n = 120)	60th - 90th (n = 125)	≥ 90th (n = 42)	whole sample (n = 412)
Self-reported data					
Frequency of calls (n/day)	0.8 (0.7)	1.3 (1.4)	1.4 (1.4)	2.7 (2.4)	1.3 (1.5)
Frequency of outgoing text messages (n/day) *	7.3 (11.9)	23.7 (20.7)	30.3 (19.4)	44.8 (13.0)	22.8 (20.9)
Data traffic on the mobile phone (min/day) *	24.0 (37.1)	41.0 (38.8)	56.2 (38.7)	84.3 (28.2)	44.9 (41.4)
	< 30th (n = 81)	30th - 60th (n = 65)	60th - 90th (n = 68)	≥ 90th (n = 19)	operator sample (n = 233)
Operator-recorded data					
Frequency of calls (n/day)	0.5 (0.5)	0.9 (1.5)	1.0 (1.2)	1.8 (1.5)	0.8 (1.2)
Frequency of outgoing text messages (n/day)	1.5 (3.28)	1.8 (1.9)	4.2 (7.3)	6.8 (5.6)	2.8 (5.1)
Data traffic on the mobile phone (MB/day)	0.7 (2.2)	2.4 (5.1)	4.1 (7.5)	13.9 (15.6)	3.2 (7.5)

* 1 missing value each for self-reported frequency of outgoing text messages and data traffic on the mobile phone

Figure S1. Median and interquartile range per Mobile Phone Problem Use Scale-10 category for frequency of calls, frequency of outgoing text messages and duration and volume of data traffic for self-reported data (left) and operator-recorded data (right), HERMES study, Switzerland, 2012



a outgoing and incoming calls
b outgoing and incoming calls
c all type of outgoing text messages (SMS and text messages sent by internet-based applications) (1 missing value)
d outgoing SMS only
e duration of data traffic (1 missing value)
f volume of data traffic

MPPUS-10 categories correspond to MPPUS-10 scores of 10-17 (< 30th percentile), 18-28 (30th – 60th percentile), 29-50 (60th – 90th percentile) and 51-100 (≥ 90th percentile), respectively.

Behaviour measured by the Parents SDQ

Table S3. Change in the Parents Strengths and Difficulties Questionnaire scores per 10 unit increase in the Mobile Phone Problem Use Scale-10 score and per Mobile Phone Problem Use Scale-10 category and the corresponding 95% confidence intervals and p values for the test for trend in the Mobile Phone Problem Use Scale-10 categories, HERMES study, Switzerland, 2012

		MPPUS-10 score				MPPUS-10 categories **									Test for trend ***
		crude		adjusted *		< 30th (n = 125)		30th - 60th (n = 120)		60th - 90th (n = 125)		≥ 90th (n = 42)			
Parents SDQ	N	Coefficient	95% CI	Coefficient	95% CI			Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI		p value
Total Difficulties Score	344	0.39	(0.08, 0.69)	0.44	(0.07, 0.82)	0	(reference)	0.32	(-0.87, 1.52)	1.34	(-0.12, 2.81)	2.55	(0.35, 4.75)		0.012
Emotional Symptoms	344	0.09	(-0.02, 0.21)	0.07	(-0.05, 0.20)	0	(reference)	-0.05	(-0.51, 0.42)	0.00	(-0.46, 0.45)	0.60	(-0.30, 1.50)		0.309
Conduct Problems	344	0.18	(0.09, 0.27)	0.17	(0.06, 0.28)	0	(reference)	0.19	(-0.15, 0.53)	0.53	(0.07, 1.00)	0.93	(0.34, 1.52)		0.002
Hyperactivity	344	0.16	(0.04, 0.29)	0.21	(0.04, 0.37)	0	(reference)	0.28	(-0.25, 0.81)	0.63	(0.01, 1.25)	1.35	(0.44, 2.26)		0.003
Peer Problems	344	-0.06	(-0.16, 0.05)	-0.01	(-0.15, 0.12)	0	(reference)	-0.10	(-0.57, 0.37)	0.18	(-0.38, 0.75)	-0.33	(-1.00, 0.34)		0.952
Prosocial Behaviour	344	-0.05	(-0.18, 0.07)	-0.05	(-0.21, 0.11)	0	(reference)	-0.23	(-0.73, 0.27)	-0.33	(-0.95, 0.29)	-0.11	(-0.96, 0.73)		0.485

* models adjusted for age, sex, nationality, school level, educational level of the parents and self-reported frequency of outgoing text messages

** MPPUS-10 categories correspond to MPPUS-10 scores of 10-17 (< 30th percentile), 18-28 (30th - 60th percentile), 29-50 (60th - 90th percentile) and 51-100 (≥ 90th percentile), respectively

*** p-value of the ordinal variable of the four MPPUS-10 categories < 30th percentile, 30th – 60th percentile, 60th – 90th percentile and ≥ 90th percentile ranging from 1 to 4 in adjusted regression models

Sensitivity analysis regarding adjustment for amount of mobile phone use

Whole sample

Table S4. Change in the Adolescents Strengths and Difficulties Questionnaire scores, Parents Strengths and Difficulties Questionnaire scores and KIDSCREEN dimensions per 10 unit increase in the Mobile Phone Problem Use Scale-10 score and the corresponding 95% confidence intervals for adjusted analysis with and without adjustment for self-reported frequency of outgoing text messages, HERMES study, Switzerland, 2012

		MPPUS-10 score			
		adjusted *		adjusted without outgoing text messages **	
Adolescents SDQ	n	Coefficient	95% CI	Coefficient	95% CI
Total Difficulties Score	412	0.96	(0.58, 1.35)	0.88	(0.56, 1.21)
Emotional Symptoms	412	0.17	(0.02, 0.32)	0.18	(0.05, 0.32)
Conduct Problems	412	0.30	(0.19, 0.41)	0.30	(0.21, 0.39)
Hyperactivity	412	0.42	(0.26, 0.57)	0.44	(0.3, 0.57)
Peer Problems	412	0.08	(-0.05, 0.21)	-0.04	(-0.15, 0.08)
Prosocial Behaviour	412	-0.14	(-0.25, -0.04)	-0.12	(-0.21, -0.02)
Parents SDQ					
Total Difficulties Score	344	0.44	(0.07, 0.82)	0.36	(0.04, 0.69)
Emotional Symptoms	344	0.07	(-0.05, 0.20)	0.07	(-0.06, 0.20)
Conduct Problems	344	0.17	(0.06, 0.28)	0.18	(0.09, 0.26)
Hyperactivity	344	0.21	(0.04, 0.37)	0.20	(0.06, 0.33)
Peer Problems	344	-0.01	(-0.15, 0.12)	-0.08	(-0.19, 0.03)
Prosocial Behaviour	344	-0.05	(-0.21, 0.11)	-0.07	(-0.19, 0.06)
KIDSCREEN					
Physical Well-being	411	-0.66	(-1.53, 0.21)	-0.36	(-0.98, 0.26)
Psychological Well-being	412	-0.62	(-1.39, 0.14)	-0.70	(-1.30, -0.10)
Moods and Emotions	412	-1.73	(-2.64, -0.82)	-1.98	(-2.69, -1.27)
Self-Perception	412	-0.90	(-1.66, -0.15)	-1.01	(-1.58, -0.44)
Autonomy	409	-0.67	(-1.28, -0.06)	-0.65	(-1.17, -0.13)
Parent Relations and Home Life	408	-1.50	(-2.09, -0.91)	-1.43	(-1.94, -0.92)
Financial Resources	405	-1.51	(-2.03, -0.99)	-1.07	(-1.56, -0.58)
Social Support and Peers	412	-0.11	(-0.72, 0.50)	0.32	(-0.18, 0.82)
School Environment	407	-0.97	(-1.54, -0.41)	-1.11	(-1.57, -0.65)
Social Acceptance	409	-0.60	(-1.36, 0.16)	-0.22	(-0.86, 0.41)

* adjusted for age, sex, nationality, school level, educational level of the parents and self-reported frequency of outgoing text messages

** the same as adjusted * except self-reported frequency of outgoing text messages

Operator sample

Table S5. Change in the Adolescents Strengths and Difficulties Questionnaire scores, Parents Strengths and Difficulties Questionnaire scores and KIDSCREEN dimensions per 10 unit increase in the Mobile Phone Problem Use Scale-10 score and the corresponding 95% confidence intervals for adjusted analysis with and without adjustment for operator-recorded frequency of outgoing text messages, HERMES study, Switzerland, 2012

		MPPUS-10 score			
		adjusted *		adjusted without outgoing text messages **	
Adolescents SDQ	N	Coefficient	95% CI	Coefficient	95% CI
Total Difficulties Score	233	0.55	(0.06, 1.04)	0.62	(0.13, 1.10)
Emotional Symptoms	233	0.04	(-0.14, 0.22)	0.10	(-0.07, 0.28)
Conduct Problems	233	0.29	(0.14, 0.44)	0.30	(0.16, 0.44)
Hyperactivity	233	0.28	(0.10, 0.46)	0.28	(0.11, 0.46)
Peer Problems	233	-0.06	(-0.25, 0.13)	-0.06	(-0.24, 0.11)
Prosocial Behaviour	233	-0.24	(-0.38, -0.10)	-0.18	(-0.31, -0.04)
Parents SDQ					
Total Difficulties Score	208	0.33	(-0.10, 0.75)	0.44	(0.02, 0.85)
Emotional Symptoms	208	0.04	(-0.14, 0.21)	0.08	(-0.10, 0.26)
Conduct Problems	208	0.18	(0.06, 0.31)	0.24	(0.12, 0.35)
Hyperactivity	208	0.16	(-0.01, 0.34)	0.17	(0.00, 0.34)
Peer Problems	208	-0.05	(-0.22, 0.12)	-0.05	(-0.20, 0.11)
Prosocial Behaviour	208	-0.13	(-0.32, 0.06)	-0.12	(-0.29, 0.05)
KIDSCREEN					
Physical Well-being	232	-0.26	(-1.21, 0.69)	-0.30	(-1.17, 0.56)
Psychological Well-being	233	-0.55	(-1.59, 0.49)	-0.74	(-1.68, 0.20)
Moods and Emotions	233	-1.58	(-2.77, -0.39)	-2.01	(-3.13, -0.89)
Self-Perception	233	-1.03	(-1.96, -0.10)	-1.09	(-1.93, -0.25)
Autonomy	231	-0.65	(-1.42, 0.12)	-0.77	(-1.47, -0.07)
Parent Relations and Home Life	231	-1.53	(-2.29, -0.78)	-1.72	(-2.42, -1.02)
Financial Resources	230	-1.60	(-2.32, -0.89)	-1.64	(-2.27, -1.00)
Social Support and Peers	233	-0.09	(-0.89, 0.71)	0.01	(-0.72, 0.73)
School Environment	231	-0.99	(-1.67, -0.30)	-1.07	(-1.71, -0.43)
Social Acceptance	233	-0.16	(-1.15, 0.84)	-0.39	(-1.28, 0.51)

* adjusted for age, sex, nationality, school level, educational level of the parents and operator-recorded frequency of outgoing text messages

** the same as adjusted * except operator-recorded frequency of outgoing text messages

5 Personal RF-EMF measurements in adolescents

Article 3: Personal radiofrequency electromagnetic field exposure measurements in Swiss adolescents

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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 μW/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.

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.,

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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 × 8 × 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.

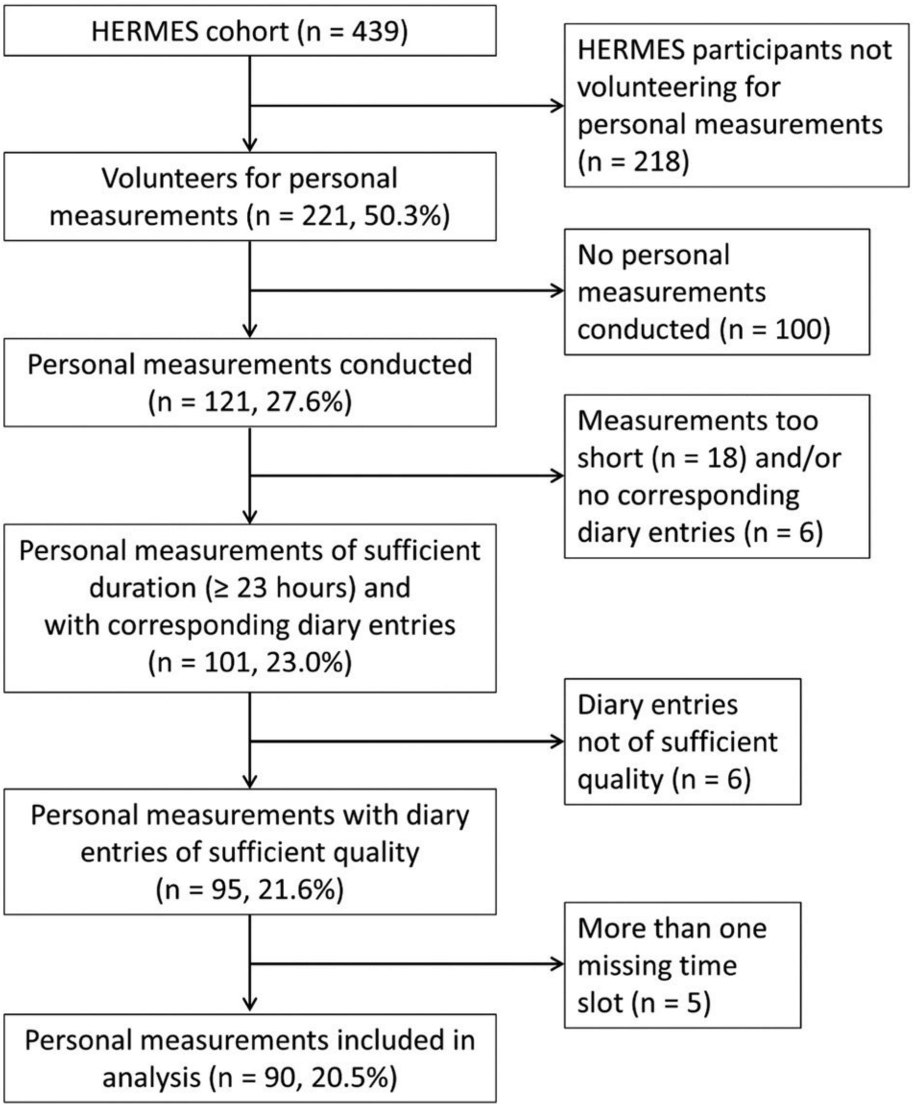

Fig. 1. Participants of the personal measurements consisting of a subgroup of the participants of the HERMES cohort.

Table 3
Summary statistics for the whole measurement period per frequency band, for uplink, downlink and total RF-EMF measurements (μW/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.

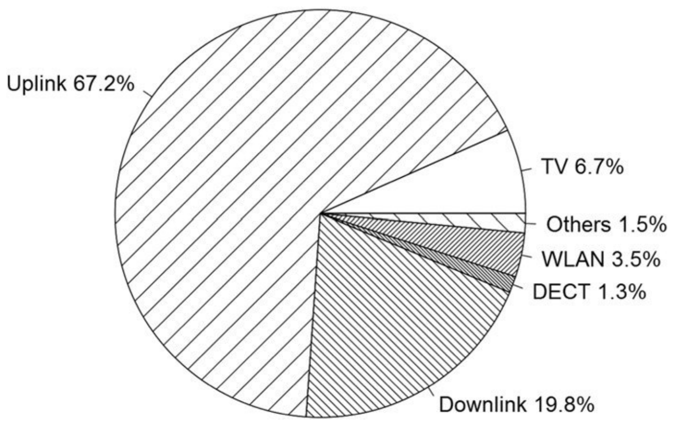

Fig. 2. Mean contributions of different sources to the total personal RF-EMF measurements (in power flux density). Mean = 63.2 μW/m^2 (0.15 V/m). *Others* refers to the frequency bands LTE 800 Downlink, LTE 800 Uplink and LTE 2600.

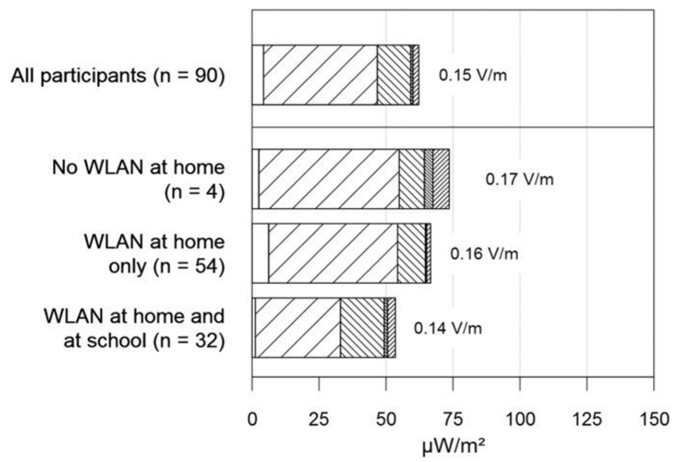

Fig. 4. Mean RF-EMF measurements for all participants (n = 90) and mean measurements for *No WLAN at home* (n = 4), *WLAN at home only* (n = 54) and *WLAN at home and in school* (n = 32). Total mean RF-EMF measurements per group are additionally added in V/m. The corresponding numbers and median values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

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/m^2 in cars, 676.3 μW/m^2 in buses and 537.1 μW/m^2 in trains) (Fig. 3 and Tables S1 and S2 in Supplementary material). The lowest measurements were measured at school (59.6 μW/m^2) and at home (31.1 μW/m^2).

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/m^2 vs. 1.5 μW/m^2). If the comparison was restricted to the measurements taken in the school, the difference was somewhat larger (7.4 μW/m^2 vs. 1.0 μW/m^2). Only four participants had no WLAN at home (thereof two had WLAN at school). Overall their mean WLAN measurements were higher (6.0 μW/m^2) than for the other two groups. However, their WLAN measurements at home were indeed minimal (0.02 W/m^2).

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/m^2). For the whole measurement period, the WLAN measurements were increased as well (2.6 vs. 0.7 μW/m^2).

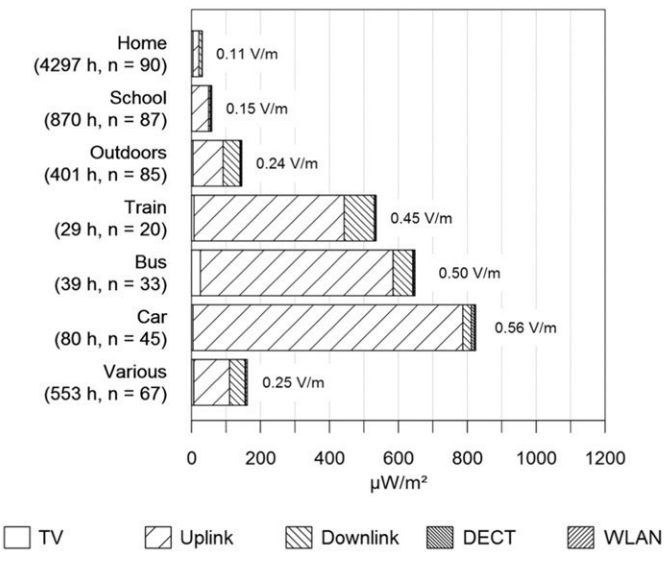

Fig. 3. Mean RF-EMF measurements from different sources at different locations. The hours in brackets indicate cumulative measurement duration at the corresponding location, n indicates the number of participants with measurements assigned to the location according to the diary. Total mean RF-EMF measurements 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.

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/m^2). The use of internet by mobile phone was associated with higher uplink measurements as well (45.3 vs. 8.9 μW/m^2). 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/m^2), but strikingly, the difference in WLAN measurements was marginal between these two groups (2.7 vs. 2.3 μW/m^2).

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/m^2) (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/m^2). 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

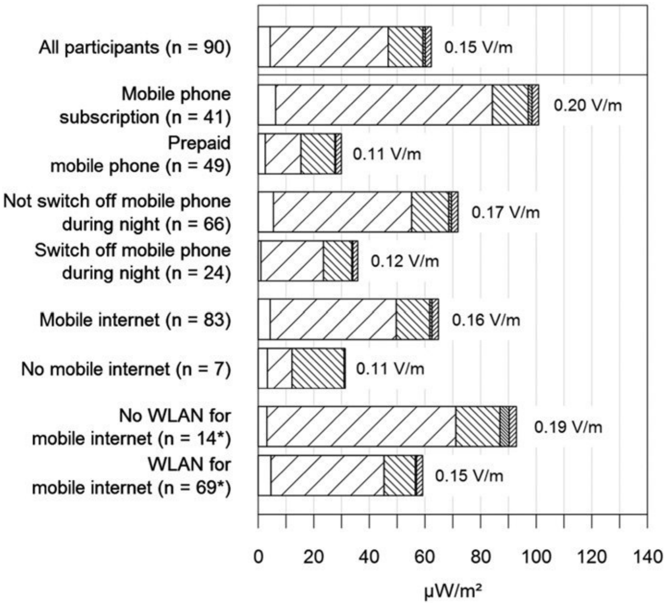

Fig. 5. Mean RF-EMF measurements for all participants and mean RF-EMF measurements for the mobile phone related factors having a mobile phone subscription (compared to using a prepaid mobile phone), not switching off the mobile phone during the night and the use of internet on the mobile phone (with 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 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.

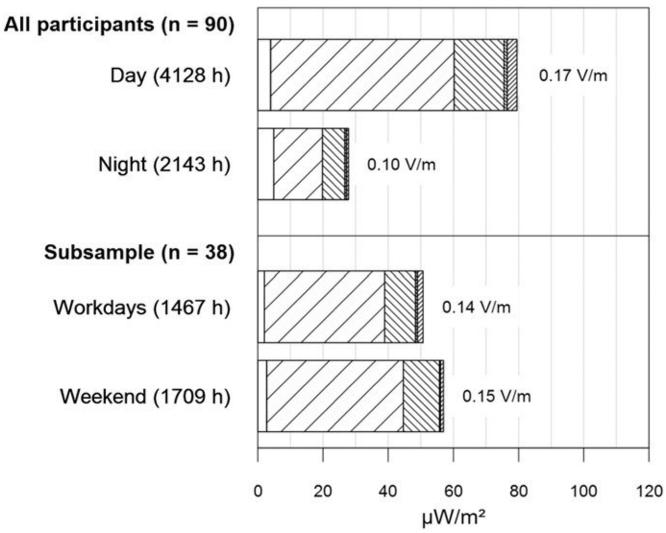

Fig. 6. Diurnal variation of mean RF-EMF measurements: For daytime and night-time ($n = 90$) and for workdays and weekend (n = 38) for different RF-EMF sources. Total mean RF-EMF measurements per time of the day and type of day are additionally added in V/m. The corresponding numbers and median values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

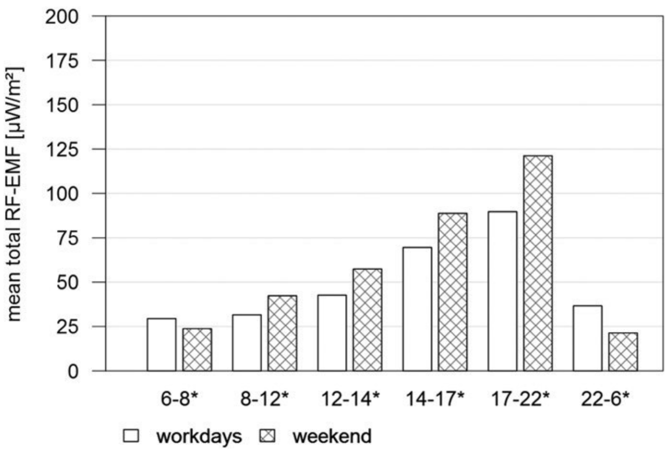

Fig. 7. Diurnal variation of the mean total RF-EMF measurements on workdays (white bars) and on weekends (shaded bars) based on data from the subsample of 38 participants with workdays and weekend measurements available. The corresponding numbers and median values can be found in Tables S9 in the Supplementary 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.

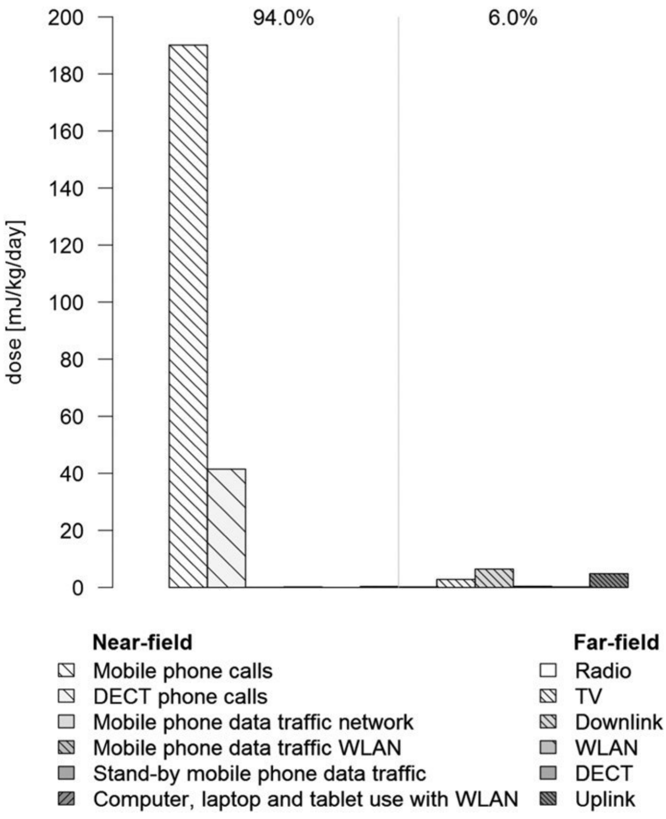

Fig. 8. Daily brain dose from the use of wireless communication devices (near-field dose; left side of the graph) and environmental sources (far-field dose; right side of the graph) for the typical (average) HERMES participant. *Numbers above the bars indicate the percentage of the near-field and the 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.

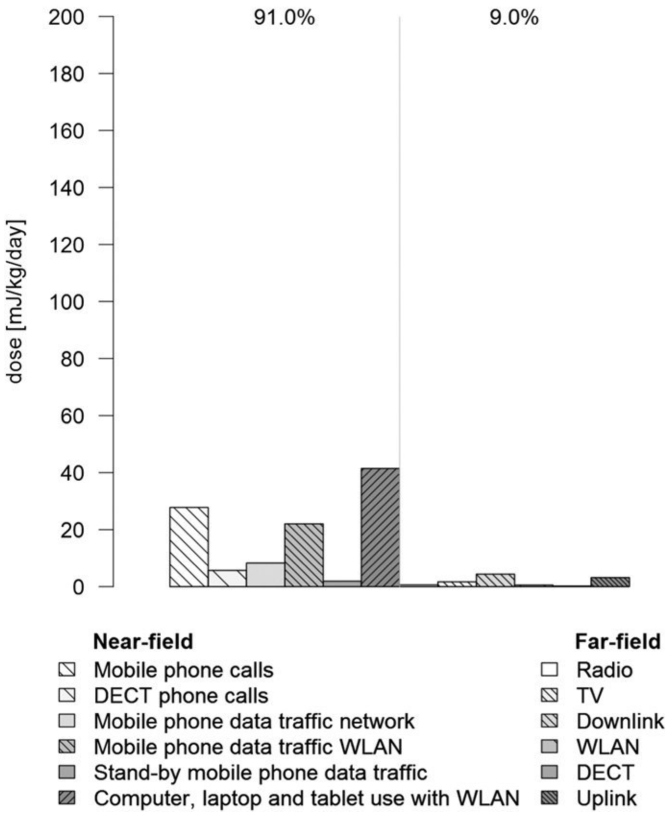

Fig. 9. Daily whole body dose from the use of wireless communication devices (near-field dose; left side of the graph) and environmental sources (far-field dose; right side of the graph) for the typical (average) HERMES participant. *Numbers above the bars indicate the percentage of the near-field and 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 μW/m^2 at home and 0.8 μW/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 μW/m^2 in German children to 180 μW/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 μW/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 μW/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 μW/m^2 what is similar to the German study. In newer studies in adults, higher exposure levels were measured: 130 μW/m^2 in Switzerland (Frei et al., 2009) and 180 μW/m^2 in the Netherlands (Bolte and Eikelboom, 2012) compared to 63.2 μW/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 μW/m^2 in trains, 676.3 μW/m^2 in buses and 839.4 μW/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 μW/m^2 in a Swiss measurement study (Frei et al., 2009), 354 μW/m^2 in the Netherlands (Bolte and Eikelboom, 2012) and 175 μW/m^2 in France (Viel et al., 2009). Measurements at home (31.1 μW/m^2 in our study) were in general lower compared to previous personal measurement studies (levels of 172 μW/m^2 (Bolte and Eikelboom, 2012), 100 μW/m^2 (Frei et al., 2009) and 106.2 μW/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/m^2 for households without DECT phone or an eco mode DECT phone compared to 420.7 μW/m^2 for households with a conventional DECT phone (Tomitsch and Dechant, 2015).

4.4. WLAN measurements

Our WLAN measurements (on average 2.2 μW/m^2) were similar to personal measurements in Switzerland (5.3 μW/m^2 (Frei et al., 2009)) and Germany (1.1 μW/m^2 (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/m^2). 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/m^2 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/m^2; for the remaining 7 participants not using internet on the mobile phone uplink exposure ranged from 0.7 to 17.7 μW/m^2.

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/m^2 (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.

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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.

References

Blas, J., Lago, F.A., Fernandez, P., Lorenzo, R.M., Abril, E.J., 2007. Potential exposure assessment errors associated with body-worn RF dosimeters. Bioelectromagnetics 28: 573–576. http://dx.doi.org/10.1002/bem.20355.

Bolte, J.F., 2016. Lessons learnt on biases and uncertainties in personal exposure measurement surveys of radiofrequency electromagnetic fields with exposimeters. Environ. Int. 94:724–735. http://dx.doi.org/10.1016/j.envint.2016.06.023.

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. http://dx.doi.org/10.1016/j.envint.2012.07.006.

Bolte, J.F., van der Zande, G., Kamer, J., 2011. Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields. Bioelectromagnetics 32:652–663. http://dx.doi.org/10.1002/bem.20677.

Breckenkamp, J., Blettner, M., Schuz, J., Bornkessel, C., Schmiedel, S., Schlehofer, B., Berg-Beckhoff, G., 2012. Residential characteristics and radiofrequency electromagnetic field exposures from bedroom measurements in Germany. Radiat. Environ. Biophys. 51:85–92. http://dx.doi.org/10.1007/s00411-011-0389-2.

Bürgi, A., Theis, G., Siegenthaler, A., Röösli, M., 2008. Exposure modeling of high-frequency electromagnetic fields. J. Expo. Sci. Environ. Epidemiol. 18:183–191. http://dx.doi.org/10.1038/sj.jes.7500575.

Bürgi, A., Frei, P., Theis, G., Mohler, E., Braun-Fahrländer, C., Fröhlich, J., Neubauer, G., Egger, M., Röösli, M., 2010. A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research. Bioelectromagnetics 31:226–236. http://dx.doi.org/10.1002/bem.20552.

Fields at Work, 2015. ExpoM-RF User Manual (Version 2.1) (http://www.fieldsatwork.ch/uploads/Downloads/Expom_RF_Manual-EN_v2.1.pdf).

Frei, P., Mohler, E., Neubauer, G., Theis, G., Bürgi, A., Fröhlich, J., Braun-Fahrländer, C., Bolte, J., Egger, M., Röösli, M., 2009. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. Environ. Res. 109:779–785. http://dx.doi.org/10.1016/j.envres.2009.04.015.

Frei, P., Mohler, E., Bürgi, A., Fröhlich, J., Neubauer, G., Braun-Fahrlander, C., Röösli, M., 2010. Classification of personal exposure to radio frequency electromagnetic fields (RF-EMF) for epidemiological research: evaluation of different exposure assessment methods. Environ. Int. 36:714–720. http://dx.doi.org/10.1016/j.envint.2010.05.005.

Gati, A., Hadjem, A., Man-Fai, W., Wiart, J., 2009. Exposure induced by WCDMA mobiles phones in operating networks. IEEE Trans. Wirel. Commun. 8:5723–5727. http://dx.doi.org/10.1109/TWC.2009.12.080758.

Gryz, K., Zradzinski, P., Karpowicz, J., 2015. The role of the location of personal exposimeters on the human body in their use for assessing exposure to the electromagnetic field in the radiofrequency range 98–2450 MHz and compliance analysis: evaluation by virtual measurements. Biomed. Res. Int. 2015 (272460). http://dx.doi.org/10.1155/2015/272460.

Hadjem, A., Conil, E., Gati, A., Wong, M.-F., Wiart, J., 2010. Analysis of power absorbed by children's head as a result of new usages of mobile phone. IEEE Trans. Electromagn. Compat. 52, 812–819.

Helsel, D.R., 2005. Nondetects and Data Analysis: Statistics for Censored Environmental Data. Wiley-Interscience.

Huang, Y., Wiart, J., Varsier, N., Person, C., 2014. Sensitivity Analysis of Downlink Received and Uplink Emitted Powers in a Geographical Area to ICT Usage Parameters. Paper Presented at the Proceedings of the Annual Meeting of BEMS and EBEA, Capetown, South Africa (June 8–13).

ICT, 2015. ICT Facts & Figures. The World in 2015 (http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2015.pdf).

Inyang, I., Benke, G., McKenzie, R., Abramson, M., 2008. Comparison of measuring instruments for radiofrequency radiation from mobile telephones in epidemiological studies: implications for exposure assessment. J. Expo. Sci. Environ. Epidemiol. 18: 134–141. http://dx.doi.org/10.1038/sj.jes.7500555.

Iskra, S., McKenzie, R., Cosic, I., 2010. Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry. Radiat. Prot. Dosim. 140: 25–33. http://dx.doi.org/10.1093/rpd/ncp309.

Joseph, W., Vermeeren, G., Verloock, L., Heredia, M.M., Martens, L., 2008. Characterization of personal RF electromagnetic field exposure and actual absorption for the general public. Health Phys. 95:317–330. http://dx.doi.org/10.1097/01.hp.0000318880.16023.61.

Juhasz, P., Bakos, J., Nagy, N., Janossy, G., Finta, V., Thuroczy, G., 2011. RF personal exposimetry on employees of elementary schools, kindergartens and day nurseries as a proxy for child exposures. Prog. Biophys. Mol. Biol. 107:449–455. http://dx.doi.org/10.1016/j.pbiomolbio.2011.09.020.

Lauer, O., Leidenberger, P., Müri, M., Zahner, M., Fröhlich, J., 2011. A Novel Measurement System for Environmental Exposure Monitoring. Paper Presented at the ACM SenSys 2011, Seattle, WA, USA.

Lauer, O., Neubauer, G., Röösli, M., Riederer, M., Frei, P., Mohler, E., Fröhlich, J., 2012. Measurement setup and protocol for characterizing and testing radio frequency personal exposure meters. Bioelectromagnetics 33:75–85. http://dx.doi.org/10.1002/bem.20687.

Lauer, O., Frei, P., Gosselin, M.C., Joseph, W., Röösli, M., Fröhlich, J., 2013. Combining near- and far-field exposure for an organ-specific and whole-body RF-EMF proxy for epidemiological research: a reference case. Bioelectromagnetics 34:366–374. http://dx.doi.org/10.1002/bem.21782.

Neubauer, G., Cecil, S., Giczi, W., Petric, B., Preiner, P., Fröhlich, J., Röösli, M., 2010. The association between exposure determined by radiofrequency personal exposimeters and human exposure: a simulation study. Bioelectromagnetics 31:535–545. http://dx.doi.org/10.1002/bem.20587.

Persson, T., Tornevik, C., Larsson, L.E., Loven, J., 2012. Output power distributions of terminals in a 3G mobile communication network. Bioelectromagnetics 33:320–325. http://dx.doi.org/10.1002/bem.20710.

Röösli, M., Frei, P., Bolte, J., Neubauer, G., Cardis, E., Feychting, M., Gajsek, P., Heinrich, S., Joseph, W., Mann, S., et al., 2010. Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environ. Health 9 (23). http://dx.doi.org/10.1186/1476-069x-9-23.

Roser, K., Schoeni, A., Bürgi, A., Röösli, M., 2015a. Development of an RF-EMF exposure surrogate for epidemiologic research. Int. J. Environ. Res. Public Health 12, 5634–5656.

Roser, K., Schoeni, A., Foerster, M., Röösli, M., 2015b. Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour? Int. J. Public Health http://dx.doi.org/10.1007/s00038-015-0751-2.

Roser, K., Schoeni, A., Roosli, M., 2016. Mobile phone use, behavioural problems and concentration capacity in adolescents: a prospective study. Int. J. Hyg. Environ. Health 219:759–769. http://dx.doi.org/10.1016/j.ijheh.2016.08.007.

Schoeni, A., Roser, K., Röösli, M., 2015a. Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: a prospective cohort study in adolescents. Environ. Int. 85:343–351. http://dx.doi.org/10.1016/j.envint.2015.09.025.

Schoeni, A., Roser, K., Röösli, M., 2015b. Symptoms and cognitive functions in adolescents in relation to mobile phone use during night. PLoS One 10, e0133528. http://dx.doi.org/10.1371/journal.pone.0133528.

Schoeni, A., Roser, K., Burgi, A., Röösli, M., 2016. Symptoms in Swiss adolescents in relation to exposure from fixed site transmitters: a prospective cohort study. Environ. Health 15 (77). http://dx.doi.org/10.1186/s12940-016-0158-4.
SEAWIND Sound Exposure & Risk Assessment of Wireless Network Devices Final Summary Report, 2013r. http://seawind-fp7.eu/uploads/SEAWIND_FINAL.pdf.
Thomas, S., Kuhnlein, A., Heinrich, S., Praml, G., Nowak, D., von Kries, R., Radon, K., 2008a. Personal exposure to mobile phone frequencies and well-being in adults: a cross-sectional study based on dosimetry. Bioelectromagnetics 29:463–470. http://dx.doi.org/10.1002/bem.20414.
Thomas, S., Kuhnlein, A., Heinrich, S., Praml, G., von Kries, R., Radon, K., 2008b. Exposure to mobile telecommunication networks assessed using personal dosimetry and well-being in children and adolescents: the German MobilEe-study. Environ. Health 7 (54). http://dx.doi.org/10.1186/1476-069x-7-54.
Thuróczy, G., Molnár, F., Jánossy, G., Nagy, N., Kubinyi, G., Bakos, J., Szabó†, J., 2008. Personal RF exposimetry in urban area annals of telecommunications. Ann. Telecommun. 63:87–96. http://dx.doi.org/10.1007/s12243-007-0008-z.
Tomitsch, J., Dechant, E., 2015. Exposure to electromagnetic fields in households–trends from 2006 to 2012. Bioelectromagnetics 36:77–85. http://dx.doi.org/10.1002/bem.21887.
Tomitsch, J., Dechant, E., Frank, W., 2010. Survey of electromagnetic field exposure in bedrooms of residences in lower Austria. Bioelectromagnetics 31:200–208. http://dx.doi.org/10.1002/bem.20548.
Urbinello, D., Röösli, M., 2013. Impact of one's own mobile phone in stand-by mode on personal radiofrequency electromagnetic field exposure. J. Expo. Sci. Environ. Epidemiol. 23:545–548. http://dx.doi.org/10.1038/jes.2012.97.
Urbinello, D., Joseph, W., Verloock, L., Martens, L., Röösli, M., 2014. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. Environ. Res. 134:134–142. http://dx.doi.org/10.1016/j.envres.2014.07.003.
Valic, B., Trcek, T., Gajsek, P., 2009. Personal Exposure to High Frequency Electromagnetic Fields in Slovenia. Paper Presented at the Joint Meeting of the Bioelectromagnetics Society and the European Bio Electromagnetics Association, Davos, Switzerland, 14–19 June 2009.
Valic, B., Kos, B., Gajsek, P., 2015. Typical exposure of children to EMF: exposimetry and dosimetry. Radiat. Prot. Dosim. 163:70–80. http://dx.doi.org/10.1093/rpd/ncu057.
Verloock, L., Joseph, W., Goeminne, F., Martens, L., Verlaek, M., Constandt, K., 2014a. Assessment of radio frequency exposures in schools, homes, and public places in Belgium. Health Phys. 107:503–513. http://dx.doi.org/10.1097/hp.0000000000000149.
Verloock, L., Joseph, W., Goeminne, F., Martens, L., Verlaek, M., Constandt, K., 2014b. Temporal 24-hour assessment of radio frequency exposure in schools and homes. Measurement 56:50–57. http://dx.doi.org/10.1016/j.measurement.2014.06.012.
Vermeeren, G., Markakis, I., Goeminne, F., Samaras, T., Martens, L., Joseph, W., 2013. Spatial and temporal RF electromagnetic field exposure of children and adults in indoor micro environments in Belgium and Greece. Prog. Biophys. Mol. Biol. 113:254–263. http://dx.doi.org/10.1016/j.pbiomolbio.2013.07.002.
Viel, J.F., Cardis, E., Moissonnier, M., de Seze, R., Hours, M., 2009. Radiofrequency exposure in the French general population: band, time, location and activity variability. Environ. Int. 35:1150–1154. http://dx.doi.org/10.1016/j.envint.2009.07.007.
WHO, 2010. WHO Research Agenda for Radiofrequency Fields.
Willemse, I., Waller, G., Süss, D., 2014. JAMES Jugend, Aktivitäten, Medien - Erhebung Schweiz, Factsheet Befunde 2014. Zurich University of Applied Sciences.

Supplementary Material

Environment International

Personal radiofrequency electromagnetic field exposure measurements in Swiss adolescents

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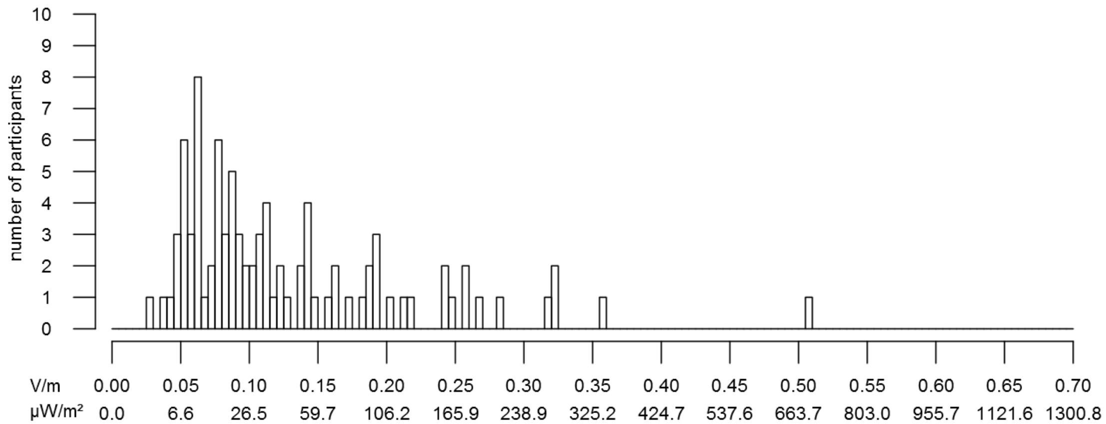
Radiofrequency electromagnetic fields dose modelling approach

Sources emitting radiofrequency electromagnetic fields (RF-EMF) are everywhere, in the near-field, close to the body and in the far-field, further away from the body. To combine the exposure from these different sources to one single brain and whole body measure a cumulative RF-EMF exposure surrogate was developed. Near-field sources included wireless communication devices used close to the body such as mobile phones for calls and data exchange, cordless phones and computers, laptops and tablets connected to WLAN. Far-field sources included environmental sources such as fixed site transmitters (mobile phone base stations and radio and TV broadcast transmitters), cordless phone base stations, WLAN access points as well as mobile phones in the surroundings. To combine these different sources, we calculated the daily dose originating from each of these sources. These contributions were then summed up to one cumulative daily dose measure for the brain and the whole body. For the use of devices, reported durations from the questionnaire were combined with SAR values derived from the literature. For the environmental sources, levels of the incident fields were estimated using geospatial propagation modelling for fixed site transmitters and multivariable regression modelling calibrated on personal measurements for DECT and WLAN exposure and exposure from other mobile phones. The RF-EMF exposure surrogate is presented and discussed in Roser et al. (2015).

Mean total RF-EMF measurements

Figure S1: Distribution of the mean total personal RF-EMF measurements (in V/m and with an additional axis in µW/m²) of the 90 study participants. Mean = 63.2 µW/m² (0.15 V/m), median = 25.5 µW/m² (0.10 V/m).



Personal measurements at different locations

Table S1: Mean RF-EMF measurements from different sources for the whole measurement location and at different locations. The hours in brackets indicate the cumulative measurement duration at the corresponding location, n indicates the number of participants with measurements assigned to the location according to the diary.

	mean [µW/m²]						mean [V/m]
Location	**TV**	**Uplink**	**Downlink**	**DECT**	**WLAN**	**Total [1]**	**Total [1]**
Whole measurement period (6269 h, n = 90)	4.26	42.49	12.50	0.83	2.18	63.23	0.15
Home (4297 h, n = 90)	4.26	17.35	8.09	0.47	0.72	31.13	0.11
School (870 h, n = 87)	0.42	49.15	5.36	0.73	3.27	59.57	0.15
Outdoors (401 h, n = 85)	4.30	86.86	49.55	1.62	3.23	147.07	0.24
Train (29 h, n = 20)	7.25	435.98	87.44	4.11	0.89	537.08	0.45
Bus (39 h, n = 33)	25.41	559.41	56.63	3.59	3.83	676.30	0.50
Car (80 h, n = 45)	4.38	782.40	24.82	9.17	3.84	839.38	0.56
Various (553 h, n = 67)	6.36	104.04	44.76	1.55	4.77	165.04	0.25

Table S2: Median RF-EMF measurements from different sources for the whole measurement period and at different locations. The hours in brackets indicate the cumulative measurement duration at the corresponding location, n indicates the number of participants with measurements assigned to the location according to the diary.

	median [µW/m²]						median [V/m]
Location	**TV**	**Uplink**	**Downlink**	**DECT**	**WLAN**	**Total [1]**	**Total [1]**
Whole measurement period (6269 h, n = 90)	0.62	12.15	5.07	0.07	0.56	25.49	0.10
Home (4297 h, n = 90)	0.51	1.33	1.51	0.02	0.23	9.94	0.06
School (870 h, n = 87)	0.08	9.19	1.77	0.03	0.41	18.09	0.08
Outdoors (401 h, n = 85)	1.32	9.97	14.68	0.05	0.25	48.98	0.14
Train (29 h, n = 20)	1.36	219.08	49.07	0.83	0.43	344.02	0.36
Bus (39 h, n = 33)	3.53	125.12	11.96	0.08	0.34	173.51	0.26
Car (80 h, n = 45)	1.16	20.86	12.39	0.06	0.50	59.25	0.15
Various (553 h, n = 67)	0.38	8.52	5.00	0.03	0.25	39.78	0.12

WLAN at school and at home

Table S3: Total 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 at school* (n = 32).

	mean [µW/m²]					
	TV	**Uplink**	**Downlink**	**DECT**	**WLAN**	**Total**
All participants (n = 90)	4.26	42.49	12.50	0.83	2.18	63.23
No WLAN at home (n = 4)	2.53	52.43	9.38	3.17	6.02	80.71
WLAN at home only (n = 54)	6.20	48.11	10.42	0.43	1.46	67.41
WLAN at home and at school (n = 32)	1.21	31.76	16.40	1.20	2.92	54.00

Table S4: Total median RF-EMF measurements for all participants (n = 90) and median measurements for *No WLAN at home* (n = 4), *WLAN at home only* (n = 54) and *WLAN at home and at school* (n = 32).

	median [µW/m²]					
	TV	**Uplink**	**Downlink**	**DECT**	**WLAN**	**Total**
All participants (n = 90)	0.62	12.15	5.07	0.07	0.56	25.49
No WLAN at home (n = 4)	2.68	10.88	7.70	0.89	0.08	18.50
WLAN at home only (n = 54)	0.95	12.15	3.86	0.07	0.55	25.49
WLAN at home and at school (n = 32)	0.52	10.62	8.45	0.07	0.68	32.08

Mobile phone use related factors

Table S5: Mean total RF-EMF measurements for all participants and mean RF-EMF measurements for the mobile phone related factors having a subscription, not switching off the mobile phone during night and use of internet on the mobile phone (with and without WLAN).

	mean [μW/m²]					
	TV	Uplink	Downlink	DECT	WLAN	Total
All participants (n = 90)	4.26	42.49	12.50	0.83	2.18	63.23
Mobile phone subscription (n = 41)	6.29	77.97	12.82	1.45	2.35	102.57
Prepaid mobile phone (n = 49)	2.57	12.80	12.23	0.30	2.04	30.32
Not switch off mobile phone during night (n = 66)	5.46	49.77	13.29	1.02	2.31	72.88
Switch off mobile phone during night (n = 24)	0.98	22.45	10.32	0.28	1.84	36.71
Mobile internet (n = 83)	4.34	45.32	11.97	0.89	2.34	65.91
No mobile internet (n = 7)	3.31	8.88	18.70	0.08	0.35	31.52
No WLAN for mobile internet (n = 14*)	3.09	68.05	15.80	3.29	2.66	95.47
WLAN for mobile internet (n = 69*)	4.60	40.71	11.20	0.40	2.27	59.91

* 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).

Table S6: Median total RF-EMF measurements for all participants and median RF-EMF measurements for the mobile phone related factors having a subscription, not switching off the mobile phone during night and use of internet on the mobile phone (with and without WLAN).

	median [μW/m²]					
	TV	Uplink	Downlink	DECT	WLAN	Total
All participants (n = 90)	0.62	12.15	5.07	0.07	0.56	25.49
Mobile phone subscription (n = 41)	0.58	27.73	5.16	0.16	0.73	49.26
Prepaid mobile phone (n = 49)	0.77	6.11	4.85	0.04	0.52	19.59
Not switch off mobile phone during night (n = 66)	0.69	11.39	5.26	0.08	0.61	30.70
Switch off mobile phone during night (n = 24)	0.54	13.25	3.36	0.07	0.55	19.51
Mobile internet (n = 83)	0.60	13.21	4.85	0.09	0.62	26.59
No mobile internet (n = 7)	1.30	9.44	12.93	0.04	0.28	23.81
No WLAN for mobile internet (n = 14*)	1.63	23.74	8.54	0.93	0.57	32.79
WLAN for mobile internet (n = 69*)	0.58	10.38	4.08	0.06	0.62	23.55

* 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).

Diurnal variation of personal measurements

Table S7: 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.

	mean [µW/m²]					
	TV	Uplink	Downlink	DECT	WLAN	Total
Day	3.93	56.27	15.32	0.97	2.99	80.81
Night	4.91	14.94	6.86	0.54	0.57	28.08
Workdays *	2.00	36.92	9.50	0.59	1.71	51.01
Weekend *	2.74	41.91	11.11	0.28	0.91	57.28

* Note that the comparison of workdays and weekend is based on the data from the subsample of 38 participants with workdays and weekend measurements available.

Table S8: Diurnal variation of median RF-EMF measurements: For daytime and night-time (n = 90) and for workdays and weekend (n = 38) for different RF-EMF sources.

	median [µW/m²]					
	TV	Uplink	Downlink	DECT	WLAN	Total
Day	0.70	14.71	5.85	0.09	0.72	31.27
Night	0.68	0.57	1.46	0.02	0.12	8.72
Workdays *	0.74	5.29	3.40	0.03	0.47	15.34
Weekend *	0.57	4.15	4.53	0.02	0.27	17.89

* Note that the comparison of workdays and weekend is based on the data from the subsample of 38 participants with workdays and weekend measurements available.

Table S9: Diurnal variation of the mean and median total RF-EMF measurements on workdays and on weekends based on data from the subsample of 38 participants with workdays and weekend measurements available.

	mean [µW/m²]						median [µW/m²]					
	06-08*	08-12*	12-14*	14-17*	17-22*	22-06*	06-08*	08-12*	12-14*	14-17*	17-22*	22-06*
Workdays	29.50	31.54	42.65	69.57	89.74	36.59	0.014	0.008	0.011	0.016	0.016	0.009
Weekend	23.72	42.31	57.40	88.81	121.27	21.32	0.005	0.013	0.014	0.015	0.014	0.007

* 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.

Use of personal measurements for dose estimations

Table S10: Daily dose from the use of wireless communication devices (near-field dose) and environmental sources (far-field dose) for the brain and the whole body for the typical (average) HERMES participant. *

	Brain dose		**Whole body dose**	
	daily dose [mJ/kg/day] (percentage on total dose [%])		**daily dose [mJ/kg/day] (percentage on total dose [%])**	
Total	246.96		117.62	
Near-field	232.15	(94.00)	107.09	(91.05)
Mobile phone calls	190.10	(76.98)	27.73	(23.58)
DECT phone calls	41.48	(16.80)	5.67	(4.82)
Mobile phone data traffic network	0.06	(0.02)	8.29	(7.05)
Mobile phone data traffic WLAN	0.17	(0.07)	22.03	(18.73)
Stand-by mobile phone data traffic	0.01	(0.00)	1.91	(1.62)
Computer, laptop and tables use with WLAN	0.32	(0.13)	41.46	(35.25)
Far-field	14.81	(6.00)	10.53	(8.95)
Radio	0.19	(0.08)	0.64	(0.54)
TV	2.80	(1.13)	1.68	(1.43)
Downlink	6.41	(2.60)	4.33	(3.68)
WLAN	0.43	(0.17)	0.53	(0.45)
DECT	0.21	(0.09)	0.21	(0.18)
Uplink	4.78	(1.94)	3.14	(2.67)

* 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.

Sensitivity Analyses

Diary cleaning

Table S11: Percentage change in the RF-EMF measurements for the different sources and the different locations of the cleaned diaries compared to an analysis based on the original (uncleaned) diary entries. A positive change means higher measurements for the locations of the cleaned diaries whereas a negative change means lower measurements for the locations of the cleaned diaries.

Location	percentage change [%]					
	TV	Uplink	Downlink	DECT	WLAN	Total
Home	1.56	-8.67	1.86	-0.51	-2.87	-4.24
School	-2.83	8.05	-20.77	-0.64	1.21	4.85
Outdoors	6.20	0.27	5.34	1.12	13.26	2.50
Train	1.88	-23.16	19.12	12.48	-10.54	-15.73
Bus	5.20	22.53	32.78	20.73	18.89	22.50
Car	20.69	-2.73	-13.34	18.25	-8.39	-2.65
Various	-25.07	-2.48	33.39	-1.50	-3.83	6.26

DECT correction algorithm

Table S12: Distribution of the DECT and total RF-EMF measurements for the whole measurement period without and with DECT correction (μW/m²). The numbers in bracket indicate the reduction factor (uncorrected/corrected).

Frequency band	DECT correction	mean		min		median		max	
DECT	**uncorrected**	4.78		0.02		0.27		207.95	
	corrected	0.83	(5.76)	0.02	(1.00)	0.07	(3.86)	14.71	(14.14)
Downlink 1800	**uncorrected**	1.49		0.04		0.62		19.51	
	corrected	1.42	(1.05)	0.04	(1.00)	0.62	(1.00)	19.45	(1.00)
Uplink 1900	**uncorrected**	10.74		0.01		0.81		373.52	
	corrected	10.67	(1.01)	0.01	(1.00)	0.81	(1.00)	373.49	(1.00)
Total	**uncorrected**	67.32		1.79		26.34		890.52	
	corrected	63.23	(1.06)	1.78	(1.01)	25.49	(1.03)	682.90	(1.30)

Table S13: Distribution of the uncorrected and corrected DECT measurements at different locations (μW/m²). The numbers in bracket indicate the reduction factor (uncorrected/corrected).

Location	DECT correction	mean		min		median		max	
Home	**uncorrected**	1.25		0.02		0.07		54.68	
	corrected	0.47	(2.66)	0.02	(1.00)	0.02	(3.50)	21.88	(2.50)
School	**uncorrected**	4.68		0.02		0.07		169.69	
	corrected	0.73	(6.41)	0.02	(1.00)	0.03	(2.33)	18.92	(8.97)
Outdoors	**uncorrected**	4.66		0.02		0.24		99.39	
	corrected	1.62	(2.88)	0.02	(1.00)	0.05	(4.80)	84.60	(1.17)
Train	**uncorrected**	35.10		0.38		4.78		261.39	
	corrected	4.11	(8.54)	0.02	(19.00)	0.83	(5.76)	58.48	(4.47)
Bus	**uncorrected**	132.17		0.03		3.22		3'736.04	
	corrected	3.59	(36.82)	0.02	(1.50)	0.08	(40.25)	48.48	(77.06)
Car	**uncorrected**	137.38		0.02		0.34		5'298.42	
	corrected	9.17	(14.98)	0.02	(1.00)	0.06	(5.67)	197.91	(26.77)
Various	**uncorrected**	16.30		0.02		0.23		728.85	
	corrected	1.55	(10.52)	0.02	(1.00)	0.03	(7.67)	35.33	(20.63)

Table S14: Distribution of the uncorrected and corrected Downlink 1800 measurements at different locations (μW/m²). The numbers in bracket indicate the reduction factor (uncorrected/corrected).

Location	DECT correction	mean		min		median		max	
Home	**uncorrected**	0.70		0.02		0.21		11.79	
	corrected	0.68	(1.03)	0.02	(1.00)	0.21	(1.00)	11.79	(1.00)
School	**uncorrected**	0.66		0.02		0.30		4.42	
	corrected	0.62	(1.06)	0.02	(1.00)	0.29	(1.03)	4.42	(1.00)
Outdoors	**uncorrected**	5.13		0.03		3.02		52.76	
	corrected	5.05	(1.02)	0.02	(1.50)	3.01	(1.00)	50.84	(1.04)
Train	**uncorrected**	8.49		0.19		4.12		47.11	
	corrected	7.98	(1.06)	0.14	(1.36)	4.11	(1.00)	47.11	(1.00)
Bus	**uncorrected**	7.76		0.05		1.60		65.59	
	corrected	7.36	(1.05)	0.04	(1.25)	1.60	(1.00)	54.23	(1.21)
Car	**uncorrected**	5.09		0.02		1.57		78.66	
	corrected	5.00	(1.02)	0.02	(1.00)	1.52	(1.03)	78.66	(1.00)
Various	**uncorrected**	9.89		0.02		0.64		308.30	
	corrected	9.77	(1.01)	0.02	(1.00)	0.64	(1.00)	308.30	(1.00)

Table S15: Distribution of the uncorrected and corrected Uplink 1900 measurements at different locations (μW/m²). The numbers in bracket indicate the reduction factor (uncorrected/corrected).

Location	DECT correction	mean		min		median		max	
Home	**uncorrected**	4.58		0.01		0.02		139.78	
	corrected	4.55	(1.01)	0.01	(1.00)	0.02	(1.00)	138.99	(1.01)
School	**uncorrected**	9.30		0.01		0.28		293.04	
	corrected	9.21	(1.01)	0.01	(1.00)	0.28	(1.00)	293.02	(1.00)
Outdoors	**uncorrected**	7.13		0.01		0.37		134.02	
	corrected	7.03	(1.01)	0.01	(1.00)	0.37	(1.00)	133.85	(1.00)
Train	**uncorrected**	92.43		7.69		31.85		665.22	
	corrected	92.38	(1.00)	7.69	(1.00)	31.83	(1.00)	665.22	(1.00)
Bus	**uncorrected**	232.50		0.01		7.16		6'219.86	
	corrected	231.81	(1.00)	0.01	(1.00)	7.16	(1.00)	6'219.82	(1.00)
Car	**uncorrected**	165.60		0.01		0.82		6'006.53	
	corrected	165.32	(1.00)	0.01	(1.00)	0.81	(1.01)	6'005.14	(1.00)
Various	**uncorrected**	29.89		0.01		0.41		1'509.97	
	corrected	29.54	(1.01)	0.01	(1.00)	0.30	(1.37)	1'509.96	(1.00)

Table S16: Distribution of the uncorrected and corrected Total measurements at different locations (μW/m²). The numbers in bracket indicate the reduction factor (uncorrected/corrected).

Location	DECT correction	mean		min		median		max	
Home	**uncorrected**	31.96		1.30		10.03		299.50	
	corrected	31.13	(1.03)	1.29	(1.01)	9.94	(1.01)	299.44	(1.00)
School	**uncorrected**	63.65		1.09		18.39		1'267.94	
	corrected	59.57	(1.07)	1.08	(1.01)	18.09	(1.02)	1'267.92	(1.00)
Outdoors	**uncorrected**	150.30		2.37		49.33		1'496.97	
	corrected	147.07	(1.02)	2.36	(1.00)	48.98	(1.01)	1'476.22	(1.01)
Train	**uncorrected**	568.64		147.85		387.06		2'297.38	
	corrected	537.08	(1.06)	124.38	(1.19)	344.02	(1.13)	2'295.21	(1.00)
Bus	**uncorrected**	805.96		13.13		180.72		14'102.44	
	corrected	676.30	(1.19)	12.89	(1.02)	173.51	(1.04)	10'376.28	(1.36)
Car	**uncorrected**	967.96		0.60		59.31		33'119.52	
	corrected	839.38	(1.15)	0.60	(1.00)	59.25	(1.00)	27'823.61	(1.19)
Various	**uncorrected**	180.26		0.57		40.10		2'329.35	
	corrected	165.04	(1.09)	0.57	(1.00)	39.78	(1.01)	1'600.96	(1.45)

References

Roser K., Schoeni A., Bürgi A., Röösli M., 2015. Development of an RF-EMF Exposure Surrogate for Epidemiologic Research. Int J. Environ. Res. Public Health 12, 5634-5656.

6 Integrative RF-EMF dose measure combining near-field and far-field exposure

Article 4: Development of an RF-EMF Exposure Surrogate for Epidemiologic Research

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Article

Development of an RF-EMF Exposure Surrogate for Epidemiologic Research

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Abstract: Exposure assessment is a crucial part in studying potential effects of RF-EMF. Using data from the HERMES study on adolescents, we developed an integrative exposure surrogate combining near-field and far-field RF-EMF exposure in a single brain and whole-body exposure measure. Contributions from far-field sources were modelled by propagation modelling and multivariable regression modelling using personal measurements. Contributions from near-field sources were assessed from both, questionnaires and mobile phone operator records. Mean cumulative brain and whole-body doses were 1559.7 mJ/kg and 339.9 mJ/kg per day, respectively. 98.4% of the brain dose originated from near-field sources, mainly from GSM mobile phone calls (93.1%) and from DECT phone calls (4.8%). Main contributors to the whole-body dose were GSM mobile phone calls (69.0%), use of computer, laptop and tablet connected to WLAN (12.2%) and data traffic on the mobile phone via WLAN (6.5%). The exposure from mobile phone base stations contributed 1.8% to the whole-body dose, while uplink exposure from other people's mobile phones contributed 3.6%. In conclusion, the proposed approach is considered useful to combine near-field and far-field exposure to an integrative exposure surrogate for exposure assessment in epidemiologic studies. However, substantial uncertainties remain about exposure contributions from various near-field and far-field sources.

Keywords: exposure assessment; RF-EMF; mobile phone; adolescents; dose calculation

1. Introduction

Mobile phones and other wireless communication devices using radiofrequency electromagnetic fields (RF-EMF) are an integral part in the everyday life of adolescents. Thus exposure to this radiation is ubiquitous and in studying potential effects of RF-EMF, exposure assessment is a crucial part in this field of research. Since there are a lot of different sources emitting RF-EMF in everyday life, one needs to find a way of combining all of these emissions to one single integrative exposure measure. On one hand there are near-field sources such as mobile phones, computers, laptops and tablets emitting close to the body. On the other hand far-field sources such as fixed site transmitters (mobile phone base stations and broadcast transmitters), Wireless Local Area Network (WLAN) base stations, Digital Enhanced Cordless Telecommunications (DECT) base stations and other mobile phones in the surrounding area contribute to the environmental exposure. So far, little attempts have been made to combine these different types of exposure to one single integrative measure.

In a German study, personal measurements in adolescents and adults have been conducted during 24 h to estimate RF-EMF exposure [1–3]. This approach considered all exposure sources in the environment. However, it is time-consuming and personal measurements may not adequately record exposure from near-field sources 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 [4,5]. Other studies focussed on far-field exposures only by using propagation models for fixed site transmitters [6–13]. Frei *et al.* combined modelled RF-EMF exposure from fixed site transmitters at home with personal exposure relevant characteristics and behaviour to estimate personal RF-EMF exposure [14]. In this study, the presence of concrete walls and metal window frames were found to modify RF-EMF exposure from fixed site transmitters. Additional exposure relevant factors included ownership of a mobile phone, ownership of a WLAN at home and having a DECT base station in the bedroom or at the place where the person spent most of their time during the day, time spent at an external workplace and hours per week spent in a train, tram or bus. However, this exposure proxy focussed on far-field sources only and near-field sources were separately considered in their epidemiological analyses on non-specific symptoms of ill health and RF-EMF exposure [15,16]. In the framework of the Interphone study, estimations of RF energy absorbed in the brain from mobile phones were assessed [17]. Lauer *et al.* calculated organ-specific and whole-body RF-EMF proxies taking into account far-field exposure from different sources and near-field exposure from calls on the mobile phone and on the DECT phone using data collected between 2007 and 2009 in Switzerland [18]. However, these data may already be outdated because in the meantime mobile phones have been developed in the direction of multifunctional devices used not only for making calls and sending text messages, but for many additional activities such as browsing the internet, watching videos and gaming. Thus, the exposure predictors are expected to have changed considerably, and a comprehensive overview of relevant factors influencing the RF-EMF exposure emitted by near-field and far-field sources is still missing. The aim of this study was to determine these relevant factors and to develop an integrative exposure assessment method combining near-field and far-field sources for the brain as well as for the whole-body RF-EMF exposure for epidemiologic research. As a result we present cumulative RF-EMF dose for adolescents of a Swiss epidemiologic study called Health Effects Related to Mobile phonE use in adolescentS (HERMES).

2. Methods

2.1. Hermes Study

The HERMES study, a cohort study conducted in Central Switzerland, aimed to prospectively investigate whether the exposure to RF-EMF emitted by mobile phones and other wireless communication devices affects cognitive functions or causes behavioural problems and non-specific health disturbances in adolescents. The investigation took place from June 2012 to March 2013. The study participants filled in a paper-and-pencil questionnaire during school time supervised by two study managers. The questionnaire included detailed questions about their mobile phone use, DECT phone use and computer, laptop and tablet use (in brackets are the corresponding near-field exposure predictors indicated):

- Duration of calls made and received with their own and other mobile phones (GSM and UMTS mobile phone calls);
- Proportion of calls with the mobile phone using a headset (GSM and UMTS mobile phone calls);
- Duration of mobile phone use for data traffic (mobile phone data traffic and mobile phone data traffic WLAN);
- Duration of carrying the mobile phone close to the body (mobile phone close to body);
- Duration of calls made and received with a DECT phone at home (DECT phone calls);
- Duration of computer, laptop and tablet use and WLAN connection of the corresponding devices (computer, laptop and tablet use with WLAN).

Additionally, they were asked about the time spent in trains and buses. Furthermore we distributed paper-and-pencil questionnaires for the parents and asked them to return these directly to the study managers. This questionnaire included questions about DECT phones, WLAN and number of smartphones at home and number of floors and floor location of the residence. In addition, the teacher or head of the school provided us with information about the availability of WLAN in the school and building characteristics of the school building (number of floors and the floor location of the class room the adolescents spent most of their school time). Informed consent was given by the study participants and their parents to obtain objective mobile phone use data from the mobile phone operators. Operator data included records for each call made and received including duration of call and network used when starting the call. The calls were categorised into calls on the Global System for Mobile Communications (GSM) network and on the Universal Mobile Telecommunications System (UMTS) network. There was no differentiation between GSM900 and GSM1800 network in the mobile phone operator data. Average proportions of network use for calls over the recorded time period were used in our analysis.

2.2. Personal Measurements in the Framework of the Hermes Study

A subgroup of the study participants also took part in personal measurements. The adolescents carried a portable measurement device, a so-called exposimeter, for three consecutive days. Two versions of the device Expom (referred to as *Expom 1* for the older version and *Expom 3* for the newer version) were used to measure 13 frequency bands ranging from Digital Video Broadcasting—Terrestrial (DVB-T, centre frequency of 620 MHz) to Worldwide Interoperability for Microwave Access (WiMa, 3500 MHz) [19]. Nine out of the 13 measured frequency bands were used in our analysis (Table 1).

Table 1. Frequency range, quantitation limits and reporting limits for the frequency bands of the measurement devices Expom 1 and Expom 3 used for the personal measurements.

Frequency Band	Frequency Range (MHz)	Quantitation Limit (V/m)		Reporting Limit (V/m)
	Expom 1 and Expom 3	Expom 1	Expom 3	Expom 1 and Expom 3
TV	470–790	0.010	0.005	0.0025
Uplink 900 *	880–915	0.015	0.005	0.0025
Downlink 900 *	925–960	0.015	0.005	0.0025
Uplink 1800 *	1710–1785	0.015	0.005	0.0025
Downlink 1800 *	1805–1880	0.005	0.005	0.0025
DECT	1880–1900	0.005	0.005	0.0025
Uplink 1900 *	1920–1980	0.003	0.003	0.0015
Downlink 2100 *	2110–2170	0.010	0.003	0.0015
WLAN	2400–2485	0.005	0.005	0.0025

* The uplink and downlink bands include all technologies using the particular frequency range. Downlink means the transmission from mobile phone base stations to mobile phone handsets and uplink the transmission from mobile phone handsets to mobile phone base stations.

Additionally, the participants filled in a time-activity diary installed as an application on a smartphone operating in flight mode. These diaries were manually corrected for implausible chronologies of diary entries. Subsequently, summary statistics were calculated after censoring the measurements at the reporting limit and 5 V/m.

2.3. Dose Calculations

We aimed to calculate personal cumulative RF-EMF doses in the brain and the whole-body combining exposure from different sources emitting RF-EMF. The processes of learning and memory are located in the hippocampus, while processes for behaviour and cognitive functions in the prefrontal cortex. The hippocampus and the prefrontal cortex consist mainly of gray matter. Therefore, specific absorption rates (SARs) for *brain gray matter* were used for the brain exposure. Additionally, the same calculations were performed for *brain white matter* and compared with the brain exposure obtained for brain gray matter since the white matter is important for these processes as well.

The personal dose in terms of the time-averaged specific absorption rate (SAR) can be calculated as follows:

$$\mathrm{dose} = \sum_{\mathrm{i}} \mathrm{dose_i} = \sum_{\mathrm{i}} \mathrm{SAR_i} * \mathrm{time_i} \quad (1)$$

with $dose_i$ (in mJ/kg) and SAR_i (in mW/kg) the dose and SAR originating from the exposure in a certain frequency band or due to a certain use of a specific wireless communcation device, and $time_i$ the duration of this exposure. Thus, the proposed integrative exposure surrogate consists of a near-field component combining the exposure from the use of wireless communication devices and a far-field component aggregating the exposure from environmental sources. Therefore, we calculated the total dose as follows:

$$\text{dose} = \text{near----field dose} + \text{far-field dose} \quad (2)$$

2.3.1. Near-Field Dose

For the near-field component, we considered *a priori* the following exposure predictors relevant:

$$\begin{aligned} \text{near-field dose} \\ &= \text{dose}_{\text{GSM mobile phone calls}} + \text{dose}_{\text{UMTS mobile phone calls}} \\ &+ \text{dose}_{\text{DECT phone calls}} + \text{dose}_{\text{mobile phone data traffic}} \\ &+ \text{dose}_{\text{mobile phone close to body}} + \text{dose}_{\text{mobile phone data traffic WLAN}} \\ &+ \text{dose}_{\text{computer,laptop and tablet use with WLAN}} \end{aligned} \quad (3)$$

The particular dose parts of the near-field component of the exposure surrogate (Equation (3)) can be calculated as follows:

$$\text{near-field dose}_i = \text{SAR}_i(\text{literature}) \times \text{time}_i(\text{HERMES questionnaire, operator data}) \quad (4)$$

where the SAR_i were derived from the literature [18,20–25] and the exposure durations $time_i$ were asked in the HERMES questionnaire. For participants with missing operator data, the proportion of network used for calls (GSM and UMTS) was estimated by regression modelling using the available mobile phone operator data from a subgroup of the study participants.

Derivation of the SARs

For the derivation of the SARs for the exposure circumstances in Equation (3) we combined the SARs provided from Lauer *et al.* for calls on the mobile phone and on the DECT phone [18] with the measured uplink output power from Persson *et al.* [24], Gati *et al.* [21] and Huang *et al.* [23]. Additionally, we took into account the SAR ranges presented in the SEAWIND Final Summary Report (referred to as *SEAWIND report*) [20].

For calls with a mobile phone Lauer *et al.* provide a brain (the *brain gray matter* values were used, referred to as *brain*) SAR of 3.198 mW/kg and a whole-body SAR of 0.411 mW/kg for GSM900/GSM1800 calls based on output powers derived from Vrijheid *et al.* for GSM900 and GSM1800 [25] (Table 2). For UMTS calls Lauer *et al.* calculated a brain SAR of 0.023 mW/kg and a whole-body SAR of 0.003 mW/kg using output power values from Gati *et al.* [21] and assuming half of the calls in buildings and the other half outdoors.

On average the SAR decreased by a factor of 1000 by having the device approximately 20 cm away from the body compared to a device touching the body [20]. Therefore, we used a brain SAR of 3.198×10^{-3} mW/kg for GSM900/GSM1800 calls with headset and a brain SAR of 0.023×10^{-3} mW/kg for UMTS calls with headset. For the whole-body exposure we used the same SAR for calls with and without headset referring to a similar distance to the body when having the mobile phone close to the ear or in front of the body while using a headset.

Table 2. Near-field *brain* and *whole-body* SARs, corresponding derivation and references for the near-field predictors.

Near-Field Predictor	Brain SAR		Whole-Body SAR		References
	(mW/kg)	Derivation	(mW/kg)	Derivation	
GSM [1] mobile phone calls without headset	3.198	−	0.411	−	[18]
GSM [1] mobile phone calls with headset	3.198×10^{-3}	3.198×0.001	0.411	0.411×1	[18,20]
UMTS mobile phone calls without headset	0.023	−	0.003	−	[18]
UMTS mobile phone calls with headset	0.023×10^{-3}	0.023×0.001	0.003	0.003×1	[18,20]
DECT phone calls without eco mode	0.373	−	0.051	−	[18]
DECT phone calls with eco mode	0.0373	0.373×0.1	0.0051	0.051×0.1	[18,20]
mobile phone data traffic with mobile internet connection	0.092×10^{-3}	$0.023 \times 4 \times 0.001$	0.012	$0.003 \times 4 \times 1$	[18,20–24]
mobile phone close to body (passive mobile phone data traffic)	0.092×10^{-3}	$0.023 \times 4 \times 0.001$	0.012	$0.003 \times 4 \times 1$	[18,20–24]
mobile phone data traffic with WLAN	0.092×10^{-3}	$0.023 \times 4 \times 0.001$	0.012	$0.003 \times 4 \times 1$	[18,20–24]
computer, laptop and tablet use with WLAN	0.092×10^{-3}	$0.023 \times 4 \times 0.001$	0.012	$0.003 \times 4 \times 1$	[18,20–24]

[1] For calls with the mobile phone on the GSM network the mean of the SARs for the GSM900 and the GSM1800 network was used because there was no differentiation between GSM900 and GSM1800 network in the mobile phone operator data.

For DECT phone calls Lauer *et al.* derived an average output power from the general transmission power of a DECT phone [18], resulting in a brain SAR of 0.373 mW/kg and a whole-body SAR of 0.051 mW/kg. The SEAWIND report showed a decrease in the SAR by a factor of 10 for calls with an eco mode DECT phone compared to a DECT phone without eco mode [20], therefore we used a brain SAR of 0.0373 mW/kg and a whole-body SAR of 0.0051 mW/kg for calls with a DECT phone provided with eco mode.

For the output power of mobile phones during data transmission we took the following available knowledge into account: Persson *et al.* measured on average an increased output power for data connections compared to voice connections in the UMTS network in the range of a factor of 3.25 to 6.8, depending on rural or urban environment and the bit rates used for the data transmission [24]. In the framework of the LEXNET project an output power increased by about a factor of 4 for data traffic service compared to voice service in the 3G network of Orange in France was found [23]. Gati *et al.* found a mean output power increased by about 6 dB on average for data traffic mode compared to voice mode [21]. Therefore, we used a by a factor of 4 increased output power of the mobile phone for data traffic compared to calls on the UMTS network. To take into account the different positions of the mobile phone during data traffic compared to those during calls (holding the mobile phone in the hand instead of close to the ear) we used the ranges delivered in the SEAWIND report for different distances between the device and the respective tissue [20]. The SAR decreased on average by a factor of 1000 by having the device approximately 20 cm away from the body compared to a device touching the body. Hadjem *et al.* found that the exposure for a mobile phone in watching-like position at 10 cm distance is about ten times below the exposure in voice position. At 40 cm distance it appeared that the exposure was about 1000 times lower [22]. These findings are comparable with the SAR ranges presented in the SEAWIND report for UMTS voice and UMTS data [20]. These considerations led us to use a brain SAR of 0.092 × 10^{-3} mW/kg for data traffic on the mobile phone via mobile internet connection. For the whole-body SAR we assumed that the mobile phone is held approximately at the same distance from the body for data traffic as for voice calls resulting in a whole-body SAR of 0.012 mW/kg for data traffic on the mobile phone via mobile internet connection.

Considering an approximately equal exposure for transmission of a fixed size data packet using UMTS or WLAN (SEAWIND report, page 3 [20]) we decided to use the same SAR for data traffic via WLAN as for data traffic via mobile internet connection for both the brain and the whole-body SAR.

For using a computer, laptop or tablet connected to the internet via WLAN we used the same SAR as for data traffic on the mobile phone using WLAN assuming approximately the same distance between the device and the brain and the body, respectively.

2.3.2. Far-Field Dose

The far-field component consisted of the following parts:

$$\begin{aligned}\text{far-field dose} = {} & \text{dose}_{\text{radio}} + \text{dose}_{\text{TV}} + \text{dose}_{\text{downlink 900}} + \text{dose}_{\text{downlink 1800}} \\ & + \text{dose}_{\text{downlink 2100}} + \text{dose}_{\text{WLAN}} + \text{dose}_{\text{DECT}} + \text{dose}_{\text{uplink}}\end{aligned} \quad (5)$$

where downlink means the transmission from mobile phone base stations to mobile phone handsets and uplink the transmission from mobile phone handsets to mobile phone base stations.

Far-field exposure from radio and TV broadcast transmitters and mobile phone base stations at home and in school were considered a priori relevant and were modelled using a geospatial propagation model [9,10]. Additionally, behaviours and characteristics relevant for the remaining far-field exposure parts (WLAN, DECT and uplink; Equation (5)) were estimated from the personal measurements. Far-field dose parts were obtained by multiplying the estimated power flux density with the normalized organ and frequency specific SAR derived from the literature [18] and the exposure duration obtained from the HERMES questionnaire or from the diary filled in during the personal measurements:

$$\begin{aligned}\text{far-field dose}_{\text{i}} = {} & \text{SAR}_{\text{i}}(\text{literature, modelling, personal measurements}) \\ & \times \text{time}_{\text{i}}(\text{HERMES questionnaire, personal measurements})\end{aligned} \quad (6)$$

Geospatial Propagation Model

Far-field exposure from fixed site transmitters was modelled using a geospatial propagation model based on a comprehensive database of transmitters, three-dimensional topography and a three-dimensional building model of the study area [9,10]. The coordinates of the home and the school addresses of the study participants were provided from the Swiss Federal Statistical Office. The number of floors of the building and the floor location of the residence and class room for calculating the height of the residence and class room were asked in the parents' and school questionnaire, respectively [9,14]. On average, a damping factor of 4.6 dB was used for outdoor-to-indoor modelling to take into account wall attenuation [9].

2.3.3. Multivariable Regression Models

Behaviours resulting in far-field exposure from WLAN base stations, DECT base stations and uplink of other mobile phones in the surroundings were identified by means of multivariable regression models using non-parametric bootstrap to estimate the coefficients. In these models, personal measurements were used as dependent variables. The explanatory variables, such as time spent in rooms or buildings with WLAN or DECT base station, number of smartphones in the household, or time spent in public transport were derived from the HERMES questionnaire. Regression models were also used to evaluate whether building characteristics modified indoor personal exposure from fixed site transmitters as was previously observed [14].

Combining Near-Field and Far-Field Dose

Using the equations above, we calculated daily brain and whole-body RF-EMF dose for each HERMES study participant. For data visualisation we have additionally chosen three HERMES study participants: a non-user, a normal user and a heavy-user. The non-user is a study participant not owning a mobile phone and not using another mobile phone (12 out of 439 study participants reported not to use a mobile phone at all). The normal user is an average mobile phone call (median = 6.4 min/day) and data traffic user (median data traffic via mobile internet connection = 2.27 min/day, median data traffic via WLAN = 19.0 min/day). The heavy-user represents maximal duration of mobile phone calls (267.1 min/day) and average mobile phone data traffic use. Note that all three users are average HERMES users in terms of calls on the DECT phone at home and computer, laptop and tablet use with WLAN (duration of DECT phone calls and us of devices with WLAN close to the median of the study population, median duration of DECT phone calls = 4.8 min/day, median use of devices with WLAN = 30 min/day).

2.4. Comparison of Dose Calculations with Personal Measurements

For the 95 participants with personal measurements we compared the dose with the personal measurements. For brain and whole-body dose three exposure categories were defined: brain or whole-body dose <50th percentile (*low*), 50th–90th percentile (*medium*) and >90th percentile (*high*).

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Lucerne, Switzerland on 9 May, 2012 (Project identification code: EK 12025).

3. Results

Four hundred and thirty nine (439) adolescents with a mean age of 14.0 years (range: 12.1–17.0 years) took part in the HERMES study. Objectively recorded operator data was available for a subgroup of

233 study participants. After data cleaning of the personal measurements and diary cleaning, 95 out of 121 collected sets of measurements and diaries could be used in our analysis.

3.1. Near-Field Dose

3.1.1. Near-Field Predictors

The adolescents of the HERMES study indicated in the questionnaire average mobile phone call duration of 17.2 min/day, of which 9.5 min were calls on the GSM network and 7.7 min calls on the UMTS network according to the recorded/predicted proportion of network use derived from the operator data (Table 3). They reported to use the DECT phone at home on for calls lasting 9.0 min per day. They used their mobile phone on average 11.5 min/day for data traffic on the mobile phone using a mobile internet connection and 30.6 min/day for data traffic using a WLAN connection. Additionally, they indicated to wear their mobile phone for 4.4 h close to the body. Lastly, they reported to use computers, laptops and tablets connected to the internet via WLAN for almost an hour per day (57.6 min).

3.1.2. Near-Field Dose

The highest dose rate (dose per 1 min) was found for calls on the mobile phone on the GSM network (without headset) with 191.88 mJ/kg/min and 24.66 mJ/kg/min followed by calls on the DECT phone (without eco mode) with 22.38 mJ/kg/min and 3.06 mJ/kg/min for brain and whole-body, respectively (Table 3). Considering all predictors, the brain near-field dose consisted mainly of the exposure from GSM mobile phone calls, on average 1451.78 mJ/kg/day (94.6%), followed by a dose of 74.10 mJ/kg/day (4.8%) from DECT phone calls (Table 3 and Figure 1). UMTS mobile phone calls counted for 8.04 mJ/kg/day (0.5%). Concerning the whole-body near-field dose, the largest part was induced by GSM mobile phone calls with a dose of 234.47 mJ/kg/day (73.3%). DECT phone calls contributed with a dose of 10.13 mJ/kg/day (3.2%). The dose contribution from mobile phone data traffic was 8.29 mJ/kg/day (2.6%) for data traffic via mobile internet connection and 22.03 mJ/kg/day (6.9%) for data traffic via WLAN connection. Using a computer, laptop and tablet connected to WLAN played a considerable role with a mean dose of 41.46 mJ/kg/day (13.0%).

Table 3. SAR, mean exposure duration (with standard deviation), dose rate (dose per 1 min), and mean (with corresponding percentage of the total near-field dose), minimum, median and maximum of the daily cumulative dose for the *brain* and *whole-body* exposure for the near-field predictors.

Near-Field Predictor	Brain SAR (mW/kg)	Whole-Body SAR (mW/kg)	Exposure Duration (min/day)	Brain Dose Rate (mJ/kg/min)	Whole-Body Dose Rate (mJ/kg/min)	Brain Dose (mJ/kg/day)				Whole-Body Dose (mJ/kg/day)			
	Value	Value	Mean (SD)	Value	Value	Mean (%)	Min	Median	Max	Mean (%)	Min	Median	Max
GSM [1] mobile phone calls without headset	3.198	0.411	7.6 (13.0)	191.88	24.66	–	–	–	–	–	–	–	–
GSM [1] mobile phone calls with headset	0.003198	0.411	1.9 (7.6)	0.19	24.66	–	–	–	–	–	–	–	–
GSM [1] mobile phone calls headset considered [2]	–	–	9.5 (16.7)	–	–	1451.78 (94.6%)	0.00	601.90	22587.02	234.47 (73.3%)	0.00	85.14	3785.98
UMTS mobile phone calls without headset	0.023	0.003	5.8 (14.8)	1.38	0.18	–	–	–	–	–	–	–	–
UMTS mobile phone calls with headset	0.000023	0.003	1.9 (8.1)	0.001	0.18	–	–	–	–	–	–	–	–
UMTS mobile phone calls headset considered [2]	–	–	7.7 (19.9)	–	–	8.04 (0.5%)	0.00	2.57	217.49	1.39 (0.4%)	0.00	0.37	34.20
DECT phone calls without eco mode	0.373	0.051	–	22.38	3.06	–	–	–	–	–	–	–	–
DECT phone calls with eco mode	0.0373	0.0051	–	2.24	0.31	–	–	–	–	–	–	–	–
DECT phone calls eco mode considered [3]	–	–	9.0 (10.9)	–	–	74.10 (4.8%)	0.00	18.70	1364.86	10.13 (3.2%)	0.00	2.61	190.28
Mobile phone data traffic	0.000092	0.012	11.5 (22.5)	0.01	0.72	0.06 (0.004%)	0.00	0.01	0.54	8.29 (2.6%)	0.00	1.63	70.89
Mobile phone close to the body (passive data traffic) [4]	0.000092	0.012	265.2 (349.5)	0.00006	0.01	0.01 (0.001%)	0.00	0.01	0.08	1.91 (0.6%)	0.00	0.86	10.37
Mobile phone data traffic WLAN	0.000092	0.012	30.6 (35.0)	0.01	0.72	0.17 (0.01%)	0.00	0.10	0.54	22.03 (6.9%)	0.00	13.68	70.89
Computer, laptop and tablet use with WLAN	0.000092	0.012	57.6 (83.3)	0.01	0.72	0.32 (0.02%)	0.00	0.17	3.42	41.46 (13.0%)	0.00	21.60	446.40

[1] For calls with the mobile phone on the GSM network the mean of the SARs for the GSM900 and the GSM1800 network was used because there was no differentiation between GSM900 and GSM1800 network in the mobile phone operator data; [2] Headset considered means that the proportion of headset use was applied to the mobile phone call duration; [3] Eco mode of the DECT phone at home was considered for all calls if the DECT phone at home was equipped with eco mode and for no calls if the DECT phone at home had no eco mode; [4] A transmission of data for 0.01*exposure duration of carrying the mobile phone close to the body was assumed.

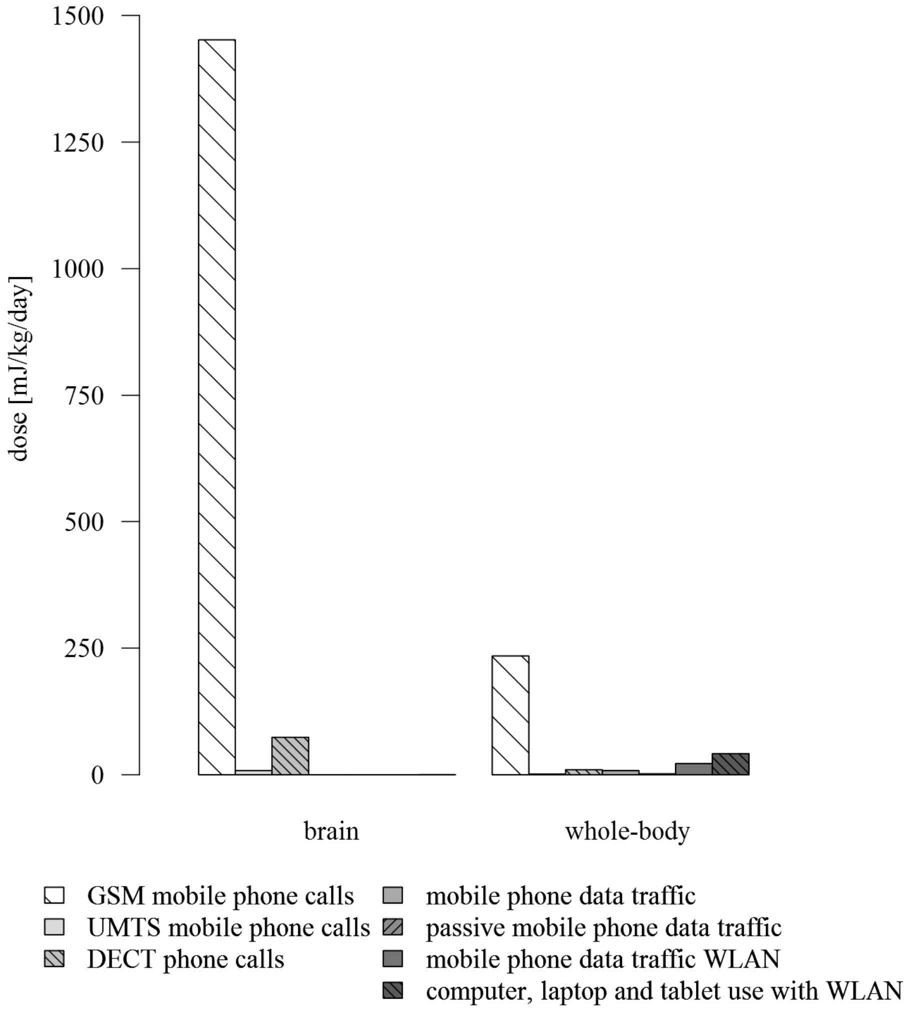

Figure 1. Mean daily cumulative *brain* (left) and *whole-body* (right) dose for the near-field predictors.

3.2. Far-Field Dose

3.2.1. Far-Field Predictors

Mean modelled downlink exposure of the HERMES study participants was 15.8 µW/m² (range: 0.0–476.9 µW/m²) at home and 10.4 µW/m² (0.003–67.1 µW/m²) in school (for details see Supplementary Table S1–Table S4). Mean values for radio broadcasting were 1.7 µW/m² (0.0–40.8 µW/m²) at home and 0.8 µW/m² (0.0–5.1 µW/m²) in school. For TV broadcasting modelled exposure was on average 0.5 µW/m² (0.0–32.1 µW/m²) at home and 0.06 µW/m² (0.0–0.7 µW/m²) in school. In other places (outdoors, in trains, buses and cars, and on locations not further defined in the diary) exposure, obtained from the personal measurements, was on average 46.2 µW/m² for downlink and 5.9 µW/m² for TV. Radio exposure was not measured by the used exposimeters and therefore taken into account only at home and in school. Identification of far-field predictors by multivariable regression models was based on personal measurements for 23.0–121.2 h (measurement duration of 71.2 h on average) from 95 HERMES participants.

When comparing personal measurements with modelling building characteristics, wall and window frame material, window glazing, window and building age, and façade renovation were not found to modify personal radio, TV or downlink indoor exposure at home or in school. Therefore, we did not take into account any building characteristics.

For the DECT far-field exposure no explanatory variable was associated with the measured DECT exposure from the personal measurements. For that reason, we decided to use the DECT measurements without modification using the average DECT exposure at home from the personal measurements which was 1.18 µW/m².

The identified far-field predictors for the WLAN and the uplink far-field exposure together with the derived exposure contribution per day were:

- Availability of WLAN in school: +0.49 µW/m² (WLAN);
- Availability of WLAN at home and not switching off the base station during night: +1.02 µW/m² (WLAN);
- Number of smartphones used at home: +9.39 µW/m² per smartphone (Uplink);
- Time spent in trains: +0.07 µW/m² per minute spent in trains (WLAN), +1.06 µW/m² per minute spent in trains (Uplink);
- Time spent in buses: +0.64 µW/m² per minute spent in buses (Uplink).

For details see Supplementary Material 1.

3.2.2. Far-Field Dose

The cumulative dose was highest for downlink and uplink for both brain and whole-body dose, whereas dose contributions from radio, TV, WLAN and DECT were small compared to the contributions from downlink and uplink (Table 4 and Table 5). The downlink dose was 8.43 mJ/kg per day (33.5%) for the brain and 6.16 mJ/kg per day (30.4%) for the whole-body. The uplink dose was 15.22 mJ/kg per day (60.4%) for the brain and 12.38 mJ/kg per day (61.2%) for the whole-body. It was mainly the exposure at home and other places (outdoors, in trains, buses and cars and locations not further defined in the diaries) that contributed to the downlink exposure (Figure 2). Being at home and, to a smaller extent, spending time in trains and buses contributed to the uplink exposure whereas a considerable part remained unexplained.

Table 4. *Brain* SAR, mean and derivation of the power flux density, *brain* dose rate (dose per 1 min) and mean (with the corresponding percentage of the total brain far-field dose), minimum, median and maximum of the *brain* dose for the far-field exposure.

Band	Description	SAR ((mW/kg)/(mW/m²))	Power Flux Density (mW/m²)		Dose Rate ((mJ/kg)/(mW/m²)/min)	Dose (mJ/kg/day)			
			Mean	Derivation		Mean (%)	Min	Median	Max
Radio [1]	Radio broadcast transmitter	0.001	0.002	modelling	0.09	0.16 (0.6%)	0.00	0.07	3.30
TV	Television broadcast transmitter	0.008	0.001	modelling and personal measurements	0.46	0.79 (3.1%)	0.58	0.58	14.40
Downlink 900	Transmission from base station to mobile phone handset	0.007	–	–	0.41	–	–	–	–
Downlink 1800	Transmission from base station to mobile phone handset	0.003	–	–	0.19	–	–	–	–
Downlink 2100	Transmission from base station to mobile phone handset	0.003	–	–	0.17	–	–	–	–
Downlink	Downlink 900+ Downlink 1800+ Downlink 2100	–	0.019	modelling and personal measurements	–	8.43 (33.5%)	3.76	5.02	124.64
WLAN	Wireless local area network	0.002	0.002	prediction regression model	0.14	0.39 (1.6%)	0.20	0.40	2.37
DECT	Digital enhanced cordless telecommunications	0.003	0.001	personal measurements	0.17	0.19 (0.8%)	0.19	0.19	0.19
Uplink [2]	Transmission from mobile phone handset to base station	0.004	0.041	prediction regression model	0.26	15.22 (60.4%)	2.96	13.54	71.16

[1] Radio = radio FM (Frequency Modulation) + DAB (Digital Audio Broadcasting); Radio was considered only at home and in school (geospatial propagation modelling) because used exposimeters did not measure radio broadcasting; [2] Uplink = Uplink 900+ Uplink 1800+ Uplink 1900; For the far-field uplink exposure from other mobile phones the average of the SARs for the downlink bands downlink 900, downlink 1800 and downlink 2100 was used.

Table 5. *Whole-body* SAR, mean and derivation of the power flux density, *whole-body* dose rate (dose per 1min) and mean (with the corresponding percentage of the total whole-body far-field dose), minimum, median and maximum of the *whole-body* dose for the far-field exposure.

Band	**Description**	**SAR ((mW/kg)/ (mW/m²))**	**Power Flux Density (mW/m²)**		**Dose Rate ((mJ/kg)/(mW/m²)/min)**	**Dose (mJ/kg/day)**			
			Mean	**Derivation**		**Mean (%)**	**Min**	**Median**	**Max**
Radio [1]	Radio broadcast transmitter	0.005	0.002	modelling	0.29	0.54 (2.7%)	0.00	0.22	11.30
TV	Television broadcast transmitter	0.005	0.001	modelling and personal measurements	0.27	0.47 (2.3%)	0.35	0.35	8.61
Downlink 900	Transmission from base station to mobile phone handset	0.004	–	–	0.26	–-	–	–	–
Downlink 1800	Transmission from base station to mobile phone handset	0.003	–	–	0.20	–	–	–	–
Downlink 2100	Transmission from base station to mobile phone handset	0.003	–	–	0.18	–	–	–	–
Downlink	Downlink 900+ Downlink 1800+ Downlink 2100	–	0.019	modelling and personal measurements	–	6.16 (30.4%)	2.46	3.47	86.19
WLAN	Wireless local area network	0.003	0.002	prediction regression model	0.17	0.48 (2.4%)	0.24	0.49	2.90
DECT	Digital enhanced cordless telecommunications	0.003	0.001	personal measurements	0.18	0.20 (1.0%)	0.20	0.20	0.20
Uplink [2]	Transmission from mobile phone handset to base station	0.004	0.041	prediction regression model	0.21	12.38 (61.2%)	2.41	11.01	57.87

[1] Radio = radio FM (Frequency Modulation) + DAB (Digital Audio Broadcasting); Radio was considered only at home and in school (geospatial propagation modelling) because used exposimeters did not measure radio broadcasting; [2] Uplink = Uplink 900+ Uplink 1800+ Uplink 1900; For the far-field uplink exposure from other mobile phones the average of the SARs for the downlink bands downlink 900, downlink 1800 and downlink 2100 was used.

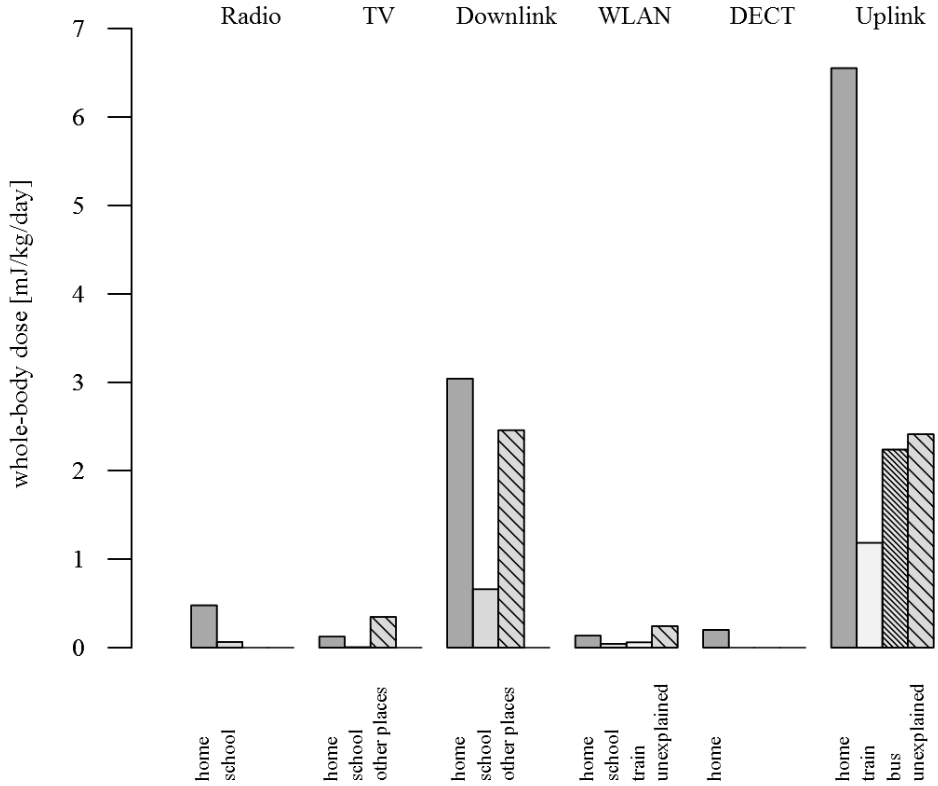

Figure 2. Mean daily cumulative *whole-body* dose for the far-field exposure at different locations; The same pattern was found for the *brain* dose.

3.3. Combining Near-Field and Far-Field Dose

The mean brain dose for the HERMES study participants was 1559.7 mJ/kg per day (range: 13.3–22,607.6 mJ/kg/day) whereas the mean whole-body dose was 339.9 mJ/kg per day (6.5–4064.7 mJ/kg/day). The near-field component counted on average for far the most of the total dose, 98.4% (1534.5 mJ/kg/day) of the total brain dose and 94.0% (319.7 mJ/kg/day) of the total whole-body dose originated from near-field sources. For the three HERMES study participants, a non-user, a normal user and a heavy-user, considerable differences in the cumulative dose and in the proportion of the far-field dose on the total dose were found (Figure 3).

Total brain white matter dose was on average 535.0 mJ/kg per day. This corresponded to 34.3% of the total average brain gray matter dose (1559.7 mJ/kg/day). The proportional contributions of the particular near-field exposure predictors and far-field bands were similar to the brain gray matter dose. The proportion of the near-field dose on the total dose was similar as well (98.4%).

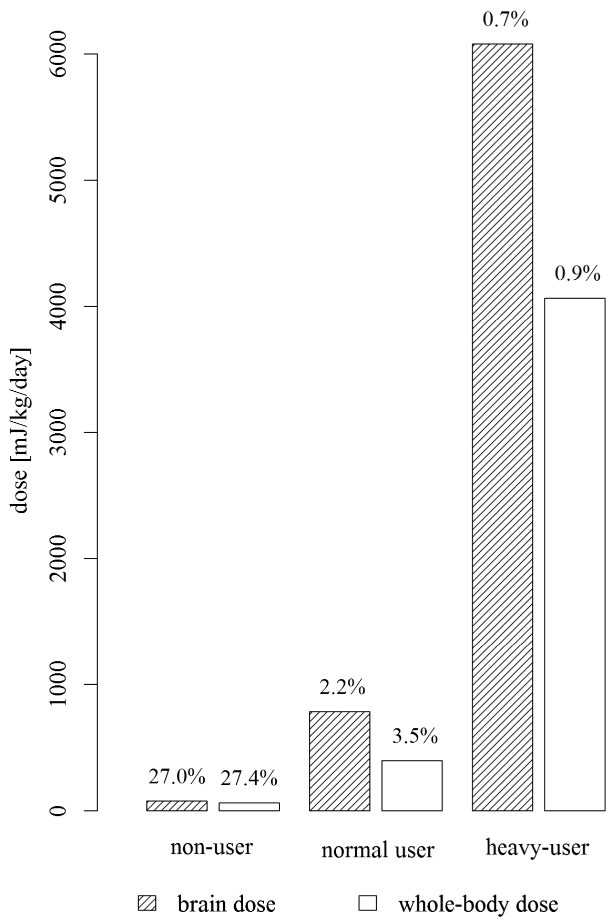

Figure 3. Total brain and whole-body dose for the three HERMES study participants (non-user, normal user, heavy-user); Percentages of the far-field dose on the total dose are indicated above the bars.

3.4. Comparing Dose Calculations and Personal Measurements

In Figure 4 dose predictions are compared with personal measurements. With respect to total dose (first row of Figure 4) there was a slight tendency that the group median of the personal measurements increased with increasing predicted dose. The Spearman correlation between the dose and the mean of the personal measurements was 0.10 (p-value = 0.34) for the brain dose and 0.05 (p-value = 0.63) for the whole-body dose. For the far-field dose the picture was similar, but with a slightly higher correlation of 0.18 (p-value = 0.08) for the brain far-field dose and 0.17 (p-value = 0.09) for the whole-body far-field dose (second row of Figure 4). If taking into account only the downlink dose and the downlink measurements (third row of Figure 4) the mean and the median of the measurements were clearly increased for increasing predicted dose. The Spearman correlation was 0.53 (p-value < 0.0001) for the brain downlink dose and 0.52 (p-value < 0.0001) for the whole-body downlink dose.

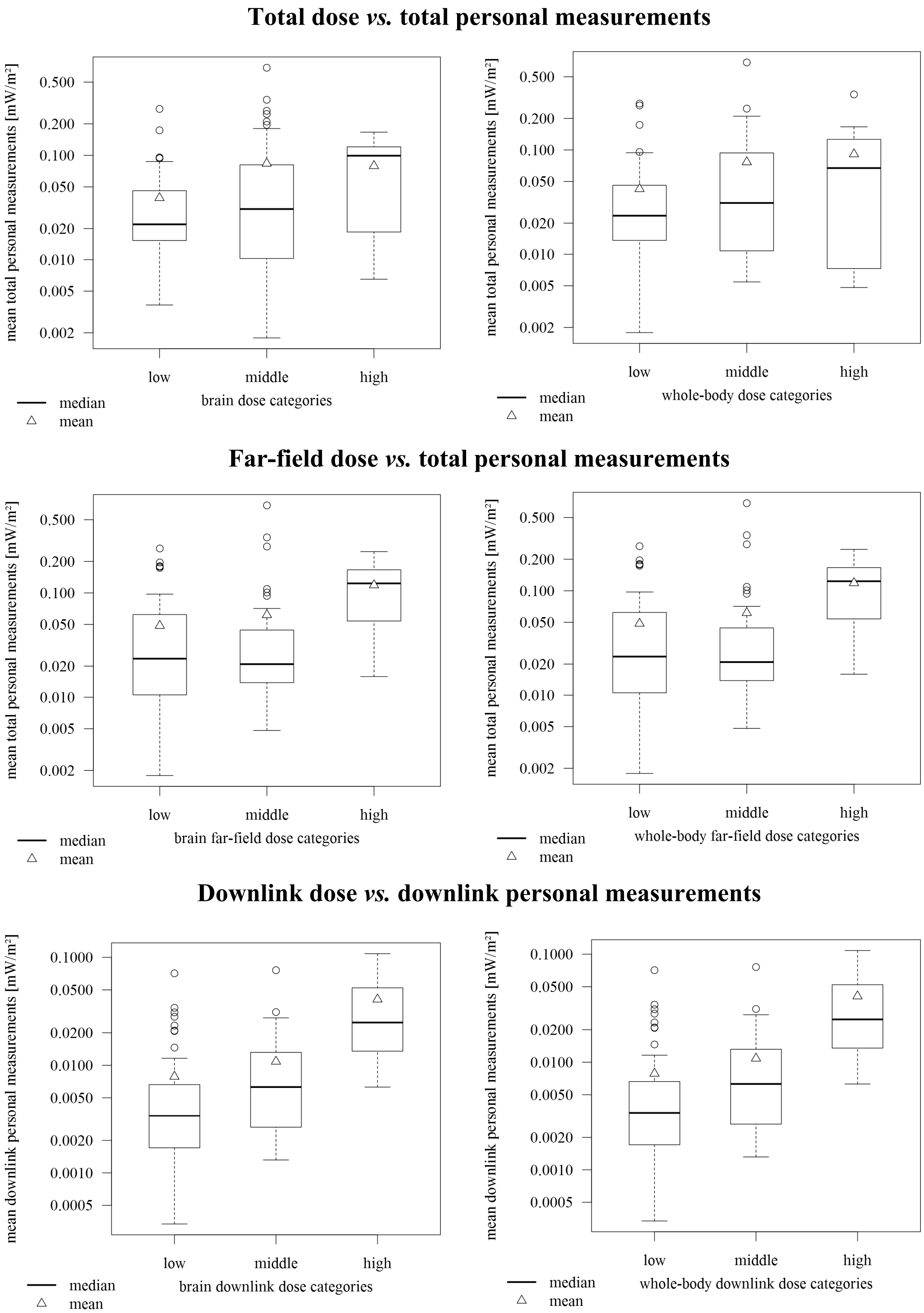

Figure 4. Comparison of predicted dose measures and personal measurements using the three dose categories <50th percentile (low), 50th–90th percentile (medium) and >90th percentile (high); First row: total dose *vs.* total personal measurements; Second row: far-field dose *vs.* total personal measurements; Third row: downlink dose *vs.* downlink personal measurements.

4. Discussion

The aim was to develop an integrative exposure surrogate consisting of a near-field and a far-field component representing together total personal RF-EMF dose. Thus we combined near-field exposure from the use of wireless communication devices and far-field exposure from environmental sources such as fixed site transmitters, WLAN and DECT base stations and other people's mobile phones in the surroundings to one single RF-EMF exposure measure.

4.1. Near-Field Exposure

We found GSM mobile phone calls contribute by far the most to the near-field exposure from the use of wireless communication devices. For the brain exposure, DECT phone calls and to a less extent UMTS mobile phone calls contributed as well. Mobile phone data traffic and computer, laptop and tablet use with WLAN played a minor role. For the whole-body exposure computer, laptop and tablet use with WLAN and mobile phone data traffic via WLAN contributed as well, followed by DECT phone calls and mobile phone data traffic via mobile internet connection. UMTS mobile phone calls played a minor role.

4.2. Far-Field Exposure

Far-field exposures from radio and TV broadcast transmitters and mobile phone base stations were estimated using geospatial propagation modelling. We did not find any influence of building characteristics on the personal measurements taken at home and in school. This is in contrast to our previous study where metal window frames and concrete walls resulted in a significant exposure reduction [14]. However, our finding is in line with a recent study on modelled mobile phone downlink exposure in the city of Amsterdam, Netherlands, where none of the building characteristics could explain additional variance of the modelled values [26]. We found the availability of WLAN at home and not switching off the base station during night and the availability of WLAN in school being relevant exposure predictors. Furthermore, the time spent in trains explained part of the measured WLAN exposure. Because of the increase of WLAN in public spaces and public transport this part of WLAN exposure may become even more important in the future. The number of smartphones being used at home was the strongest predictor for the far-field uplink exposure followed by the time spent in trains and buses. A considerable part of the uplink exposure however remained unexplained. Previous studies have also demonstrated high uplink exposure in public transport [27–29] or investigated the influence of small cells in trains on the exposure of mobile phone users [30]. The relevance of mobile phones in stand-by mode for exposure is still quite unclear. Urbinello *et al.* demonstrated that personal RF-EMF exposure was affected by one's own mobile phone in stand-by mode because of its regular location updates and push functions implemented in applications [29]. This finding may explain why the number of smartphones at home is one of the exposure relevant predictors. And, additionally, this finding led us to include passive mobile phone data traffic for the near-field exposure estimate. Carrying a mobile phone on the body contributed on average 0.56% to the total whole-body exposure of the HERMES participants.

The contribution of the far-field exposure is small compared to the contribution of the near-field exposure (1.6% of the brain dose and 6.0% of the whole-body dose originated from far-field sources). Nevertheless, far-field exposure is relevant: There are public concerns about potential health effects related to mobile phone base stations [31] and exposure from broadcast transmitters and mobile phone base stations is not lifestyle related which complicates the investigation of soft outcomes (e.g., symptoms and behaviour). Furthermore, far-field exposure is long-term and continuous and people are exposed during night as well, which might be a critical time window. Therefore we think it is worth the effort to investigate far-field exposure as well.

4.3. Comparing Dose Calculations and Personal Measurements

In our exposure assessment approach we combined questionnaire data, operator data, modelling and personal measurements from a subsample. This is more efficient than conducting personal measurements in a large sample which is very time- and resource-consuming. Furthermore, near-field exposure from the use of wireless communication devices is not recorded adequately by personal measurements because the measured values depend highly on the distance between the emitting device and the exposimeter, which is not necessarily the same as the distance between the emitting device and the body [4,5]. Only the latter is relevant for exposure. This may also explain why we found only a small correlation between predicted brain and whole-body exposure and personal measurements (Figure 4). For both exposure proxies, the brain dose and the whole-body dose, GSM mobile phone calls are most relevant, but the resulting exposure is not measured accurately with exposimeters during personal measurements [4,5]. However, the predicted far-field dose was also only weakly correlated with personal measurements. This may have several reasons. First, radio broadcasting is not measured by the exposimeters used but modelled at home and in school and thus considered for the dose. Nevertheless, this contribution is small and cannot explain the discrepancy. Second, the prediction models for the WLAN and uplink far-field exposure have limited explanatory power and for DECT no exposure predictor could be identified at all. Thus, there is more work needed to figure out what predictors are able to predict these exposures in a more accurate way. Strikingly, the downlink dose and the personal downlink exposure measurements correlated well. Thus, modelled exposure at home and in school may well be used to predict downlink exposure.

Obviously, the dose calculations are subject to a large uncertainty. We relied our calculations on self-reported amount of mobile phone use, which is typically overestimated by adolescents [32,33]. In our study, overestimation was on average by a factor of 9.3 according to a comparison with operator recorded duration of mobile phone calls. Subsequent dose estimations for our study sample with operator recorded mobile phone data yielded on average a brain gray matter dose of 139.3 mJ/kg per day and a whole-body dose of 24.9 mJ/kg per day for mobile phone calls (brain dose of 1459.8 mJ/kg/day and whole-body dose of 235.9 mJ/kg/day for self-reported duration of mobile phone calls). For the normal user, the proportion of the far-field dose on the total dose was 9.4% for the brain dose and 4.3% for the whole-body dose if taking into account operator recorded duration of mobile phone calls (2.2% and 3.5% for the brain and the whole-body dose, respectively for self-reported duration of mobile phone calls, Figure 3).

We have obtained SAR values from the literature, however, such data are still rare and have a large uncertainty range. Unfortunately, systematic analyses of this uncertainty are not yet published and could thus not be considered in our study. Most of the uncertainty is due to the unknown position of the device in relation to the body. Ideally, this should be measured permanently for each study participant. However, this is impossible and one has thus to rely on assumptions about typical positions. A further source of uncertainty is the emitted output power of mobile phones, in particular during data transmission and in stand-by mode. Depending on the type of data transmission (e.g., watching videos and playing games while connected to the internet, using social networks and reading news), a mobile phone may mainly act as receiver or transmitter. We did not find any data about proportion of time the mobile phone is transmitting data when set in stand-by mode, and which factors are relevant for these emissions. Additional uncertainty remains regarding SARs for newer devices such as tablets. Due to lack of data, we did not take into account exposure from use of the mobile phone as mobile hotspot. Inherent uncertainties are related to the geospatial propagation modelling and predictions derived from the personal measurements. Also the assessment of the proportion of calls made on the GSM and UMTS network comes with uncertainties.

5. Conclusions

Despite all these uncertainties and limitations, the proposed approach is considered useful to combine near-field and far-field exposure to one single integrative exposure surrogate either for the whole-body or for specific organs. However, more work is needed to deepen the understanding of far-field exposure predictors on one hand and near-field exposure from rapidly developing devices such as smartphones and tablets on the other hand. If this approach is refined, the integrative exposure surrogate can be adapted to any population of epidemiologic studies if modelled RF-EMF exposure from fixed site transmitters for the study area, operator data including type of network and specific questionnaire data are available.

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Author Contributions

Martin Röösli conceived and designed the study; Anna Schoeni and Katharina Roser conducted the study; Alfred Bürgi was responsible for the geo-spatial propagation model; Katharina Roser analyzed the data; Katharina Roser wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Heinrich, S.; Thomas, S.; Heumann, C.; von Kries, R.; Radon, K. Association between exposure to radiofrequency electromagnetic fields assessed by dosimetry and acute symptoms in children and adolescents: A population based cross-sectional study. *Environ. Health* **2010**, doi:10.1186/1476-069X-9-75.
2. Heinrich, S.; Thomas, S.; Heumann, C.; von Kries, R.; Radon, K. The impact of exposure to radio frequency electromagnetic fields on chronic well-being in young people—A cross-sectional study based on personal dosimetry. *Environ. Int.* **2011**, *37*, 26–30.
3. Thomas, S.; Heinrich, S.; von Kries, R.; Radon, K. Exposure to radio-frequency electromagnetic fields and behavioural problems in Bavarian children and adolescents. *Eur. J. Epidemiol.* **2010**, *25*, 135–141.
4. Inyang, I.; Benke, G.; McKenzie, R.; Abramson, M. Comparison of measuring instruments for radiofrequency radiation from mobile telephones in epidemiological studies: Implications for exposure assessment. *J. Expo. Sci. Environ. Epidemiol.* **2008**, *18*, 134–141.
5. Röösli, M.; Frei, P.; Bolte, J.; Neubauer, G.; Cardis, E.; Feychting, M.; Gajsek, P.; Heinrich, S.; Joseph, W.; Mann, S.; *et al.* Conduct of a personal radiofrequency electromagnetic field measurement study: Proposed study protocol. *Environ. Health* **2010**, doi:10.1186/1476-069X-9-23.
6. Beekhuizen, J.; Vermeulen, R.; Kromhout, H.; Bürgi, A.; Huss, A. Geospatial modelling of electromagnetic fields from mobile phone base stations. *Sci. Total Environ.* **2013**, *445*, 202–209.
7. Breckenkamp, J.; Neitzke, H.P.; Bornkessel, C.; Berg-Beckhoff, G. Applicability of an exposure model for the determination of emissions from mobile phone base stations. *Radiat. Prot. Dosim.* **2008**, *131*, 474–481.
8. Briggs, D.; Beale, L.; Bennett, J.; Toledano, M.B.; de Hoogh, K. A geographical model of radio-frequency power density around mobile phone masts. *Sci. Total Environ.* **2012**, *426*, 233–243.
9. Bürgi, A.; Frei, P.; Theis, G.; Mohler, E.; Braun-Fahrländer, C.; Fröhlich, J.; Neubauer, G.; Egger, M.; Röösli, M. A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research. *Bioelectromagnetics* **2010**, *31*, 226–236.
10. Bürgi, A.; Theis, G.; Siegenthaler, A.; Röösli, M. Exposure modeling of high-frequency electromagnetic fields. *J. Expo. Sci. Environ. Epidemiol.* **2008**, *18*, 183–191.
11. Elliott, P.; Toledano, M.B.; Bennett, J.; Beale, L.; de Hoogh, K.; Best, N.; Briggs, D.J. Mobile phone base stations and early childhood cancers: Case-control study. *BMJ* **2010**, doi:10.1136/bmj.c3077.

12. Ha, M.; Im, H.; Lee, M.; Kim, H.J.; Kim, B.C.; Gimm, Y.M.; Pack, J.K. Radio-frequency radiation exposure from AM radio transmitters and childhood leukemia and brain cancer. *Amer. J. Epidemiol.* **2007**, *166*, 270–279.
13. Merzenich, H.; Schmiedel, S.; Bennack, S.; Bruggemeyer, H.; Philipp, J.; Blettner, M.; Schuz, J. Childhood leukemia in relation to radio frequency electromagnetic fields in the vicinity of TV and radio broadcast transmitters. *Amer. J. Epidemiol.* **2008**, *168*, 1169–1178.
14. Frei, P.; Mohler, E.; Bürgi, A.; Fröhlich, J.; Neubauer, G.; Braun-Fahrländer, C.; Röösli, M. A prediction model for personal radio frequency electromagnetic field exposure. *Sci. Total Environ.* **2009**, *408*, 102–108.
15. Frei, P.; Mohler, E.; Braun-Fahrländer, C.; Fröhlich, J.; Neubauer, G.; Röösli, M. Cohort study on the effects of everyday life radio frequency electromagnetic field exposure on non-specific symptoms and tinnitus. *Environ. Int.* **2012**, *38*, 29–36.
16. Mohler, E.; Frei, P.; Fröhlich, J.; Braun-Fahrländer, C.; Röösli, M. Exposure to radiofrequency electromagnetic fields and sleep quality: a prospective cohort study. *PLoS One* **2012**, doi:10.1371/journal.pone.0037455.
17. Cardis, E.; Varsier, N.; Bowman, J.D.; Deltour, I.; Figuerola, J.; Mann, S.; Moissonnier, M.; Taki, M.; Vecchia, P.; Villegas, R., *et al.* Estimation of RF energy absorbed in the brain from mobile phones in the interphone study. *Occup. Environ. Med.* **2011**, *68*, 686–693.
18. Lauer, O.; Frei, P.; Gosselin, M.C.; Joseph, W.; Röösli, M.; Fröhlich, J. Combining near- and far-field exposure for an organ-specific and whole-body RF-EMF proxy for epidemiological research: A reference case. *Bioelectromagnetics* **2013**, *34*, 366–374.
19. Lauer, O., Leidenberger, P., Müri, M., Zahner, M., Fröhlich, J. A Novel Measurement System for Environmental Exposure Monitoring. In *Proceedings of the ACM Conference on Embedded Networked Sensor Systems*, Seattle, WA, USA, 1–4 November, 2011.
20. SEAWIND Sound Exposure & Risk Assessment of Wireless Network Devices Final Summary Report, 2013. Available online: http://seawind-fp7.eu/uploads/SEAWIND_FINAL.pdf (accessed on 7 June 2013).
21. Gati, A.; Hadjem, A.; Man-Fai, W.; Wiart, J. Exposure induced by WCDMA mobiles phones in operating networks. *IEEE Wirel. Commun.* **2009**, *8*, 5723–5727.
22. Hadjem, A.; Conil, E.; Gati, A.; Wong, M.-F.; Wiart, J. Analysis of power absorbed by children's head as a result of new usages of mobile phone. *IEEE Trans. Electromagn. Compat.* **2010**, *52*, 812–819.
23. Huang, Y.; Wiart, J.; Varsier, N.; Person, C. Sensitivity Analysis of Downlink Received and Uplink Emitted Powers in a Geographical Area to ICT Usage Parameters. In Proceedings of The Annual Meeting of BEMS and EBEA, Capetown, South Africa, 8-13 June, 2014.
24. Persson, T.; Tornevik, C.; Larsson, L.E.; Loven, J. Output power distributions of terminals in a 3G mobile communication network. *Bioelectromagnetics* **2012**, *33*, 320–325.
25. Vrijheid, M.; Mann, S.; Vecchia, P.; Wiart, J.; Taki, M.; Ardoino, L.; Armstrong, B.K.; Auvinen, A.; Bedard, D.; Berg-Beckhoff, G.; *et al.* Determinants of mobile phone output power in a multinational study: Implications for exposure assessment. *Occup. Environ. Med.* **2009**, *66*, 664–671.

26. Beekhuizen, J.; Vermeulen, R.; van Eijsden, M.; van Strien, R.; Bürgi, A.; Loomans, E.; Guxens, M.; Kromhout, H.; Huss, A. Modelling indoor electromagnetic fields (EMF) from mobile phone base stations for epidemiological studies. *Environ. Int.* **2014**, *67*, 22–26.
27. Bolte, J.F.; Eikelboom, T. Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area. *Environ. Int.* **2012**, *48*, 133–142.
28. Frei, P.; Mohler, E.; Neubauer, G.; Theis, G.; Bürgi, A.; Fröhlich, J.; Braun-Fahrländer, C.; Bolte, J.; Egger, M.; Röösli, M. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. *Environ. Res.* **2009**, *109*, 779–785.
29. Urbinello, D.; Röösli, M. Impact of one's own mobile phone in stand-by mode on personal radiofrequency electromagnetic field exposure. *J. Expo. Sci. Environ. Epidemiol.* **2013**, *23*, 545–548.
30. Aerts, S.; Plets, D.; Thielens, A.; Martens, L.; Joseph, W. Impact of a small cell on the RF-EMF exposure in a train. *Int. J. Environ. Res. Public Health* **2015**, *12*, 2639–2652.
31. Roosli, M.; Frei, P.; Mohler, E.; Hug, K. Systematic review on the health effects of exposure to radiofrequency electromagnetic fields from mobile phone base stations. *Bull. World Health Organ.* **2010**, *88*, 887–896.
32. Aydin, D.; Feychting, M.; Schuz, J.; Andersen, T.V.; Poulsen, A.H.; Prochazka, M.; Klaeboe, L.; Kuehni, C.E.; Tynes, T.; Roosli, M. Impact of random and systematic recall errors and selection bias in case—Control studies on mobile phone use and brain tumors in adolescents (CEFALO study). *Bioelectromagnetics* **2011**, *32*, 396–407.
33. Inyang, I.; Benke, G.; Morrissey, J.; McKenzie, R.; Abramson, M. How well do adolescents recall use of mobile telephones? Results of a validation study. *BMC Med. Res. Methodol.* **2009**, doi:10.1186/1471-2288-9-36.

Development of an RF-EMF Exposure Surrogate for Epidemiologic Research

Table S1. WLAN prediction model: predicted far-field WLAN exposure contribution from a multivariable regression model using bootstrap (1000 replications), n = 95.

Mean WLAN Personal Measurements (µW/m²)	Exposure Contribution (µW/m²)	95% Confidence Interval	*p*-Value
WLAN in school	0.49	(−1.29, 2.26)	0.589
WLAN at home and not switched off during night	1.02	(−0.80, 2.83)	0.272
Time spent in trains (min/day)	0.07	(−0.06, 0.19)	0.290
Unexplained by the model	1.00	(−0.51, 2.52)	0.195

Table S2. Uplink prediction model: predicted far-field uplink exposure contribution from a multivariable regression model using bootstrap (1000 replications), n = 95.

Mean Uplink Personal Measurements (µW/m²)	Exposure Contribution (µW/m²)	95% Confidence Interval	*p*-Value
Number of smartphones at home	9.39	(−6.33, 25.12)	0.242
Time spent in trains (min/day)	1.06	(0.24, 1.87)	0.011
Time spent in buses (min/day)	0.64	(−0.02, 1.30)	0.057
Unexplained by the model	7.89	(−18.40, 34.18)	0.556

Table S3. Mean exposure duration (per day) of the different locations for the calculation of the far-field dose.

Location	Mean Exposure Duration (per day)
Home day [1]	8 h 21 min
Home night [1]	7 h 21 min
Home	15 h 41 min
School	4 h 43 min
Outside	1 h 41 min
Train	0 h 6 min
Bus	0 h 9 min
Car	0 h 13 min
Unspecified location [2]	1 h 27 min

[1] Home day and night: Home day means the time being at home in the time period 6:00 until 22:00; Home night means the time being at home in the time period 22:00 until 6:00; [2] Unspecified location means diary entries recorded as miscellaneous or other activity or location than the prespecified activities and locations in the time-activity diary.

Table S4. Measured, modelled or predicted mean power flux densities (μW/m²) at the different locations for the calculation of the far-field dose.

Band	Description	Power Flux Density (μW/m²)									
		Home Day [2]	**Home Night [2]**	**Home**	**School**	**Outside**	**Train**	**Bus**	**Car**	**Unspecified Location [3]**	**Unexplained [4]**
Radio [1]	Radio broadcast transmitter	1.73	1.73	–	0.77	–	–	–	–	–	–
TV	Television broadcast transmitter	0.48	0.48	–	0.06	4.14	7.25	24.70	4.38	6.16	–
Downlink 900	Transmission from base station to mobile phone handset	6.52	4.32	–	4.98	35.80	64.30	31.60	16.60	27.60	–
Downlink 1800	Transmission from base station to mobile phone handset	5.15	3.97	–	3.56	5.18	8.49	7.80	5.09	9.89	–
Downlink 2100	Transmission from base station to mobile phone handset	5.81	4.15	–	1.90	6.88	15.20	16.30	3.21	6.09	–
WLAN	Wireless local area network	–	–	0.56	0.18	–	0.24	–	–	–	1.00
DECT	Digital enhanced cordless telecommunications	–	–	1.18	–	–	-	–	–	–	–
Uplink [5]	Transmission from mobile phone handset to base station	–	–	21.48	–	–	3.88	7.33	–	–	7.89

For RF-EMF a power flux density of 1 μW/m² = 0.001 mW/m² corresponds to an electric field strength of 0.019 V/m; [1] Radio = radio FM (Frequency Modulation) + DAB (Digital Audio Broadcasting); Radio was considered only at home and in school (geospatial propagation modelling) because used exposimeters did not measure radio broadcasting; [2] Home day and night: Home day means the time being at home in the time period 6:00 until 22:00; Home night means the time being at home in the time period 22:00 until 6:00; [3] Unspecified location means diary entries recorded as miscellaneous or other activity or location than the prespecified activities and locations in the time-activity diary; [4] Unexplained means the part of the predicted WLAN and uplink power flux density not explained through the relevant far-field predictors found in the multivariable regression model used to predict WLAN and uplink exposure, respectively; [5] Uplink = Uplink 900 + Uplink 1800 + Uplink 1900.

7 Behaviour and concentration of adolescents in relation to mobile phone use and RF-EMF exposure

Article 5: Mobile phone use, behavioural problems and concentration capacity in adolescents: a prospective study

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Mobile phone use, behavioural problems and concentration capacity in adolescents: A prospective study

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ABSTRACT

The aim of this study is to prospectively investigate whether exposure to radiofrequency electromagnetic fields (RF-EMF) emitted by mobile phones and other wireless communication devices is related to behavioural problems or concentration capacity in adolescents.

The HERMES (Health Effects Related to Mobile phonE use in adolescentS) study sample consisted of 439 Swiss adolescents aged 12–17 years. Behavioural problems were assessed using the Strengths and Difficulties Questionnaire (SDQ), concentration capacity of the adolescents was measured by means of a standardized computerized cognitive test named FAKT. Cross-sectional and longitudinal (1 year of follow-up) analyses were performed to investigate possible associations between behavioural problems and concentration capacity and different exposure measures: self-reported and operator-recorded wireless communication device use, cumulative RF-EMF brain and whole body dose and measured personal RF-EMF exposure.

In the cross-sectional analyses behavioural problems were associated with several self-reported wireless device use measures but not operator-recorded mobile phone use measures, concentration capacity was associated with several self-reported and operator-recorded exposures. The longitudinal analyses point towards absence of associations.

The lack of consistent exposure-response patterns in the longitudinal analyses suggests that behavioural problems and concentration capacity are not affected by the use of wireless communication devices or RF-EMF exposure. Information bias and reverse causality are likely explanations for the observed cross-sectional findings.

1. Introduction

Mobile phones are nowadays omnipresent, in particular among adolescents. A recent representative survey in 1086 Swiss adolescents aged 12–19 years revealed that 98% of the adolescents own a mobile phone and 97% of these devices are smartphones (Willemse et al., 2014). Furthermore, the use of these devices is frequent, 94% of the adolescents used their mobile phone daily or several times per week for exchanging messages via internet-based applications, 87% for browsing the internet and 53% for gaming (Willemse et al., 2014). This widespread and intensive use has created concern that it may cause behavioural or concentration problems, which belong to the most common health complaints of adolescents.

Swiss paediatricians estimated the percentage of children with attention deficit hyperactivity disorder (ADHD) or conduct problems seen in their practice at 9% (In-Albon et al., 2010). In a German study including 7000 adolescents aged 11–17 years parent-rated behavioural problems measured by the Strengths and Difficulties Questionnaire (SDQ, (Goodman, 1997)) were found in 7% of the adolescents (Hölling et al., 2007). Among specific problems, conduct problems were most frequently reported (14%), followed by problems with peers (13%) and emotional symptoms (10%). Hyperactivity was reported for 7% of the adolescents and 4% showed antisocial behaviour (Hölling et al., 2007). Among 825 Swiss 7th grade students antisocial behaviour was on average exhibited once a month (Müller et al., 2015).

In Sweden, concentration difficulties were among the most frequent reported health complaints in adolescents (Söderqvist et al., 2008) and in Germany, 32% of the adolescents participating in a measurement study reported to have concentration problems

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(Heinrich et al., 2010). In Chinese adolescents, the prevalence of inattention was reported to be as high as 70% (Zheng et al., 2014).

A possible link between behavioural problems and RF-EMF exposure has been investigated in 1508 adolescents from Germany using 24 h personal RF-EMF measurements for exposure assessment (Thomas et al., 2010b). In the highest exposure group (4th quartile) the risk for overall behavioural problems (adjusted OR = 2.2; 95% CI: 1.1–4.5) and conduct problems (adjusted OR = 3.7; 95% CI: 1.6–8.4) was found to be elevated. A Swedish study found the duration of mobile phone and cordless phone calls associated with self-reported concentration difficulties in adolescents (Söderqvist et al., 2008) and the number of mobile phone calls was associated with impaired attention performance in Australian adolescents (Abramson et al., 2009). In contrast, measured RF-EMF exposure and duration of mobile phone use were not associated with acute concentration problems in 1508 German adolescents (Heinrich et al., 2010) and mobile phone calls were not found to be associated with ADHD symptoms in 2422 Korean children (Byun et al., 2013) or inattention in 7102 Chinese adolescents (Zheng et al., 2014). But interestingly, they found mobile phone use for playing games (Byun et al., 2013) and the time spent on the mobile phone for entertainment (Zheng et al., 2014) being associated with ADHD symptoms and inattention, respectively. However, all these studies were of cross-sectional design and prospective studies are still missing.

A further limitation is the use of self-reported mobile or cordless phone use as proxy for RF-EMF exposure, because such reports are inaccurate (Aydin et al., 2011; Inyang et al., 2009) and do not take into account other sources that contribute to the RF-EMF exposure of adolescents such as the use of computers, laptops and tablets connected to wireless internet (WLAN) or the exposure from fixed site transmitters for broadcast and mobile telecommunication (Lauer et al., 2013; Roser et al., 2015a).

To overcome these limitations and in line with the recommendations of the World Health Organisation (WHO) to conduct prospective cohort studies in children and adolescents with outcomes including behavioural disorders with a high priority (WHO, 2010), the HERMES (Health Effects Related to Mobile phonE use in adolescentS) study was set up. The HERMES study is a prospective cohort study with a one year follow-up period. To differentiate between effects from RF-EMF exposure and effects from mobile phone use per se, an RF-EMF dose measure was developed taking into account various RF-EMF sources and including prospectively collected operator data (Roser et al., 2015a). Applying this RF-EMF dose measure in combination with use measures will help to disentangle possible effects from RF-EMF or from the use per se.

The aim of this study conducted in the framework of the HERMES study was to prospectively investigate whether RF-EMF exposure from mobile phones and other wireless communication devices is related to behavioural problems or concentration capacity in adolescents.

2. Methods

2.1. HERMES study

The baseline investigation of the HERMES study was conducted between June 2012 and March 2013 in Central Switzerland. The follow-up investigation was conducted approximately one year later. The study participants filled in a paper and pencil questionnaire and performed a cognitive concentration test using a standardized, computerized cognitive test battery. The investigation took place in school during school time and was supervised by two study managers. Furthermore paper and pencil questionnaires for the parents were distributed and returned directly to the study managers.

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

2.2. Exposures

2.2.1. Self-reported exposure

The adolescents' questionnaire included questions on mobile phone use: call duration with own and any other mobile phone, duration of data traffic on the mobile phone and number of all kind of text messages sent (short message system (SMS) as well as messages sent by internet-based applications). Furthermore, the call duration with cordless (fixed line) phones and the duration of gaming on computer, laptops, tablets and TV were reported. The study participants were asked to refer to an average use per day and the period of six months prior to the investigation. The number of text messages sent and the duration of gaming on computer and TV are not or only marginally relevant for RF-EMF exposure and were thus used as negative exposure control variables in the analyses.

2.2.2. Objective exposure

A subsample of the study participants and their parents gave informed consent obtaining objectively recorded mobile phone use data from the mobile phone operators. These data included duration of each call and the network (Global System for Mobile Communications (GSM) or Universal Mobile Telecommunications System (UMTS)) at which it started, number of SMS sent and amount of data traffic volume transmitted. Data were obtained for up to 18 months, six months before baseline until follow-up investigation one year later.

2.2.3. RF-EMF dose measures

To calculate the cumulative RF-EMF dose of the brain and the whole body for the participating adolescents, an integrative RF-EMF exposure surrogate including various factors contributing to near-field and far-field RF-EMF exposure was developed (Roser et al., 2015a). The near-field component combines the exposure from the use of wireless communication devices (mobile phones, cordless phones, computers, laptops and tablets connected to WLAN). The far-field component aggregates the exposure from environmental sources. To predict the exposures from radio and television broadcast transmitters and mobile phone base stations a geospatial propagation model was used (Bürgi et al., 2010, 2008). Exposures from cordless phone and WLAN base stations as well as other people's mobile phones were estimated by means of linear regression models calibrated on the personal measurement data for 95 study participants (Roser et al., 2015a). For each of the considered exposure circumstances, average specific absorption rates (SAR) for the brain and the whole body were derived from the literature (Gati et al., 2009; Hadjem et al., 2010; Huang et al., 2014; Lauer et al., 2013; Persson et al., 2012; SEAWIND, 2013; Vrijheid et al., 2009). To obtain a cumulative daily brain and whole body dose for each study participant, the SAR values were multiplied by the average exposure duration per day for each exposure situation and summed up to one single brain and whole body dose measure. This calculation was done twice: first, for the whole sample using self-reported duration of mobile phone calls; and secondly, for the subsample with operator-recorded data mobile phone call duration was derived from the mobile phone operator records. All other RF-EMF dose factors were identical for both calculations.

2.2.4. Personal RF-EMF measurements

As an additional exposure proxy we considered personal RF-EMF measurements, which were conducted in a subgroup of the

HERMES study participants. The adolescents carried a portable RF-EMF measurement device for three consecutive days and filled in a time-activity diary. These measurements are described in detail in (Roser et al. under preparation). Personal measurement data were available for 91 of the HERMES participants. Exposures for the personal measurements analysis included average personal downlink exposure (exposure from mobile phone base stations), fixed site transmitters exposure (exposure from mobile phone base stations and television broadcast transmitters), total RF-EMF exposure and total RF-EMF exposure without uplink (exposure from mobile phone handsets) over the whole measurement period of the personal measurements.

2.3. Outcomes

2.3.1. Behavioural problems

The self-reported SDQ in the questionnaire of the adolescents (referred to as *SDQ Adolescents*) and the parent-rated SDQ in the parents' questionnaire (referred to as *SDQ Parents*) assess behavioural and affective problems of adolescents (Goodman, 1997). They consist of five scales assessing emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems and prosocial behaviour on five items each answered on a 3-point Likert scale. A *total difficulties* score can be calculated by summing up the scores for emotional symptoms, conduct problems, hyperactivity/inattention and peer relationship problems and the *total strengths* score refers to the prosocial behaviour scale. Higher scores on the scales assessing difficulties (emotional symptoms, conduct problems, hyperactivity/inattention, and peer relationship problems) mean more difficulties; a higher score on the prosocial behaviour scale means more strengths. Individuals with a total difficulty score of ≥20 (SDQ Adolescents) and ≥17 (SDQ Parents) are considered to have difficulties. For the difficulty subscales the corresponding cut-offs are 7 and 5 (emotional symptoms), 5 and 4 (conduct problems), 7 and 7 (hyperactivity/inattention) and 6 and 4 (peer relationship problems) for the SDQ Adolescents and SDQ Parents, respectively. Individuals scoring ≤ 4 on the total strengths scale (SDQ Adolescents and SDQ Parents) are considered to have a problematic lack of strengths. Reliability and validity of the SDQ were shown to be satisfactory in a nationwide British sample of adolescents (Cronbach's alpha of 0.73 measuring internal consistency, retest stability of 0.62) (Goodman, 2001). Furthermore, the German SDQ was shown to be just as useful and valid as the English original scale in terms of similar factorial structure, reliability and validation of the scales (Klasen et al., 2003). Main analyses include behavioural problems measured by the SDQ Adolescents; results of the analyses using the SDQ Parents are presented in the Supplementary material.

2.3.2. Concentration capacity

We used a standardized, computerized cognitive test battery named FAKT-II (Frankfurter Adaptiver Konzentrationsleistungs-Test-II, (Moosbrugger and Goldhammer, 2007)) to measure the concentration capacity of the adolescents. Concentration capacity measures included homogeneity, power and accuracy of concentration. By means of discrimination tasks, the participant had to discriminate as accurately and as quickly as possible between target and non-target items by pressing "0" for non-target items and "1" for target items. Items with either two or three points in either a circle or a square appeared. Target items were either two points in a square or three points in a circle. Other combinations acted as non-target items. Before starting the 6-min test, the participant performed a trial-run. The FAKT is an adaptive test adjusting the speed of the item display according to the speed of the answers given.

Homogeneity of concentration is a measure of the uniformity of the working speed. It measures the variance of the time an item is displayed. The higher the homogeneity of concentration, the more uniform the study participant worked. Power of concentration is a measure of the working speed. It measures the number of displayed items per 100 s. The higher the power of concentration, the faster the study participant worked and the more items were displayed. Accuracy of concentration is a measure of the relative correctness. It measures the percentage of non-false items that have been processed. The higher the accuracy of concentration, the more precise the study participant worked. The test was conducted once at baseline and once at follow-up investigation.

2.4. Statistical analysis

Three main analyses were performed to investigate possible associations between behavioural problems and concentration capacity and different exposure measures.

The exposure measures included:

1) Negative exposure control variables (*usage not or only marginally related to RF-EMF exposure*): Self-reported: duration of gaming on the computer or TV (min/day), frequency of text messages sent (x/day).
   Operator-recorded: frequency of SMS sent (x/day).
2) Radiation related factors in the context of mobile phone use (*usage related to RF-EMF exposure*): Self-reported: duration of data traffic on the mobile phone (min/day), duration of cordless phone calls (min/day), duration of mobile phone calls (min/day).
   Operator-recorded: volume of data traffic on the mobile phone (MB/day), duration of mobile phone calls (min/day).
3) RF-EMF exposure (*cumulative RF-EMF dose*): Whole sample: brain dose (mJ/kg/day), whole body dose (mJ/kg/day) based on self-reported exposure data.
   Operator sample: brain dose (mJ/kg/day), whole body dose (mJ/kg/day) based on operator-recorded mobile phone call duration and self-reported data for other wireless device use.
4) Personal RF-EMF measurements: Downlink exposure (exposure from mobile phone base stations), fixed site transmitters exposure (exposure from mobile phone base stations and television broadcast transmitters), total RF-EMF exposure, total RF-EMF exposure without uplink (exposure from mobile phone handsets).

The three main analyses were the following:

a) A cross-sectional mixed model analysis using baseline and follow-up exposure and outcome variables.
b) A longitudinal analysis to investigate whether cumulative exposure was followed by a change in outcome.
c) A cross-sectional analysis of the follow-up outcomes with respect to personal RF-EMF measurements in the subsample with personal measurements.

The cross-sectional mixed model analysis (a) was based on a combined data set of baseline and follow-up data for both, exposure and outcome variables. Exposure referred to the average use or dose within six months prior to the investigation. For the longitudinal analysis (b) changes in outcomes (difference between follow-up and baseline) were related to the cumulative exposure between baseline and follow-up investigation. For better interpretation cumulative exposure between baseline and follow-up was expressed as average daily values. The cross-sectional analysis in the personal measurements subsample (c) was based on the average measured RF-EMF exposure during three consecutive days and outcomes at follow-up. Personal measurements were conducted between 7.3 months before and 1 month after the follow-up investigation.

All models were adjusted for age, sex, nationality, school level (college preparatory high school or high school), frequency of physical activity, frequency of alcohol consumption and highest educational level of the parents. In the longitudinal analysis, models were additionally adjusted for change in height between baseline and follow-up and time between baseline and follow-up.

To be able to compare the effect sizes of the different exposure measures, coefficients were standardized using the interquartile range of the corresponding exposure variable.

For sensitivity analysis, the exposure measures were categorised into a reference category (<50th percentile) and two other categories defined by 50th–75th percentile and >75th percentile.

Linear regression imputation (14 missing values at baseline and 10 missing values at follow-up for frequency of alcohol consumption; 7 missing values at baseline and 6 missing values at follow-up for information on height) or imputation of a common category (2 missing values at baseline and 1 missing value at follow-up for frequency of physical activity; 60 missing values for educational level of the parents) was used to impute missing values in the covariate variables. Statistical analyses were carried out using STATA version 12.1 (StataCorp, College Station, USA). Figures were made with the software R using version R for Windows 3.0.1.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent was obtained from all individual participants included in the study.

3. Results

3.1. Study participants

439 students (participation rate: 36.8%) with a mean age of 14 years (ranging from 12 to 17 years) from 24 schools (participation rate: 19.1%) in rural and urban areas in Central Switzerland participated in the baseline investigation of the HERMES study. 425 study participants (participation rate: 96.8%) took part in the follow-up investigation, which was on average 12.8 months later. 412 (93.8%) and 416 (97.9%) study participants owned a mobile phone at baseline and at follow-up, respectively. 60.4% of the participants were female, 79.3% were Swiss, 14.1% had mixed nationality and 6.6% had a foreign nationality. 22.6% attended a college preparatory high school. 71.8% of the participants reported to be physically active up to three times a week. Two third of the participants (68.8%) did not consume alcohol at all, another third (30.5%) up to once a week. For half of the parents (50.3%), a training school was the highest educational level achieved, 30.1% attended a college of higher education, 8.2% a university, 7.5% a college of preparatory high school, 3.2% the mandatory school and 0.7% had no education. The operator sample was slightly older and more participants attended a college preparatory high school (28.3%). The subsample with personal RF-EMF measurements contained more Swiss and fewer adolescents with mixed nationality compared to the whole sample. The other covariates were similarly distributed for the whole sample, the operator sample and the personal measurement sample.

3.2. Exposures

Table 1 shows the descriptive statistics of the exposure measures for the cross-sectional mixed model analysis and the longitudinal analysis. The exposures were similar for the whole sample and the operator sample. In the longitudinal analysis, the participants reported to use their mobile phone for on average 16.0 min of calling per day, the average daily operator-recorded mobile phone call duration was 1.9 min. They indicated to send 31 text messages per day and to game on computer and TV for 45.2 min.

3.3. Outcomes

According to the baseline SDQ Adolescents, 3.2% of the adolescents showed *total difficulties* (Table 2). Among the specific problems, hyperactivity/inattention was the most common reported problem (9.8%), followed by conduct problems (6.2%) and peer relationship problems (4.6%). Emotional symptoms were reported by 3.2% of the adolescents and 2.5% reported problematic *total strengths*. According to the SDQ Parents, *total difficulties* were similarly prevalent (3.3%); the prevalence for the specific problems was higher except for hyperactivity/inattention for which it was lower (3.0%). Table 2 further displays the descriptive statistics of the SDQ Adolescents, the SDQ Parents and concentration capacity measured by the FAKT.

3.4. Behavioural problems

In the cross-sectional analyses, *SDQ Adolescents total strengths* were not associated with any of the exposure variables (Table 3 and Fig. S1 in Supplementary material). However, the *SDQ Adolescents total difficulties score* was significantly positively associated with several self-reported use measures but not with operator-recorded exposure variables. Altogether there was no consistent pattern in relation to the extent of RF-EMF exposure related to these exposure variables. For instance, *SDQ Adolescents total difficulties* were positively correlated with self-reported duration of gaming and frequency of text messages sent (usage not related to RF-EMF exposure), with self-reported duration of data traffic on the mobile phone, duration of cordless phone and mobile phone calls (usage related to RF-EMF exposure) and cumulative EMF brain and whole body dose for the whole sample as well as whole body dose for the operator sample. Regarding specific behavioural problems, similar association patterns were seen for *SDQ Adolescents conduct problems* and *hyperactivity/inattention* and partly for *emotional symptoms* as well (Fig. S2 in Supplementary material). For *SDQ Adolescents peer relationship problems* the pattern was different for text messages: the more text messages sent, the less peer relationship problems. Gaming and whole body dose for the whole sample were positively associated with peer relationship problems as for all other difficulty scales. The pattern was similar for parent-rated behavioural problems measured by the SDQ Parents (Table S1 and Figs. S3 and S4 in Supplementary material).

In the longitudinal analysis only a few significant effects were observed, all in the direction of a positive impact from exposure: in the whole sample the duration of mobile phone calls and the cumulative RF-EMF brain and whole-body dose were associated with a decrease in *SDQ Adolescents total difficulties* over one year (Table 3). However, these associations were neither seen for operator-recorded exposure measures nor for any exposure measure in relation to the *SDQ Parents total difficulties* (Table S1). Duration of gaming was associated with an increase in the *SDQ Adolescents total strengths* between baseline and follow-up. The adjustment for confounders had little impact on the results and the results were comparable for the analysis with categorical exposure measures (data not shown).

Table 1
Descriptive statistics of the mixed (cross-sectional mixed model analysis) and cumulative (longitudinal analysis) exposure measures for the whole sample and the operator sample: mean (standard deviation (SD)), minimum (min), maximum (max) and interquartile range (IQR).

	Cross-sectional mixed model analysis (baseline and follow-up)								Longitudinal analysis							
	Whole sample (n = 864)				Operator sample (n = 462)				Whole sample (n = 425)				Operator sample (n = 234)			
	mean (SD)	min	max	IQR	mean (SD)	min	max	IQR	mean (SD)	min	max	IQR	mean (SD)	min	max	IQR
Usage not related to RF-EMF exposure																
self-reported																
duration gaming [min/d]	45.36 (64.05)	0.00	457.14	68.57	42.64 (62.08)	0.00	457.14	60.00	45.23 (54.65)	0.00	257.86	58.57	41.83 (52.51)	0.00	257.86	51.86
text messages sent [x/d]	30.99 (25.88)	0.00	101.19	47.20	29.93 (25.08)	0.50	101.19	47.20	30.93 (20.84)	0.00	76.41	36.81	29.81 (20.10)	0.50	76.41	34.48
operator-recorded																
SMS sent [x/d]	–	–	–	–	2.09 (3.94)	0.00	40.77	1.72	–	–	–	–	1.67 (2.25)	0.00	16.05	1.32
Usage related to RF-EMF exposure																
self-reported																
duration data traffic mobile phone [min/d]	48.31 (40.80)	0.00	111.88	82.32	48.56 (41.31)	0.00	111.88	82.32	48.18 (33.18)	0.00	107.76	51.82	48.57 (35.02)	0.00	107.76	57.62
duration cordless phone calls [min/d]	7.44 (9.52)	0.00	60.99	8.00	6.50 (7.71)	0.00	50.23	8.00	7.33 (7.62)	0.00	53.15	6.93	6.58 (6.67)	0.00	47.87	5.79
duration mobile phone calls [min/d]	16.32 (31.71)	0.00	485.00	16.57	15.02 (25.78)	0.00	267.14	14.43	16.00 (25.65)	0.00	293.93	15.57	15.25 (26.93)	0.00	293.93	13.43
operator-recorded																
volume data traffic mobile phone [MB/d]	–	–	–	–	7.72 (22.26)	0.00	263.74	8.05	–	–	–	–	8.97 (18.95)	0.00	140.18	10.88
duration mobile phone calls [min/d]	–	–	–	–	1.76 (3.52)	0.00	30.22	1.45	–	–	–	–	1.87 (3.57)	0.00	28.61	1.56
Cumulative RF-EMF dose																
whole sample																
brain dose [mJ/kg/d]	1'411 (2'278)	13	22'608	1'467	1'268 (2'243)	13	22'608	1'209	1'421 (1'979)	18	16'233	1'579	1'258 (1'851)	18	13'168	1'297
whole body dose [mJ/kg/d]	322 (452)	7	6'630	261	295 (385)	7	4'065	220	322 (431)	12	6'044	260	303 (468)	16	6'044	224
operator sample																
brain dose [mJ/kg/d]	–	–	–	–	210 (329)	14	3'400	182	–	–	–	–	235 (432)	23	4'787	176
whole body dose [mJ/kg/d]	–	–	–	–	123 (85)	12	607	101	–	–	–	–	125 (87)	16	756	84

Table 2
Prevalence for behavioural problems and descriptive statistics of the mixed (baseline and follow-up; cross-sectional mixed model analysis) and cumulative (difference follow-up – baseline; longitudinal analysis) behavioural problems (SDQ) and concentration capacity (FAKT).

Behavioural problems	Baseline prevalence[b]		Cross-sectional mixed model analysis (baseline and follow-up)									Longitudinal analysis							
			Whole sample (n = 864)				Operator sample (n = 462)					Whole sample (n = 425)				Operator sample (n = 234)			
	n[a]	%	n[a]	mean (SD)	min	max	n[a]	mean (SD)	min	max	theoretical range	n[a]	mean (SD)	min	max	n[a]	mean (SD)	min	max
SDQ Adolescents																			
Total difficulties[c]	439	3.2	863	9.59 (4.66)	0	31	462	9.44 (4.60)	1	31	(0, 40)	424	−0.76 (4.12)	−24	13	234	−0.51 (3.98)	−14	11
Emotional symptoms	439	3.2	863	2.42 (1.99)	0	9	462	2.38 (1.95)	0	9	(0, 10)	424	−0.05 (1.95)	−9	7	234	0.09 (2.02)	−6	7
Conduct problems	439	6.2	863	1.71 (1.43)	0	7	462	1.64 (1.48)	0	7	(0, 10)	424	−0.25 (1.45)	−5	4	234	−0.29 (1.46)	−5	4
Hyperactivity/Inattention	439	9.8	864	3.42 (1.97)	0	10	462	3.44 (1.89)	0	9	(0, 10)	425	−0.35 (1.83)	−8	5	234	−0.25 (1.71)	−5	4
Peer relationship problems	439	4.6	863	2.05 (1.69)	0	10	462	1.99 (1.70)	0	10	(0, 10)	424	−0.12 (1.58)	−6	6	234	−0.06 (1.57)	−6	5
Total strengths[d]	439	2.5[e]	863	8.14 (1.57)	0	10	462	8.22 (1.51)	2	10	(0, 10)	424	0.15 (1.60)	−6	5	234	0.11 (1.56)	−6	5
SDQ Parents																			
Total difficulties[c]	367	3.3	712	5.83 (4.40)	0	27	406	5.66 (4.27)	0	22	(0, 10)	317	−0.52 (3.84)	−25	12	188	−0.39 (3.49)	−13	12
Emotional symptoms	367	5.2	712	1.16 (1.53)	0	10	406	1.08 (1.39)	0	10	(0, 10)	317	−0.28 (1.44)	−10	4	188	−0.18 (1.33)	−5	4
Conduct problems	367	8.2	712	1.27 (1.33)	0	8	406	1.22 (1.30)	0	7	(0, 10)	317	−0.08 (1.23)	−6	4	188	0.01 (1.17)	−4	4
Hyperactivity/Inattention	367	3.0	712	2.19 (1.90)	0	10	406	2.15 (1.86)	0	8	(0, 10)	317	−0.09 (1.66)	−7	5	188	−0.05 (1.63)	−7	5
Peer relationship problems	367	10.1	712	1.22 (1.60)	0	9	406	1.21 (1.63)	0	9	(0, 10)	317	−0.08 (1.41)	−6	4	188	−0.16 (1.39)	−6	4
Total strengths[d]	367	5.2[e]	712	8.00 (1.77)	1	10	406	8.04 (1.73)	2	10	(0, 10)	317	−0.01 (1.78)	−8	6	188	0.07 (1.78)	−5	6
Concentration capacity																			
Homogeneity of concentration	–	–	703	30.09 (20.88)	5	132	382	30.76 (21.69)	5	132	>0	290	11.42 (20.95)	−42	87	161	10.02 (20.98)	−36	87
Power of concentration	–	–	703	88.64 (30.16)	17	177	382	89.21 (30.24)	17	177	>0	290	20.83 (24.10)	−43	88	161	18.75 (23.08)	−43	78
Accuracy of concentration	–	–	703	80.29 (5.87)	67	99	382	80.48 (6.05)	67	99	(0, 100)	290	2.35 (5.85)	−13	22	161	2.10 (5.82)	−11	22

[a] Due to non-response (SDQ) and technical failures of the computerized testing system (FAKT) data was not available for all participants.
[b] The baseline prevalence was calculated based on (Goodman et al., 1998) for the SDQ Adolescents and (Goodman, 1997) for the SDQ Parents and is referring to the percentage of adolescents in the "abnormal" band. For the cut-offs see text.
[c] Higher scores on the difficulties scales mean more difficulties.
[d] Higher scores on the total strengths scale mean more strengths.
[e] Prevalence of problematic lack of *total strengths*.

Table 3
Crude and adjusted changes in behavioural scores (coefficients) and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for SDQ Adolescents total difficulties and total strengths for the cross-sectional mixed model analysis and the longitudinal analysis. Significant results ($p < 0.05$) are indicated in bold. For corresponding figures see Figs. S1 and S2 in the Supplementary material. For results for SDQ Parents total difficulties and total strengths see Table S1 in the Supplementary material.

	Cross-sectional mixed model analysis		Longitudinal analysis	
	crude Coeff (95% CI)	adjusted [a] Coeff (95% CI)	crude Coeff (95% CI)	adjusted [b] Coeff (95% CI)
1) SDQ Adolescents total difficulties				
a) Usage not related to RF-EMF exposure				
self-reported				
duration gaming [min/d]	**0.64 (0.33, 0.95)**	**0.68 (0.35, 1.01)**	0.14 (−0.29, 0.56)	0.12 (−0.38, 0.62)
text messages sent [x/d]	−0.04 (−0.54, 0.46)	**0.69 (0.11, 1.26)**	−0.10 (−0.80, 0.60)	0.00 (−0.76, 0.75)
operator-recorded				
SMS sent [x/d]	0.13 (−0.03, 0.29)	0.11 (−0.05, 0.26)	0.01 (−0.30, 0.31)	−0.01 (−0.33, 0.31)
b) Usage related to RF-EMF exposure				
self-reported				
duration data traffic mobile phone [min/d]	**0.60 (0.04, 1.16)**	**0.98 (0.41, 1.55)**	−0.02 (−0.63, 0.60)	−0.01 (−0.66, 0.64)
duration cordless phone calls [min/d]	**0.43 (0.20, 0.66)**	**0.36 (0.12, 0.59)**	−0.05 (−0.42, 0.31)	−0.05 (−0.43, 0.33)
duration mobile phone calls [min/d]	**0.29 (0.14, 0.44)**	**0.28 (0.13, 0.43)**	**−0.32 (−0.56, −0.08)**	**−0.34 (−0.59, −0.08)**
operator-recorded				
volume data traffic mobile phone [MB/d]	−0.02 (−0.14, 0.11)	0.02 (−0.10, 0.15)	0.11 (−0.19, 0.40)	0.07 (−0.23, 0.37)
duration mobile phone calls [min/d]	0.06 (−0.10, 0.22)	0.06 (−0.10, 0.21)	−0.08 (−0.31, 0.14)	−0.10 (−0.33, 0.14)
c) Cumulative RF-EMF dose				
whole sample				
brain dose [mJ/kg/d]	**0.36 (0.19, 0.54)**	**0.33 (0.15, 0.50)**	**−0.59 (−0.90, −0.29)**	**−0.61 (−0.93, −0.28)**
whole-body dose [mJ/kg/d]	**0.43 (0.26, 0.59)**	**0.41 (0.25, 0.57)**	**−0.35 (−0.58, −0.11)**	**−0.39 (−0.63, −0.14)**
operator sample				
brain dose [mJ/kg/d]	0.22 (−0.01, 0.45)	0.19 (−0.04, 0.42)	−0.14 (−0.35, 0.07)	−0.19 (−0.40, 0.03)
whole-body dose [mJ/kg/d]	**1.13 (0.65, 1.62)**	**1.19 (0.70, 1.68)**	0.10 (−0.40, 0.60)	−0.03 (−0.55, 0.50)
2) SDQ Adolescents total strengths				
a) Usage not related to RF-EMF exposure				
self-reported				
duration gaming [min/d]	**−0.25 (−0.36, −0.14)**	−0.08 (−0.20, 0.03)	0.14 (−0.02, 0.30)	**0.26 (0.06, 0.45)**
text messages sent [x/d]	0.09 (−0.09, 0.28)	−0.04 (−0.24, 0.16)	−0.04 (−0.31, 0.23)	0.05 (−0.25, 0.35)
operator-recorded				
SMS sent [x/d]	0.04 (−0.02, 0.09)	0.03 (−0.02, 0.09)	0.01 (−0.10, 0.13)	0.00 (−0.13, 0.13)
b) Usage related to RF-EMF exposure				
self-reported				
duration data traffic mobile phone [min/d]	−0.08 (−0.28, 0.12)	−0.19 (−0.39, 0.01)	−0.01 (−0.25, 0.23)	0.06 (−0.19, 0.32)
duration cordless phone calls [min/d]	0.02 (−0.06, 0.11)	0.00 (−0.08, 0.09)	0.03 (−0.11, 0.17)	0.05 (−0.10, 0.20)
duration mobile phone calls [min/d]	0.00 (−0.05, 0.06)	−0.02 (−0.08, 0.03)	0.01 (−0.08, 0.10)	0.03 (−0.07, 0.13)
operator-recorded				
volume data traffic mobile phone [MB/d]	−0.02 (−0.06, 0.03)	−0.02 (−0.07, 0.02)	−0.08 (−0.20, 0.03)	−0.08 (−0.20, 0.04)
duration mobile phone calls [min/d]	0.03 (−0.03, 0.08)	0.03 (−0.03, 0.08)	0.01 (−0.07, 0.10)	0.00 (−0.09, 0.09)
c) Cumulative RF-EMF dose				
whole sample				
brain dose [mJ/kg/d]	0.00 (−0.06, 0.06)	−0.02 (−0.08, 0.04)	−0.02 (−0.14, 0.10)	0.00 (−0.13, 0.13)
whole-body dose [mJ/kg/d]	−0.02 (−0.08, 0.03)	−0.05 (−0.11, 0.01)	−0.01 (−0.10, 0.08)	0.01 (−0.09, 0.11)
operator sample				
brain dose [mJ/kg/d]	−0.03 (−0.11, 0.05)	−0.03 (−0.10, 0.05)	0.00 (−0.08, 0.09)	0.00 (−0.08, 0.09)
whole-body dose [mJ/kg/d]	−0.08 (−0.25, 0.09)	−0.08 (−0.25, 0.09)	−0.04 (−0.24, 0.15)	−0.03 (−0.24, 0.17)

[a] Cross-sectional models were adjusted for age, sex, nationality, school level, frequency of physical activity, frequency of alcohol consumption (asked in the adolescents' questionnaire) and highest educational level of the parents (asked in the parent's questionnaire).
[b] Longitudinal models were additionally adjusted for change in height between baseline and follow-up (asked in adolescents' questionnaire) and time between baseline and follow-up.

3.5. Concentration capacity

Concentration capacity was significantly negatively associated with some self-reported as well as objectively recorded use and dose measures in the cross-sectional mixed model analysis: However, no associations were seen in the longitudinal analysis except a decrease in homogeneity and power of concentration over one year in relation to duration of gaming (Fig. 1 and Table S2 in Supplementary material). The adjustment for confounders did not much change the results and results were comparable for categorical exposure measures (data not shown).

3.6. Personal measurements

In the subset of 91 adolescents with personal measurements, mean total RF-EMF exposure was 66.8 $\mu W/m^2$ (interquartile range = 64.5 $\mu W/m$), mean total exposure without uplink (mobile phone handsets) was 24.7 $\mu W/m^2$ (35.7 $\mu W/m$), mean fixed site transmitters exposure 17.0 $\mu W/m^2$ (16.0 $\mu W/m$) and mean downlink exposure (mobile phone base stations) 12.7 $\mu W/m^2$ (11.5 $\mu W/m^2$). *SDQ Adolescents total difficulties* and *total strengths* and *SDQ Parents total difficulties* and *total strengths* were not related to measured RF-EMF exposure (Table 4 and Table S3 in Supplementary material). Homogeneity and power of concentration were significantly negatively associated with total RF-EMF exposure if uplink was not considered, but not with downlink and fixed site transmitters exposure alone (Table 4). Accuracy of concentration was not associated with either of the measured exposures.

4. Discussion

In this study the associations of behavioural problems and concentration capacity with several self-reported and operator-recorded exposure measures involving different extent of RF-EMF

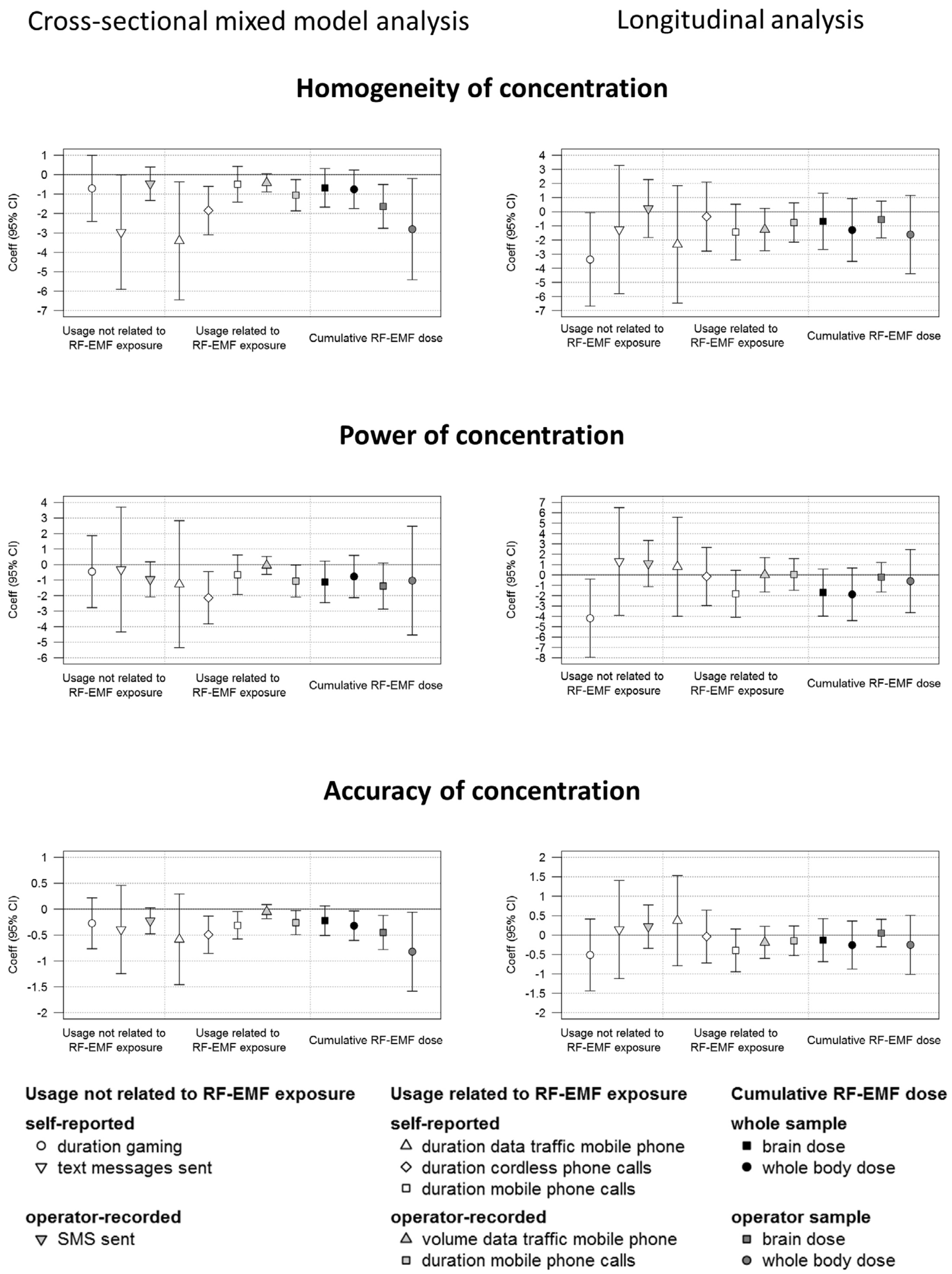

Fig. 1. Adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for concentration capacity (FAKT) for the cross-sectional mixed model analysis and the longitudinal analysis. For corresponding numbers see Table S2 in the Supplementary material.

exposure were explored applying a cross-sectional as well as a longitudinal approach. Behavioural problems and concentration capacity were associated with several wireless device use and RF-EMF dose exposure variables in the cross-sectional analysis, but less so in the longitudinal analysis. Thus, in summary we did not find indications that RF-EMF exposure affects behaviour or concentration capacity of adolescents.

The cross-sectional associations for self-reported duration of gaming and data traffic on the mobile phone are in line with the findings of Byun et al. (2013) and Zheng et al. (2014) of ADHD symptoms being related to mobile phone use for gaming (Byun et al., 2013) and of inattention to time spent on the mobile phone for entertainment (Zheng et al., 2014). For these cross-sectional analyses reverse causality is of concern. It is conceivable that hyperactive adolescents with problems in attention are prone to game longer and use their mobile phone with its various possibilities to entertain more often than other adolescents. But if indeed extensive gaming or extensive mobile phone use would cause behavioural problems, one would expect to see this in the longitudinal analyses as well. However, this was not the case; rather we found self-reported duration of mobile phone calls and RF-EMF dose measures to be associated with a *decrease* in *SDQ Adolescents total difficulties* over one year. Though, these relations were neither seen for objectively recorded mobile phone call duration nor for the *SDQ Parents*

Table 4
Crude and adjusted changes in behavioural scores (coefficients) and corresponding 95% confidence intervals (95% CI) per interquartile change in personal exposure measurement variables for SDQ Adolescents total difficulties and total strengths and concentration capacity (FAKT). Significant results ($p < 0.05$) are indicated in bold. For results for SDQ Parents total difficulties and total strengths see Table S3 in the Supplementary material.

Behavioural problems	n[e]	crude Coeff (95% CI)	adjusted[f] Coeff (95% CI)
SDQ Adolescents total difficulties			
Downlink[a]	91	0.09 (−0.60, 0.78)	0.16 (−0.58, 0.90)
Fixed site transmitters[b]	91	0.15 (−0.58, 0.88)	0.20 (−0.59, 0.98)
Total[c]	91	0.24 (−0.45, 0.92)	0.16 (−0.59, 0.91)
Total without uplink[d]	91	0.39 (−0.43, 1.22)	0.43 (−0.46, 1.32)
SDQ Adolescents total strengths			
Downlink[a]	91	−0.01 (−0.20, 0.19)	−0.10 (−0.31, 0.10)
Fixed site transmitters[b]	91	−0.09 (−0.29, 0.12)	−0.20 (−0.41, 0.01)
Total[c]	91	0.05 (−0.15, 0.24)	−0.03 (−0.24, 0.18)
Total without uplink[d]	91	−0.03 (−0.26, 0.21)	−0.16 (−0.41, 0.08)
Concentration capacity			
Homogeneity of concentration			
Downlink[a]	79	−1.39 (−5.22, 2.45)	−0.19 (−3.53, 3.16)
Fixed site transmitters[b]	79	−2.43 (−6.96, 2.11)	−0.75 (−4.78, 3.29)
Total[c]	79	−0.78 (−3.11, 1.54)	−2.04 (−4.14, 0.05)
Total without uplink[d]	79	−2.65 (−6.44, 1.13)	**−3.50 (−6.79, −0.20)**
Power of concentration			
Downlink[a]	79	−2.69 (−7.45, 2.08)	−1.15 (−5.60, 3.30)
Fixed site transmitters[b]	79	−4.36 (−9.98, 1.26)	−2.31 (−7.66, 3.04)
Total[c]	79	−1.24 (−4.14, 1.66)	−2.37 (−5.18, 0.44)
Total without uplink[d]	79	−4.94 (−9.58, −0.29)	**−6.00 (−10.30, −1.71)**
Accuracy of concentration			
Downlink[a]	79	−0.11 (−1.13, 0.90)	−0.02 (−1.06, 1.01)
Fixed site transmitters[b]	79	−0.19 (−1.39, 1.02)	−0.03 (−1.28, 1.22)
Total[c]	79	−0.03 (−0.64, 0.59)	−0.09 (−0.76, 0.57)
Total without uplink[d]	79	−0.27 (−1.28, 0.74)	−0.35 (−1.40, 0.70)

[a] Downlink means exposure from mobile phone base stations.
[b] Fixed site transmitters means exposure from fixed site transmitters (TV broadcast transmitters and mobile phone base stations).
[c] Total means the total RF-EMF exposure.
[d] Total without uplink means total RF-EMF exposure without exposure from mobile phone handsets.
[e] Due to technical failures of the computerized testing system (FAKT) data was not available for all participants.
[f] Models were adjusted for age, sex, nationality, school level, frequency of physical activity, frequency of alcohol consumption (asked in the adolescents' questionnaire) and highest educational level of the parents (asked in the parents' questionnaire).

total difficulties. Concentration capacity of the adolescents was negatively associated with several self-reported and objectively recorded use and dose measures in the cross-sectional analysis. These cross-sectional findings are in line with other cross-sectional studies on self-reported concentration difficulties and mobile and cordless phone use (Söderqvist et al., 2008) and measured concentration performance and number of mobile phone calls (Abramson et al., 2009). But they contradict a study in students from Hong Kong where mobile phone users showed a better performance in one of three cognitive tasks measuring attention (Lee et al., 2001).

In agreement with a longitudinal Australian study (Thomas et al., 2010a) we did not find cumulative mobile phone use between baseline and follow-up related to changes in concentration capacity over one year in the longitudinal analysis. However, we found cumulative duration of gaming associated with a reduction in concentration capacity over one year. One may speculate that regular gamers in our sample were less motivated compared to the rest of the sample to conduct concentration tests, which may appear rather boring compared to computer games.

To the best of our knowledge, this is the first study investigating behavioural problems and concentration capacity of adolescents using a longitudinal approach and combining various exposure measures including self-reported and operator-recorded mobile phone use and cumulative RF-EMF dose measures. The RF-EMF dose measures consider various exposure relevant circumstances such as the use of mobile phones for calling and data transmission, cordless phone use, the use computers, laptops and tablets connected to WLAN and environmental sources such as mobile phone base stations, broadcast transmitters, cordless phone and WLAN base stations and mobile phones in the surroundings.

In contrast to previous studies on this subject we additionally considered objectively recorded duration of mobile phone calls, frequency of SMS sent and amount of data traffic on the mobile phone. Thus, recall bias is not of concern for these analyses.

Strikingly, cross-sectional associations for behavioural problems were systematically stronger for self-reported use compared to objectively recorded use. This indicates that information bias may be relevant in this context for our study as well as for other cross-sectional studies. Such a pattern was not seen for the concentration test.

To measure concentration capacity, a standardized computerized cognitive test battery was used. Although factors such as carefulness or motivation may have influenced the performance of the adolescents, these factors would only act as confounders, if they were related to the exposures as well. Behavioural problems were self-reported by the adolescents using a standardized and widely used scale. We had additionally parent-rated behavioural problems available. We found slightly more associations for the self-reported behavioural problems compared to the parent-rated behavioural problems. These may be caused by information bias.

One major aim of this study was to differentiate between effects from RF-EMF exposure and other factors related to the use of wireless communication devices such as addiction (Roser et al., 2015b), sleep deprivation from blue screen (Cajochen et al., 2011) or being awakened at night by a mobile phone (Schoeni et al., 2015b; Van den Bulck, 2003). We hypothesized that if there was a causal association between RF-EMF exposure and behaviour or concentration capacity, one would expect more pronounced associations for dose measures compared to simple usage surrogates as we have seen for memory performance in our study (Schoeni et al., 2015a). However, this was not the case. Associations for RF-EMF dose measures tended to be similar to usage measures and thus RF-EMF exposure is unlikely to be relevant for the observed associations. Nevertheless, the fact that some usage measures are used to estimate the RF-EMF doses limits the possibility to disentangle effects from RF-EMF exposure and effects from device us itself. For instance cumulative duration of self-reported mobile phone calls is the main contributor to the brain dose (93.6%) and the whole body dose (69.4%) producing a high correlation. This high correlation explains why in the longitudinal analysis a decrease of *SDQ Adolescents total difficulties* with increasing brain and whole-body RF-EMF dose was observed, which was similar to the association with self-reported mobile phone call duration. From the comparison with operator recorded mobile phone use, it becomes obvious that self-reported mobile phone use is overestimated and thus, the lack of consistency in terms of operator-recorded data and parental SDQ rating does not indicate an EMF effect for *total difficulties*.

In addition to calculated RF-EMF dose measures, we used personal RF-EMF measurements from a subsample of the participants to investigate RF-EMF exposure and behavioural problems and concentration capacity. We did not find an association between behavioural problems and measured personal RF-EMF exposure. This is in contrast to a German study showing significantly more behavioural problems in adolescents with higher measured exposure (Thomas et al., 2010b). However, homogeneity and power of concentration were negatively related to measured total RF-EMF exposure without uplink (exposure from mobile phone handsets). Measured total exposure without uplink represents mainly exposure from fixed site transmitters (broadcast transmitters and mobile phone base stations) and to a smaller extent exposure from cordless phone and WLAN base stations (Roser et al. under preparation). Unlike uplink, these environmental sources are not related to lifestyle and less heavily affected by the own behaviour. However, these environmental sources contribute only minimally (1.6% of the brain dose and 6.0% of the whole body dose (Roser et al., 2015a)) to the total RF-EMF dose. In addition, the sample for this analysis is small. Thus, these results should be interpreted with caution. The most comparable study in terms of this type of exposure is the experimental study by Riddervold et al. (2008) showing no effects of 45 min of UMTS base station exposure on attention performance in adolescents (Riddervold et al., 2008). In our HERMES cohort self-reported symptoms were not consistently associated with modelled RF-EMF exposure from fixed site transmitters (Schoeni et al., 2016).

5. Conclusions

We have confirmed previous cross-sectional studies reporting associations between behavioural problems and self-reported duration of wireless device use. Our associations were weaker if objectively recorded usage data were considered, which suggests that recall bias has affected the cross-sectional associations based on self-reported exposure. Further, the lack of consistent exposure-response patterns in our longitudinal analyses on behaviour and concentration capacity indicates the absence of causality but rather reverse causality as an explanation for observed associations in cross-sectional analyses. In summary, we did not find indications that RF-EMF exposure affects behaviour or concentration capacity of adolescents.

Competing financial interests

The authors declare no competing financial interests.

Author contributions

MR conceived and designed the study. KR and AS performed the study. KR analysed the data. AS, KR and MR contributed materials and analysis tools. KR wrote the paper. AS and MR reviewed and revised the manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijheh.2016.08.007.

References

Abramson, M.J., Benke, G.P., Dimitriadis, C., Inyang, I.O., Sim, M.R., Wolfe, R.S., Croft, R.J., 2009. Mobile telephone use is associated with changes in cognitive function in young adolescents. Bioelectromagnetics 30, 678–686, http://dx.doi.org/10.1002/bem.20534.

Aydin, D., Feychting, M., Schuz, J., Andersen, T.V., Poulsen, A.H., Prochazka, M., Klaeboe, L., Kuehni, C.E., Tynes, T., Röösli, M., 2011. Predictors and overestimation of recalled mobile phone use among children and adolescents. Prog. Biophys. Mol. Biol. 107, 356–361, http://dx.doi.org/10.1016/j.pbiomolbio.2011.08.013.

Bürgi, A., Theis, G., Siegenthaler, A., Röösli, M., 2008. Exposure modeling of high-frequency electromagnetic fields. J. Expo. Sci. Environ. Epidemiol. 18, 183–191, http://dx.doi.org/10.1038/sj.jes.7500575.

Bürgi, A., Frei, P., Theis, G., Mohler, E., Braun-Fahrländer, C., Fröhlich, J., Neubauer, G., Egger, M., Röösli, M., 2010. A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research. Bioelectromagnetics 31, 226–236, http://dx.doi.org/10.1002/bem.20552.

Byun, Y.H., Ha, M., Kwon, H.J., Hong, Y.C., Leem, J.H., Sakong, J., Kim, S.Y., Lee, C.G., Kang, D., Choi, H.D., et al., 2013. Mobile phone use, blood lead levels and attention deficit hyperactivity symptoms in children: a longitudinal study. PLoS One 8, e59742, http://dx.doi.org/10.1371/journal.pone.0059742.

Cajochen, C., Frey, S., Anders, D., Spati, J., Bues, M., Pross, A., Mager, R., Wirz-Justice, A., Stefani, O., 2011. Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance. J. Appl. Physiol. (1985) 110, 1432–1438, http://dx.doi.org/10.1152/japplphysiol.00165.2011.

Gati, A., Hadjem, A., Man-Fai, W., Wiart, J., 2009. Exposure induced by WCDMA mobiles phones in operating networks. IEEE Trans. Wireless Commun. 8, 5723–5727, http://dx.doi.org/10.1109/TWC.2009.12.080758.

Goodman, R., Meltzer, H., Bailey, V., 1998. The strengths and difficulties questionnaire: a pilot study on the validity of the self-report version. Eur. Child Adolesc. Psychiatry 7, 125–130.

Goodman, R., 1997. The strengths and difficulties questionnaire: a research note. J. Child Psychol. Psychiatry 38, 581–586.

Goodman, R., 2001. Psychometric properties of the strengths and difficulties questionnaire. J. Am. Acad. Child Adolesc. Psychiatry 40, 1337–1345, http://dx.doi.org/10.1097/00004583-200111000-00015.

Hölling, H., Erhart, M., Ravens-Sieberer, U., Schlack, R., 2007. Verhaltensauffälligkeiten bei Kindern und Jugendlichen Bundesgesundheitsblatt – Gesundheitsforschung – Gesundheitsschutz, 50, 784–793, http://dx.doi.org/10.1007/s00103-007-0241-7.

Hadjem, A., Conil, E., Gati, A., Wong, M.-F., Wiart, J., 2010. Analysis of power absorbed by children's head as a result of new usages of mobile phone. IEEE Trans. Electromagn. Compat. 52, 812–819.

Heinrich, S., Thomas, S., Heumann, C., von Kries, R., Radon, K., 2010. Association between exposure to radiofrequency electromagnetic fields assessed by dosimetry and acute symptoms in children and adolescents: a population based cross-sectional study. Environ. Health 9 (75), http://dx.doi.org/10.1186/1476-069x-9-75.

Huang, Y., Conil, E., Wiart, J., Varsier, N., Person, C., 2014. Sensitivity analysis of downlink received and uplink emitted powers in a geographical area to ICT usage parameters. In: Paper presented at the Proceedings of the Annual Meeting of BEMS and EBEA, Capetown, South Africa, June 8–13, 2014.

In-Albon, T., Zumsteg, U., Muller, D., Schneider, S., 2010. Mental disorders in the pediatric setting – results of a Swiss survey. Swiss Med. Wkly. 140, w13092, http://dx.doi.org/10.4414/smw.2010.13092.
Inyang, I., Benke, G., Morrissey, J., McKenzie, R., Abramson, M., 2009. How well do adolescents recall use of mobile telephones? Results of a validation study. BMC Med. Res. Methodol. 9, 36, http://dx.doi.org/10.1186/1471-2288-9-36.
Klasen, H., Woerner, W., Rothenberger, A., Goodman, R., 2003. German version of the strength and difficulties questionnaire (SDQ-German)—overview and evaluation of initial validation and normative results. Prax. Kinderpsychol. Kinderpsychiatr. 52, 491–502.
Lauer, O., Frei, P., Gosselin, M.C., Joseph, W., Röösli, M., Fröhlich, J., 2013. Combining near- and far-field exposure for an organ-specific and whole-body RF-EMF proxy for epidemiological research: a reference case. Bioelectromagnetics 34, 366–374, http://dx.doi.org/10.1002/bem.21782.
Lee, T.M., Ho, S.M., Tsang, L.Y., Yang, S.H., Li, L.S., Chan, C.C., Yang, S.Y., 2001. Effect on human attention of exposure to the electromagnetic field emitted by mobile phones. Neuroreport 12, 729–731.
Müller, C.M., Hofmann, V., Fleischli, J., Studer, F., 2015. Effects of classroom composition on the development of antisocial behavior in lower secondary school. J. Res. Adolesc., http://dx.doi.org/10.1111/jora.12195, n/a–n/a.
Moosbrugger, H., Goldhammer, F., 2007. FAKT-II Frankfurter Adaptiver Konzentrationsleistungs-Test II Manual Verlag Hans Huber. Hogrefe AG, Bern.
Persson, T., Tornevik, C., Larsson, L.E., Loven, J., 2012. Output power distributions of terminals in a 3G mobile communication network. Bioelectromagnetics 33, 320–325, http://dx.doi.org/10.1002/bem.20710.
Riddervold, I.S., Pedersen, G.F., Andersen, N.T., Pedersen, A.D., Andersen, J.B., Zachariae, R., Molhave, L., Sigsgaard, T., Kjaergaard, S.K., 2008. Cognitive function and symptoms in adults and adolescents in relation to RF radiation from UMTS base stations. Bioelectromagnetics 29, 257–267, http://dx.doi.org/10.1002/bem.20388.
Roser, K., Schoeni, A., Bürgi, A., Röösli, M., 2015a. Development of an RF-EMF exposure surrogate for epidemiologic research. Int. J. Environ. Res. Public Health 12, 5634–5656.
Roser, K., Schoeni, A., Foerster, M., Röösli, M., 2015b. Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour? Int. J. Public Health, http://dx.doi.org/10.1007/s00038-015-0751-2.
Roser, K., Schoeni, A., Struchen, B., Zahner, M., M., Eeftens, Fröhlich, J., Röösli, M. (under preparation) Personal radiofrequency electromagnetic field exposure measurements in Swiss adolescents.
Söderqvist, F., Carlberg, M., Hardell, L., 2008. Use of wireless telephones and self-reported health symptoms: a population-based study among Swedish adolescents agedyears. Environ. Health 7 (18), 15–19, http://dx.doi.org/10.1186/1476-069x-7-18.
SEAWIND, 2013. SEAWIND Sound Exposure & Risk Assessment of Wireless Network Devices Final Summary Report. http://seawind-fp7.eu/uploads/SEAWIND_FINAL.pdf.
Schoeni, A., Roser, K., Röösli, M., 2015a. Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: a prospective cohort study in adolescents. Environ. Int. 85, 343–351, http://dx.doi.org/10.1016/j.envint.2015.09.025.
Schoeni, A., Roser, K., Röösli, M., 2015b. Symptoms and cognitive functions in adolescents in relation to mobile phone use during night. PLoS One 10, e0133528, http://dx.doi.org/10.1371/journal.pone.0133528.
Schoeni, A., Roser, K., Burgi, A., Roosli, M., 2016. Symptoms in Swiss adolescents in relation to exposure from fixed site transmitters: a prospective cohort study. Environ. Health 15 (77), http://dx.doi.org/10.1186/s12940-016-0158-4.
Thomas, S., Benke, G., Dimitriadis, C., Inyang, I., Sim, M.R., Wolfe, R., Croft, R.J., Abramson, M.J., 2010a. Use of mobile phones and changes in cognitive function in adolescents. Occup. Environ. Med. 67, 861–866, http://dx.doi.org/10.1136/oem.2009.054080.
Thomas, S., Heinrich, S., von Kries, R., Radon, K., 2010b. Exposure to radio-frequency electromagnetic fields and behavioural problems in Bavarian children and adolescents. Eur. J. Epidemiol. 25, 135–141, http://dx.doi.org/10.1007/s10654-009-9408-x.
Van den Bulck, J., 2003. Text messaging as a cause of sleep interruption in adolescents evidence from a cross-sectional study. J. Sleep Res. 12, 263.
Vrijheid, M., Mann, S., Vecchia, P., Wiart, J., Taki, M., Ardoino, L., Armstrong, B.K., Auvinen, A., Bedard, D., Berg-Beckhoff, G., et al., 2009. Determinants of mobile phone output power in a multinational study: implications for exposure assessment. Occup. Environ. Med. 66, 664–671, http://dx.doi.org/10.1136/oem.2008.043380.
WHO, 2010. WHO Research Agenda for Radiofrequency Fields.
Willemse, I., Waller, G., Süss, D., 2014. JAMES Jugend, Aktivitäten, Medien – Erhebung Schweiz, Factsheet Befunde. Zurich University of Applied Sciences.
Zheng, F., Gao, P., He, M., Li, M., Wang, C., Zeng, Q., Zhou, Z., Yu, Z., Zhang, L., 2014. Association between mobile phone use and inattention in 7102 Chinese adolescents: a population-based cross-sectional study. BMC Public Health 14 (1022), http://dx.doi.org/10.1186/1471-2458-14-1022.

Supplementary Material

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Mobile phone use, behavioural problems and concentration capacity in adolescents: a prospective study

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Behavioural problems (SDQ)

Table S1. Crude and adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for SDQ Parents total difficulties and total strengths for the cross-sectional mixed model analysis and the longitudinal analysis. Significant results ($p < 0.05$) are indicated in bold. For corresponding figures see Figures S3 and S4.

	Cross-sectional mixed model analysis		Longitudinal analysis	
	crude Coeff (95% CI)	**adjusted[a] Coeff (95% CI)**	**crude Coeff (95% CI)**	**adjusted[b] Coeff (95% CI)**
SDQ Parents total difficulties				
Usage not related to RF-EMF exposure				
self-reported				
duration gaming [min/d]	**0.64 (0.34, 0.95)**	**0.51 (0.19, 0.84)**	-0.03 (-0.48, 0.42)	0.06 (-0.45, 0.58)
text messages sent [x/d]	-0.32 (-0.87, 0.23)	-0.21 (-0.84, 0.41)	0.00 (-0.72, 0.73)	-0.04 (-0.83, 0.74)
operator-recorded				
SMS sent [x/d]	**0.19 (0.03, 0.36)**	**0.18 (0.02, 0.35)**	-0.07 (-0.32, 0.19)	-0.03 (-0.29, 0.24)
Usage related to RF-EMF exposure				
self-reported				
duration data traffic mobile phone [min/d]	**0.75 (0.11, 1.38)**	**0.91 (0.26, 1.56)**	-0.26 (-0.96, 0.44)	-0.33 (-1.07, 0.41)
duration cordless phone calls [min/d]	0.18 (-0.10, 0.45)	0.17 (-0.10, 0.44)	-0.13 (-0.47, 0.21)	-0.15 (-0.50, 0.20)
duration mobile phone calls [min/d]	-0.03 (-0.20, 0.15)	-0.02 (-0.20, 0.16)	-0.07 (-0.36, 0.22)	-0.10 (-0.40, 0.21)
operator-recorded				
volume data traffic mobile phone [MB/d]	-0.05 (-0.13, 0.03)	-0.04 (-0.12, 0.05)	-0.09 (-0.30, 0.11)	-0.06 (-0.26, 0.15)
duration mobile phone calls [min/d]	0.11 (-0.02, 0.25)	0.10 (-0.03, 0.24)	-0.02 (-0.20, 0.16)	-0.01 (-0.19, 0.17)
Cumulative RF-EMF dose				
whole sample				
brain dose [mJ/kg/d]	0.02 (-0.17, 0.20)	0.02 (-0.17, 0.20)	-0.13 (-0.47, 0.20)	-0.18 (-0.53, 0.16)
whole-body dose [mJ/kg/d]	0.14 (-0.05, 0.34)	0.15 (-0.05, 0.35)	-0.16 (-0.49, 0.17)	-0.19 (-0.53, 0.16)
operator sample				
brain dose [mJ/kg/d]	**0.19 (0.00, 0.38)**	0.16 (-0.03, 0.35)	-0.01 (-0.18, 0.16)	0.00 (-0.17, 0.16)
whole-body dose [mJ/kg/d]	**0.78 (0.34, 1.22)**	**0.74 (0.29, 1.18)**	0.05 (-0.43, 0.53)	0.13 (-0.37, 0.62)
SDQ Parents total strengths				
Usage not related to RF-EMF exposure				
self-reported				
duration gaming [min/d]	-0.11 (-0.24, 0.02)	0.00 (-0.14, 0.14)	0.11 (-0.10, 0.32)	-0.01 (-0.25, 0.24)
text messages sent [x/d]	-0.10 (-0.34, 0.13)	-0.06 (-0.32, 0.20)	0.09 (-0.25, 0.43)	0.15 (-0.22, 0.52)
operator-recorded	0.02 (-0.05, 0.09)	0.01 (-0.06, 0.08)	0.06 (-0.06, 0.19)	0.07 (-0.06, 0.20)
SMS sent [x/d]				
Usage related to RF-EMF exposure	-0.18 (-0.44, 0.09)	-0.15 (-0.43, 0.12)	0.01 (-0.32, 0.33)	0.00 (-0.35, 0.35)
self-reported	-0.02 (-0.14, 0.09)	-0.05 (-0.16, 0.07)	0.03 (-0.13, 0.19)	0.04 (-0.12, 0.21)
duration data traffic mobile phone [min/d]				
duration cordless phone calls [min/d]				
duration mobile phone calls [min/d]	0.01 (-0.06, 0.08)	-0.01 (-0.08, 0.07)	0.09 (-0.04, 0.23)	0.14 (-0.01, 0.28)
operator-recorded	0.03 (-0.01, 0.07)	0.03 (-0.01, 0.07)	0.04 (-0.06, 0.15)	0.02 (-0.08, 0.13)
volume data traffic mobile phone [MB/d]				
duration mobile phone calls [min/d]	-0.01 (-0.07, 0.05)	-0.01 (-0.07, 0.05)	0.04 (-0.05, 0.13)	0.04 (-0.05, 0.14)
Cumulative RF-EMF dose				
whole sample				
brain dose [mJ/kg/d]	-0.01 (-0.09, 0.06)	-0.03 (-0.11, 0.05)	0.06 (-0.09, 0.22)	0.09 (-0.07, 0.25)
whole-body dose [mJ/kg/d]	-0.03 (-0.12, 0.05)	-0.05 (-0.13, 0.03)	0.04 (-0.11, 0.19)	0.06 (-0.10, 0.22)
operator sample				
brain dose [mJ/kg/d]	-0.04 (-0.12, 0.04)	-0.04 (-0.11, 0.04)	0.01 (-0.07, 0.10)	0.00 (-0.08, 0.09)
whole-body dose [mJ/kg/d]	-0.09 (-0.28, 0.10)	-0.05 (-0.24, 0.14)	-0.01 (-0.25, 0.24)	-0.06 (-0.31, 0.19)

[a] Cross-sectional models were adjusted for age, sex, nationality, school level, frequency of physical activity, frequency of alcohol consumption (asked in the adolescents' questionnaire) and highest educational level of the parents (asked in the parent's questionnaire).
[b] Longitudinal models were additionally adjusted for change in height between baseline and follow-up (asked in adolescents' questionnaire) and time between baseline and follow-up.

Figure S1. Adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for SDQ Adolescents total difficulties and total strengths for the cross-sectional mixed model analysis and the longitudinal analysis.

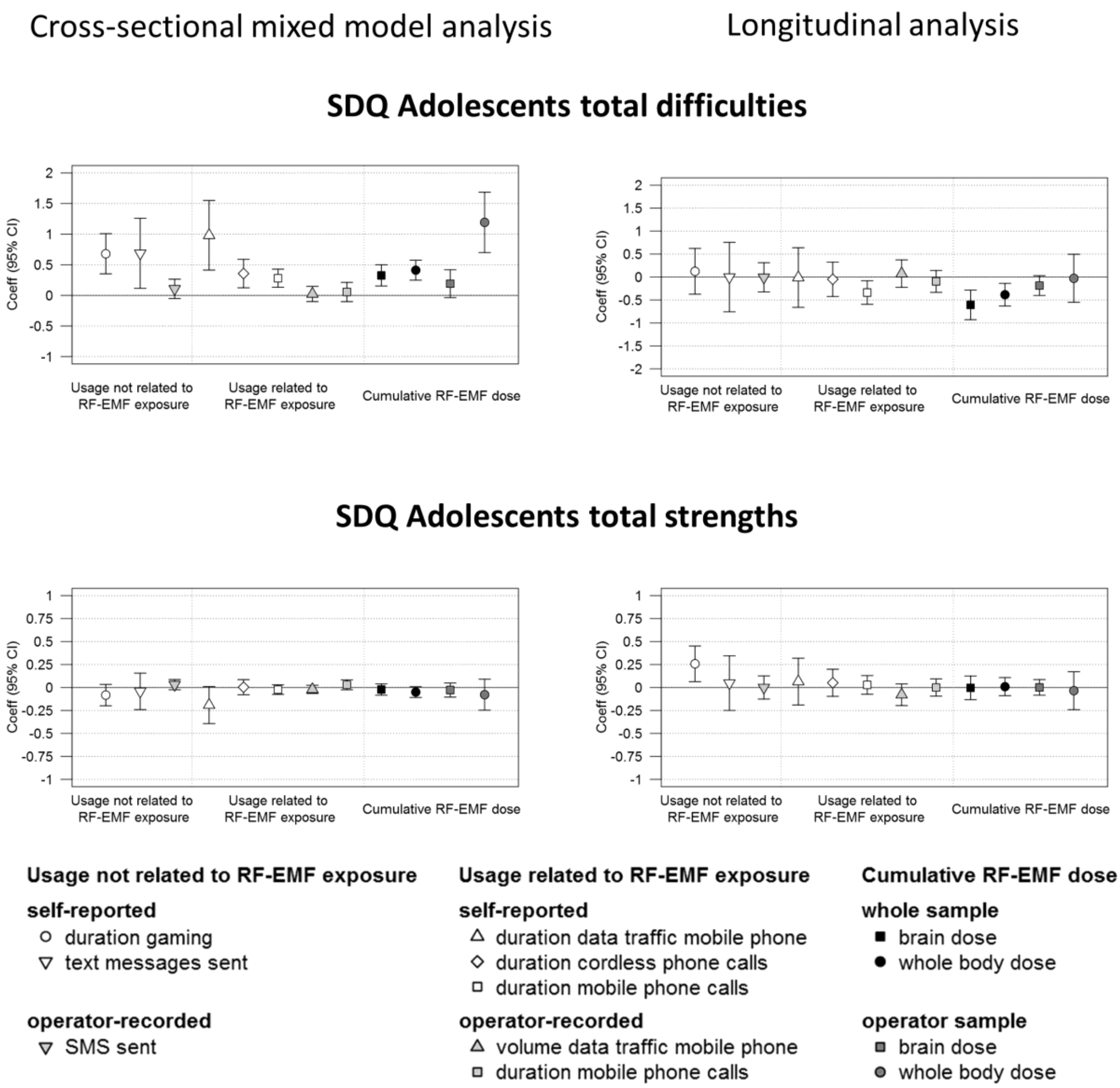


Figure S2. Adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for SDQ Adolescents emotional symptoms, conduct problems, hyperactivity/inattention and peer relationship problems for the cross-sectional mixed model analysis and the longitudinal analysis.

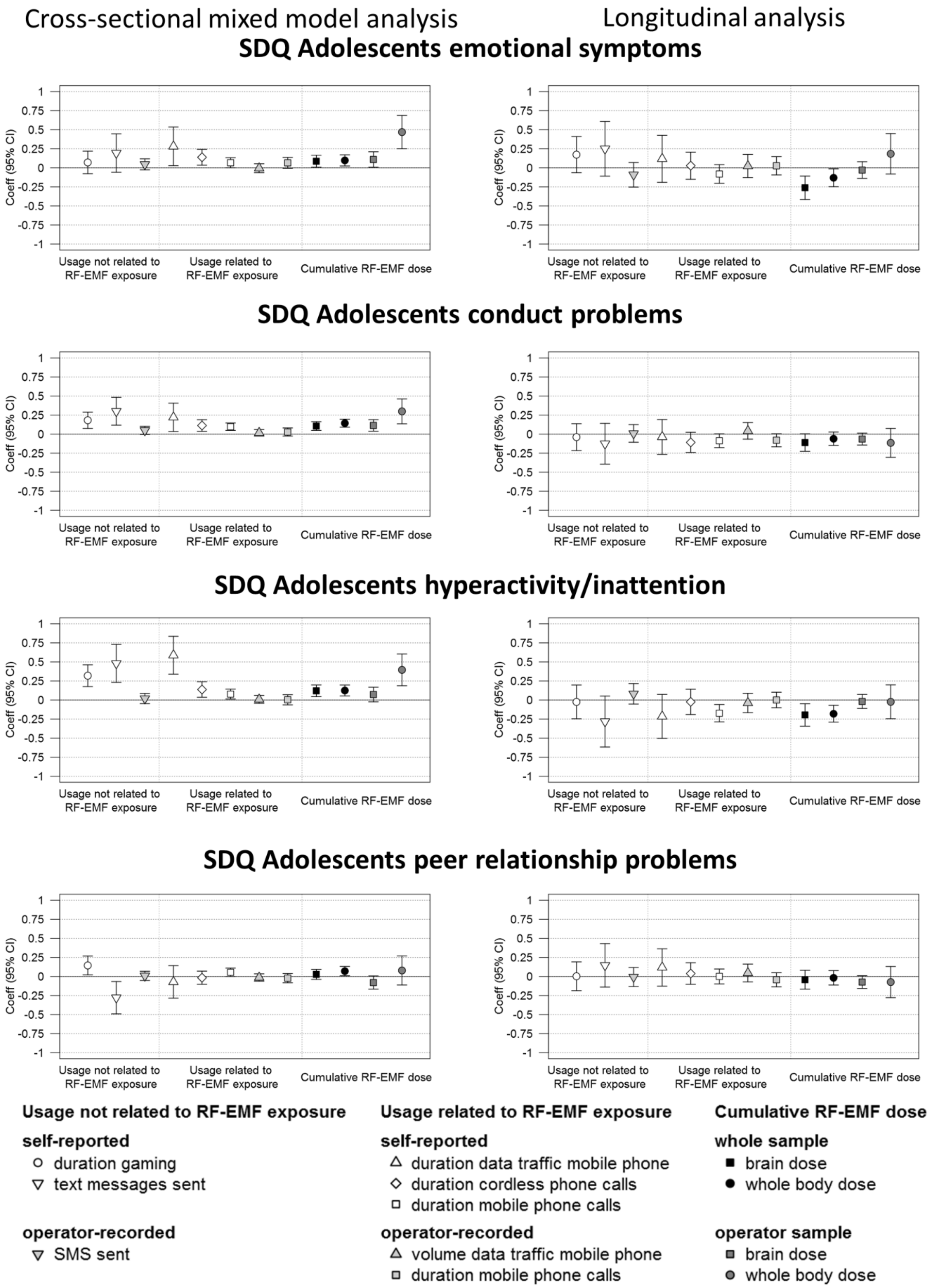


Figure S3. Adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for SDQ Parents total difficulties and total strengths for the cross-sectional mixed model analysis and the longitudinal analysis.

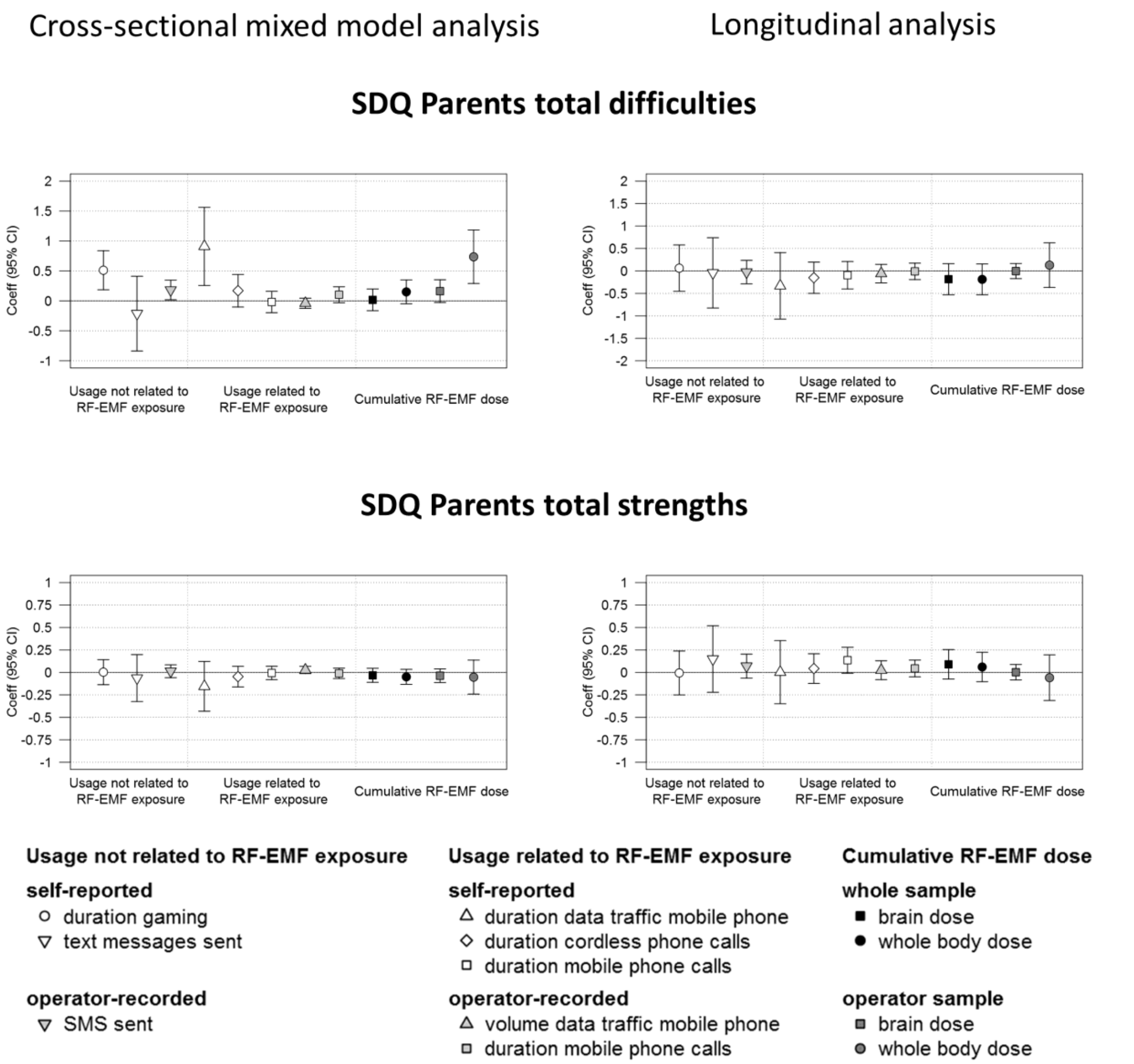
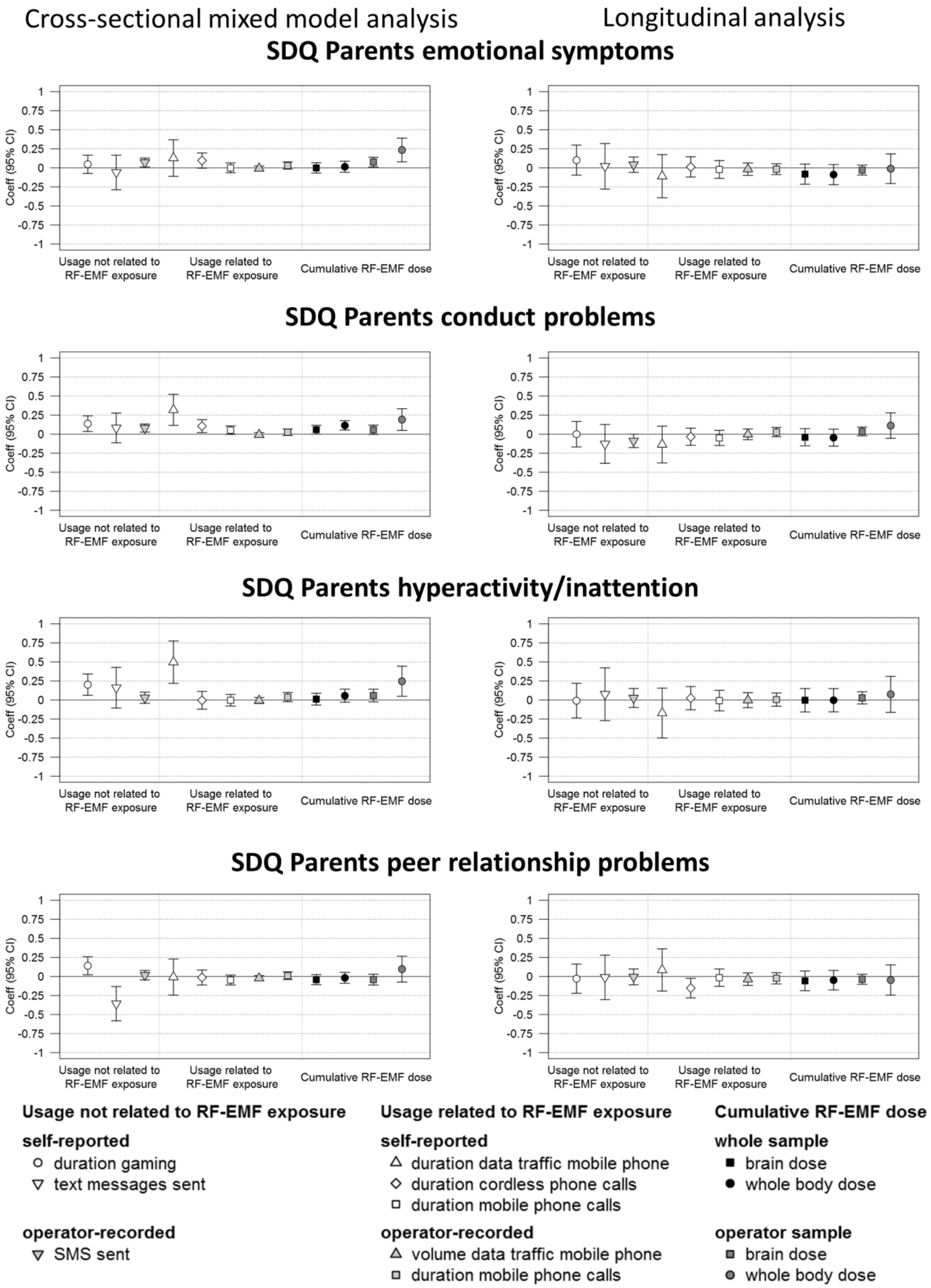


Figure S4. Adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for SDQ Parents emotional symptoms, conduct problems, hyperactivity/inattention and peer relationship problems for the cross-sectional mixed model analysis and the longitudinal analysis.



Concentration capacity (FAKT)

Table S2. Crude and adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in exposure variables for concentration capacity (FAKT) for the cross-sectional mixed model analysis and the longitudinal analysis. Significant results ($p < 0.05$) are indicated in bold.

	Cross-sectional mixed model analysis		Longitudinal analysis	
	crude Coeff (95% CI)	adjusted[a] Coeff (95% CI)	crude Coeff (95% CI)	adjusted[b] Coeff (95% CI)
Homogeneity of concentration				
Usage not related to RF-EMF exposure				
self-reported				
duration gaming [min/d]	-1.13 (-2.74, 0.47)	-0.71 (-2.41, 0.99)	-1.54 (-4.17, 1.09)	**-3.38 (-6.68, -0.08)**
text messages sent [x/d]	1.80 (-0.93, 4.53)	**-2.97 (-5.91, -0.02)**	-2.45 (-6.54, 1.65)	-1.26 (-5.80, 3.28)
objective				
SMS sent [x/d]	-0.52 (-1.42, 0.39)	-0.47 (-1.33, 0.40)	0.32 (-1.55, 2.20)	0.23 (-1.82, 2.28)
Usage related to RF-EMF exposure				
self-reported				
duration data traffic mobile phone [min/d]	-0.88 (-3.97, 2.20)	**-3.41 (-6.44, -0.37)**	-3.16 (-7.05, 0.73)	-2.31 (-6.48, 1.85)
duration cordless phone calls [min/d]	**-2.24 (-3.53, -0.94)**	**-1.85 (-3.09, -0.60)**	-0.93 (-3.24, 1.39)	-0.34 (-2.79, 2.10)
duration mobile phone calls [min/d]	-0.36 (-1.29, 0.57)	-0.49 (-1.41, 0.43)	-1.70 (-3.48, 0.08)	-1.44 (-3.42, 0.54)
objective				
volume data traffic mobile phone [MB/d]	-0.11 (-0.60, 0.39)	-0.42 (-0.89, 0.05)	-1.30 (-2.76, 0.15)	-1.26 (-2.76, 0.24)
duration mobile phone calls [min/d]	**-0.85 (-1.69, -0.02)**	**-1.06 (-1.86, -0.26)**	-0.83 (-2.10, 0.44)	-0.76 (-2.15, 0.63)
Cumulative RF-EMF dose				
whole sample				
brain dose [mJ/kg/d]	-0.63 (-1.65, 0.40)	-0.68 (-1.67, 0.31)	-1.05 (-2.91, 0.81)	-0.68 (-2.67, 1.31)
whole body dose [mJ/kg/d]	-0.63 (-1.64, 0.38)	-0.76 (-1.75, 0.23)	-1.73 (-3.80, 0.35)	-1.29 (-3.51, 0.93)
operator sample				
brain dose [mJ/kg/d]	**-1.38 (-2.57, -0.20)**	**-1.64 (-2.76, -0.51)**	-0.71 (-1.94, 0.52)	-0.55 (-1.85, 0.75)
whole body dose [mJ/kg/d]	-1.46 (-4.10, 1.18)	**-2.81 (-5.41, -0.20)**	-1.92 (-4.46, 0.63)	-1.62 (-4.39, 1.16)
Power of concentration				
Usage not related to RF-EMF exposure				
self-reported				
duration gaming [min/d]	-0.95 (-3.28, 1.37)	-0.46 (-2.77, 1.86)	-2.49 (-5.51, 0.53)	**-4.18 (-7.95, -0.40)**
text messages sent [x/d]	**8.80 (4.98, 12.62)**	-0.32 (-4.33, 3.70)	-0.15 (-4.86, 4.57)	1.30 (-3.90, 6.50)
operator-recorded				
SMS sent [x/d]	-1.21 (-2.46, 0.03)	-0.95 (-2.08, 0.18)	0.62 (-1.44, 2.68)	1.10 (-1.14, 3.33)
Usage related to RF-EMF exposure				
self-reported				
duration data traffic mobile phone [min/d]	3.38 (-1.03, 7.78)	-1.27 (-5.35, 2.82)	-0.50 (-4.99, 4.00)	0.80 (-3.98, 5.58)
duration cordless phone calls [min/d]	**-3.25 (-5.10, -1.40)**	**-2.14 (-3.82, -0.46)**	-0.88 (-3.55, 1.79)	-0.15 (-2.95, 2.65)
duration mobile phone calls [min/d]	-0.34 (-1.69, 1.00)	-0.66 (-1.93, 0.62)	**-2.16 (-4.21, -0.12)**	-1.82 (-4.09, 0.44)
operator-recorded				
volume data traffic mobile phone [MB/d]	0.48 (-0.18, 1.14)	-0.05 (-0.63, 0.53)	-0.21 (-1.82, 1.41)	0.01 (-1.64, 1.67)
duration mobile phone calls [min/d]	-0.78 (-1.93, 0.38)	**-1.06 (-2.09, -0.03)**	-0.35 (-1.75, 1.05)	0.05 (-1.48, 1.57)
Cumulative RF-EMF dose				
whole sample				
brain dose [mJ/kg/d]	-1.03 (-2.50, 0.44)	-1.12 (-2.46, 0.22)	-2.00 (-4.13, 0.14)	-1.70 (-3.97, 0.57)
whole body dose [mJ/kg/d]	-0.55 (-2.00, 0.91)	-0.77 (-2.13, 0.59)	-2.36 (-4.74, 0.02)	-1.88 (-4.42, 0.66)
operator sample				
brain dose [mJ/kg/d]	-1.02 (-2.67, 0.63)	-1.38 (-2.87, 0.10)	-0.48 (-1.84, 0.88)	-0.22 (-1.65, 1.21)
whole body dose [mJ/kg/d]	1.16 (-2.54, 4.86)	-1.03 (-4.54, 2.47)	-1.31 (-4.12, 1.50)	-0.60 (-3.65, 2.45)

[a] Cross-sectional models were adjusted for age, sex, nationality, school level, frequency of physical activity, frequency of alcohol consumption (asked in the adolescents' questionnaire) and highest educational level of the parents (asked in the parent's questionnaire).
[b] Longitudinal models were additionally adjusted for change in height between baseline and follow-up (asked in adolescents' questionnaire) and time between baseline and follow-up.

Continuation Table S2

	Cross-sectional mixed model analysis		Longitudinal analysis	
	crude Coeff (95% CI)	**adjusted[a] Coeff (95% CI)**	**crude Coeff (95% CI)**	**adjusted[b] Coeff (95% CI)**
Accuracy of concentration				
Usage n related to RF-EMF exposure				
self-reported				
duration gaming [min/d]	-0.27 (-0.72, 0.19)	-0.27 (-0.76, 0.22)	-0.20 (-0.94, 0.53)	-0.51 (-1.43, 0.41)
text messages sent [x/d]	0.59 (-0.18, 1.35)	-0.39 (-1.24, 0.46)	-0.11 (-1.26, 1.03)	0.14 (-1.12, 1.41)
operator-recorded				
SMS sent [x/d]	-0.24 (-0.50, 0.01)	-0.22 (-0.48, 0.03)	0.04 (-0.48, 0.56)	0.22 (-0.34, 0.78)
Usage related to RF-EMF exposure				
self-reported				
duration data traffic mobile phone [min/d]	0.01 (-0.85, 0.87)	-0.58 (-1.46, 0.29)	0.18 (-0.91, 1.27)	0.37 (-0.79, 1.53)
duration cordless phone calls [min/d]	**-0.58 (-0.94, -0.22)**	**-0.49 (-0.85, -0.13)**	-0.19 (-0.84, 0.46)	-0.04 (-0.72, 0.64)
duration mobile phone calls [min/d]	-0.24 (-0.51, 0.02)	**-0.31 (-0.58, -0.05)**	-0.42 (-0.92, 0.07)	-0.40 (-0.95, 0.16)
operator-recorded				
volume data traffic mobile phone [MB/d]	0.01 (-0.13, 0.15)	-0.05 (-0.19, 0.09)	-0.25 (-0.66, 0.15)	-0.19 (-0.60, 0.22)
duration mobile phone calls [min/d]	-0.22 (-0.45, 0.01)	**-0.26 (-0.49, -0.03)**	-0.20 (-0.55, 0.16)	-0.15 (-0.53, 0.23)
Cumulative RF-EMF dose				
whole sample				
brain dose [mJ/kg/d]	-0.17 (-0.46, 0.11)	-0.22 (-0.51, 0.06)	-0.21 (-0.73, 0.31)	-0.13 (-0.68, 0.42)
whole body dose [mJ/kg/d]	-0.25 (-0.53, 0.04)	**-0.32 (-0.61, -0.03)**	-0.34 (-0.92, 0.24)	-0.26 (-0.88, 0.36)
operator sample				
brain dose [mJ/kg/d]	**-0.40 (-0.73, -0.07)**	**-0.45 (-0.78, -0.12)**	-0.02 (-0.37, 0.32)	0.05 (-0.31, 0.41)
whole body dose [mJ/kg/d]	-0.57 (-1.31, 0.17)	**-0.82 (-1.58, -0.06)**	-0.41 (-1.11, 0.30)	-0.25 (-1.01, 0.51)

[a] Cross-sectional models were adjusted for age, sex, nationality, school level, frequency of physical activity, frequency of alcohol consumption (asked in the adolescents' questionnaire) and highest educational level of the parents (asked in the parent's questionnaire).

[b] Longitudinal models were additionally adjusted for change in height between baseline and follow-up (asked in adolescents' questionnaire) and time between baseline and follow-up.

Personal RF-EMF measurements

Table S3. Crude and adjusted coefficients and corresponding 95% confidence intervals (95% CI) per interquartile change in personal exposure measurement variables for SDQ Parents total difficulties and total strengths. Significant results ($p < 0.05$) are indicated in bold.

	n[e]	crude Coeff (95% CI)	adjusted[f] Coeff (95% CI)
Behavioural problems			
SDQ Parents total difficulties			
Downlink[a]	81	0.21 (-0.37, 0.80)	0.40 (-0.26, 1.05)
Fixed site transmitters[b]	81	0.20 (-0.40, 0.80)	0.38 (-0.29, 1.05)
Total[c]	81	0.42 (-0.10, 0.95)	0.41 (-0.16, 0.99)
Total without uplink[d]	81	0.52 (-0.14, 1.18)	0.63 (-0.10, 1.36)
SDQ Parents total strengths			
Downlink[a]	81	0.01 (-0.19, 0.22)	-0.03 (-0.26, 0.20)
Fixed site transmitters[b]	81	0.02 (-0.19, 0.23)	-0.02 (-0.25, 0.22)
Total[c]	81	-0.13 (-0.31, 0.06)	-0.07 (-0.28, 0.13)
Total without uplink[d]	81	-0.10 (-0.33, 0.14)	-0.06 (-0.32, 0.20)

[a] Downlink means exposure from mobile phone base stations.
[b] Fixed site transmitters means exposure from fixed site transmitters (TV broadcast transmitters and mobile phone base stations).
[c] Total means the total RF-EMF exposure.
[d] Total without uplink means total RF-EMF exposure without exposure from mobile phone handsets.
[e] Due to technical failures of the computerized testing system (FAKT) data was not available for all participants.
[f] Models were adjusted for age, sex, nationality, school level, frequency of physical activity, frequency of alcohol consumption (asked in the adolescents' questionnaire) and highest educational level of the parents (asked in the parent's questionnaire).

8 Summary of main findings

In the following, the results of the objectives outlined in section 2 are presented as short summaries of the main findings that are discussed in detail in the respective articles in the sections 4 to 7.

Objective 1

Investigate problematic mobile phone use of adolescents and its relation to mental health and behavioural problems.

Derivation of a short scale MPPUS-10: The derivation of the short scale was based on the baseline data of the HERMES study restricted to the participants owning a mobile phone and complete MPPUS data (n = 377). The PCA revealed four factors related to symptoms of addiction (loss of control, withdrawal, negative life consequences and craving) and a fifth factor reflecting the social component of problematic mobile phone use (peer dependence) considered being especially important in adolescents. The shortened scale MPPUS-10 highly reflects the original MPPUS (Kendall's $\tau = 0.80$ with 90% concordant pairs). The internal consistency of the MPPUS-10 was good (Cronbach's $\alpha = 0.85$). In conclusion, the short version MPPUS-10 is a suitable instrument for research in adolescents. It will help to further clarify the definition of problematic mobile phone use in adolescents.

Problematic mobile phone use: 412 of the 439 adolescents participating in the HERMES study owned a mobile phone and were therefore included in the analysis. 319 (77.4%) of these adolescents owned a smartphone. In these adolescents, problematic mobile phone use measured by the MPPUS-10 was higher (30.6 vs. 20.0) whereas the average score for all mobile phone owners was 28.2. Problematic mobile phone use was significantly higher in girls, increased significantly with age and was significantly decreased with increasing educational level of the parents.

Amount of mobile phone use: The amount of mobile phone use was correlated with problematic use. The Spearman correlation was $\rho = 0.59$ for self-reported frequency of outgoing messages. For other types of use, correlations were moderate ranging from $\rho = 0.32$ for self-reported frequency of calls to $\rho = 0.42$ for self-reported duration of data traffic (all $p < 0.001$).

Behavioural problems: Problematic mobile phone use was significantly positively associated with overall behavioural problems (0.96; 95% CI: (0.58, 1.35) units increase in SDQ score per 10 units increase in MPPUS-10 score). Among the specific behavioural problems measured by the self-reported SDQ, most pronounced association was observed for hyperactivity (0.42; (0.26, 0.57)), followed by conduct problems (0.30; (0.19, 0.41)), emotional symptoms (0.17; (0.02, 0.32)) and antisocial behaviour (-0.14; (-0.25, -0.04)). The results for the parent-rated behavioural problems showed a similar pattern.

HRQOL: Six out of the ten HRQOL dimensions were significantly decreased for increasing problematic mobile phone use (moods and emotions, self-perception, autonomy, parent relations and home life, financial resources and school environment). Social support and peers and social acceptance were not related to problematic use. Physical well-being and psychological well-being were significantly decreased in the 10% adolescents with highest problematic use.

Control for amount of mobile phone use: We controlled the analysis for the amount of mobile phone use (frequency of outgoing text messages). The associations were similar if adjusting for operator-recorded amount of mobile phone use and if dropping the adjustment for amount of mobile phone use and for other measures of the amount of mobile phone use (call frequency or data traffic). This indicates that the observed associations are independently related to problematic aspects of use and not to the amount of use itself.

Objective 2

Describe the personal RF-EMF exposure of Swiss adolescents and evaluate exposure relevant factors.

Participants of the personal measurements: We conducted personal measurements in 121 adolescents participating in the HERMES study. After data cleaning, 90 of these sets of measurements and corresponding diary entries were applicable for the analysis. The measurement study participants were comparable to the HERMES follow-up cohort (n = 425) according to sex, age, school level, WLAN in school and at home, owning a mobile phone or a smartphone and mobile phone use besides that fewer adolescents had a mobile phone subscription (compared to using a prepaid mobile phone). More Swiss adolescents and fewer adolescents with mixed nationality participated in the measurement study.

Exposure contributions and levels: Total personal RF-EMF measurements on average were 67.1 µW/m² (0.16 V/m). Median total RF-EMF measurements were considerably lower (26.3 µW/m²) reflecting the highly skewed data distribution of the measurements. The exposure from mobile phones contributed most to total measurements (63.2%), followed by exposure from fixed site transmitters (mobile phone base stations: 18.7%, TV broadcast transmitters: 6.4%). WLAN exposure accounted on average for 3.3%, DECT for 7.1%. The measurements were highest in public transport and cars (966.9 µW/m² in cars, 806.0 µW/m² in buses and 568.6 µW/m² in trains) and lowest in schools (63.6 µW/m²) and at home (31.9 µW/m²). Total measurements clearly were higher during daytime compared to night-time (85.9 vs. 29.4 µW/m²). For the participants having measurements during workdays and on weekends (n = 38), the measurements were somewhat higher on the weekend (65.0 vs. 54.2 µW/m²).

WLAN in school and at home: WLAN in school and at home had very little impact on the average WLAN measurements. *Not* switching off the WLAN modem at home during night meant higher average WLAN measurements at home (0.9 vs. 0.4 µW/m²) and for the whole measurement period (2.6 vs. 0.7 µW/m²).

Mobile phone use: The own mobile phone use had substantial impact on personal uplink measurements. The participants with a mobile phone subscription had higher average uplink measurements compared to those using prepaid mobile phones (77.7 vs. 12.8 µW/m²). Average uplink measurements were also higher if reporting to *not* switch off the mobile phone during night (49.6 vs. 22.5 µW/m²) and if using internet by the mobile phone (45.2 vs. 8.9 µW/m²). Stating *not* to use WLAN by mobile phone resulted in higher average uplink measurements (68.3 vs. 40.5 µW/m²), but strikingly, the difference in average WLAN measurements was marginal (2.7 vs. 2.3 µW/m²).

Use of personal measurements for dose calculations: The personal measurements were combined with the exposure from wireless device use to calculate the daily RF-EMF dose for the typical (average) HERMES participant. For the uplink exposure, the mean uplink measurements from the participants not using mobile internet was used since it is assumed that these measurements were less influenced by the own mobile phone use. The far-field exposure derived from the personal measurements contributed 6.4% to the brain dose and 9.8% to the whole body dose.

Sensitivity analyses: The manual diary cleaning resulted in changes in measurements for locations with short durations (train and bus), whereas measurements with long durations (home and school) were little affected.

Objective 3

Development of an RF-EMF exposure surrogate combining various near-field and far-field RF-EMF sources.

Near-field predictors: The highest dose rate (dose for 1 min of use) was found for mobile phone calls on the GSM network (191.9 mJ/kg/min for the brain and 24.7 mJ/kg/min for the whole body) followed by DECT phone calls (22.4 mJ/kg/min for brain and 3.1 mJ/kg/min for the whole body). Regarding cumulative daily dose, GSM mobile phone calls contributed most to the brain and the whole body dose (94.6% and 73.3%, respectively). For the brain, second most contributing predictor was DECT phone calls (4.8%). For the whole body, computer, laptop and tablet use with WLAN contributed for 13.0% of the daily dose. Other predictors (UMTS mobile phone calls and mobile phone data traffic) contributed little to the dose.

Far-field predictors: We found uplink (61.2%) and downlink (30.4%) contributing most to the far-field dose. Multivariable regression models revealed that attending a school with WLAN, not switching off the WLAN base station at home during night and the time spent in trains explained parts of the WLAN exposure, whereas the number of smartphones used at home and the time spent in trains and buses explained parts of the uplink exposure. However, a considerable part of WLAN and uplink exposure remained unexplained. For the DECT measurements, no available explanatory variable was associated with DECT exposure. For that reason, the average personal DECT measurements at home were used to calculate the dose originating from DECT base stations at home.

Combining near-field and far-field dose: The dose originating from the use of devices accounted for 98.4% of the brain dose and 94.0% of the whole body dose. Depending on the mobile phone use, considerable differences were seen in the cumulative dose and in the proportion of the far-field dose on the total dose: For a non-mobile phone user, 27.0% of the dose originated from far-field sources. For a user calling for 6.4 min/day and using the mobile phone for 21.3 min/day for data exchange, 2.2% of the dose originated from far-field sources, and for a heavy user calling for 267.1 min/day and active data exchange of 84.7min/day the proportion of far-field dose dropped to 0.7%. The pattern was similar for the whole body dose (27.4, 3.5 and 0.9%, respectively).

Comparing dose calculations with personal measurements: The dose predictions were compared with personal measurements in a subgroup of the participants. They did not correlate with personal measurements (Spearman correlation coefficients of $\rho = 0.10$ ($p = 0.34$) for the brain dose and $\rho = 0.05$ ($p = 0.63$) for the whole body dose). If restricted to the far-field dose, correlations were slightly higher ($\rho = 0.18$ ($p = 0.08$) for the brain dose and $\rho = 0.17$ ($p = 0.09$) for the whole body dose). If taking into account only downlink dose predictions and downlink measurements, correlations were $\rho = 0.53$ ($p < 0.001$) for the brain and $\rho = 0.52$ ($p < 0.001$) for the whole body dose.

Objective 4

Investigate whether mobile phone use or RF-EMF exposure causes behavioural problems or affects concentration capacity of adolescents.

Behavioural problems: In the cross-sectional analysis, behavioural problems were significantly positively associated with several self-reported use measures but not with operator-recorded mobile phone use. In the longitudinal analysis, the self-reported cumulative duration of mobile phone calls and the cumulative dose were associated with a *decrease* in self-reported behavioural problems over one year. However, these associations were not seen for parent-rated behavioural problems and operator-recorded mobile phone call duration. There was no consistent pattern in relation to RF-EMF exposure.

Concentration capacity: Concentration capacity was significantly negatively associated with some self-reported as well as objectively recorded exposure measures in the cross-sectional analysis, but not in the longitudinal analysis except for a correlation between duration of gaming on computers and TV and a decrease in homogeneity and power of concentration over one year. No systematic pattern in relation to RF-EMF exposure was observed.

Personal RF-EMF measurements: Behavioural problems were not related to measured personal RF-EMF exposure. Homogeneity and power of concentration were significantly negatively associated with total RF-EMF exposure without uplink, but not with downlink and fixed site transmitters exposure alone. Accuracy of concentration was not associated with either of the measured exposures.

9 Discussion

The specific objectives of this thesis are discussed in the respective articles. This section provides a general discussion.

The aim of the HERMES study was to prospectively investigate whether the use of mobile phones and other wireless communication devices or RF-EMF exposure impacts health, behaviour or cognitive function of adolescents.

9.1 Problematic mobile phone use

If the frequent mobile phone use of adolescents has a negative impact on daily life, it may become problematic. One major problem in research on problematic mobile phone use is that no established definition and no common assessment tool of problematic mobile phone use are available yet (Billieux 2012). The MPPUS by Bianchi and Phillips (2005) is a frequently used 27-item questionnaire. But it is rather long with its 27 questions, especially if it is included in a questionnaire covering a lot of other topics as well. Our aim therefore was to shorten this scale using the baseline data of the HERMS study. The shortened version MPPUS-10 consisting of 10 out of the 27 original items showed a good internal consistency and was highly correlated with the original 27-item scale (Article 1). Thus the MPPUS-10 is a suitable instrument to measure problematic mobile phone use in adolescents. It was included in the questionnaire of the continuation of the HERMES study within the international Geronimo study (GERoNiMO 2015). It will hopefully contribute to research in problematic mobile phone use in adolescents in becoming a widely used measurement tool enabling to compare different studies using the same measurement tool.

Applying the MPPUS-10, we found problematic mobile phone use related to internal and external factors of adolescents' life (Article 2). External factors associated with problematic mobile phone use were worse school environment and home environment; internal factors were impaired HRQOL and behavioural problems. We controlled our analysis for amount of mobile phone use. For that purpose, self-reported and operator-recorded mobile phone use was used. The results were similar if dropping the adjustment for the amount of use. Thus these factors were related to the problematic aspects of mobile phone use and not the amount itself. The study presented in article 2 was of cross-sectional design. Thus, we were not able to conclude if problematic mobile phone use was caused by these factors or the other way around. For both directions, there are plausible pathways (Article 2). The continuation of the HERMES study within the international Geronimo study (GERoNiMO 2015) will allow repeating the analysis in a larger data set and with a longitudinal design.

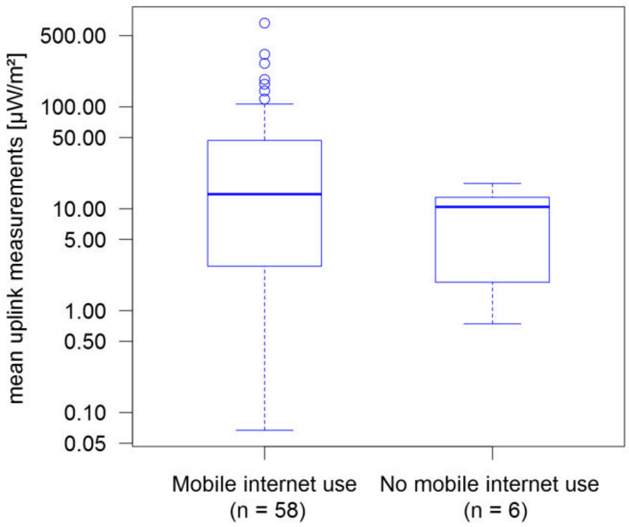
9.2 Personal RF-EMF measurements

9.2.1 Personal uplink measurements

The own mobile phone use of the adolescents increased the average uplink measurements.

Figure 6 illustrates that the uplink measurements were increased for the participants using internet on their mobile phone (Article 3; median = 13.9 µW/m² for mobile internet users and median = 10.4 µW/m² for non-users).

Figure 6. Distribution of the mean uplink measurements during the personal measurements for the adolescents using mobile internet (n = 58) and not using mobile internet (n = 6) for the participants with the measurement questionnaire available (n = 64 out of 90 participants of the measurement study). Note that the y axis is in logarithmic scale.



The measurement questionnaire filled in directly after the measurement period was available for 64 of the 90 measurement study participants. For the remaining 26 participants, we used the follow-up questionnaire data instead. The duration of mobile internet use and the mean uplink measurements were not correlated (Spearman correlation $\rho = 0.08$ ($p = 0.47$) for all 90 participants and $\rho = 0.10$ ($p = 0.42$) for the 64 participants with the measurement questionnaire available). The additional information of the proportion of time using WLAN for the mobile internet connection (included in the questionnaire as well) explained at least a part of the measured uplink exposure (the correlations increased to $\rho = 0.21$ ($p = 0.05$) for all participants and $\rho = 0.22$ ($p = 0.07$) for the 64 participants with measurement questionnaire available).

Adolescents may have estimated their mobile internet use inexactly. Or the duration of use is not as relevant for the uplink exposure as for example the type of internet use (for instance watching an online video means more data transmitted compared to the exchange of messages what results in higher output power (Gati et al. 2009)). Operator data records or applications such as XMobiSense recording the mobile phone use will help to clarify such open questions.

9.2.2 Limitations of personal measurements

Personal measurements with body-worn exposimeters have the advantage to represent the exposure during all everyday activities of the adolescents and therefore to valuably represent personal exposure to RF-EMF emitted by sources in the environment. But personal RF-EMF measurements come also with limitations such as the influence of the body on the measurements (Bolte et al. 2011; Gryz et al. 2015; Neubauer et al. 2010), crosstalk between neighbouring bands (Lauer et al. 2012) or differences in the measurement performance by different devices.
Body shielding occurs if the body is between the RF-EMF emitting source and the exposimeter and the body shields the RF-EMFs. 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 the average exposure, the situation is less dramatic, but different aspects seem to influence the level of uncertainty introduced by body shielding. Numerical simulations of different exposure scenarios and various frequencies in the RF-EMF range showed a wide range of uncertainty for measurements introduced by the presence of the body (Gryz et al. 2015; Iskra et al. 2010; Neubauer et al. 2010). Test measurements comparing measurements with and without a person present revealed a frequency-dependent large range of uncertainty as well (Bolte et al. 2011). Consequently, a comprehensive measurement campaign would be necessary to determine device, frequency, situation and even study participant depending correction factors that can be used in measurement studies (Bolte et al. 2011; Gryz et al. 2015; Neubauer et al. 2010). In our measurement study, we instructed the participants to place the exposimeter in their vicinity, but not directly on the body, when not moving. Furthermore, we on average used almost 60,000 single measurements per participant for the measurement analysis. Therefore the influence of the body is assumed to be averaged.

A recent study proposed to use multiple exposimeters at once or exposimeters with multiple nodes to reduce the influence of the body (de Miguel-Bilbao et al. 2015). Measurements and numerical simulations showed that two antennas or exposimeters, one in front and one in back of the body, are sufficient (Thielens et al. 2013) and that the uncertainty caused by the presence of the body can be reduced if using two exposimeters (reduced interquartile range by a factor of 1.8 compared to measurements with one exposimeter) or newly developed exposimeters with two textile antennas worn on the body (reduced interquartile range by a factor of 9 compared to a single antenna) (Thielens et al. 2015a; Thielens et al. 2015b). These body-worn exposimeters with textile antennas are not yet available for the widespread use in personal measurements, but they are a promising approach to improve the exposure assessment for RF-EMF under far-field conditions.

Crosstalk occurs, if the emission from one frequency band is reported in another frequency band. This problem especially concerns the narrow DECT band (1880 – 1900 MHz) that adjoins the neighbouring downlink 1800 frequency band (1805 – 1880 MHz) (Lauer et al. 2012). We approached this problem in applying a DECT correction algorithm to the measurements and conducted a sensitivity analysis investigating the impact of the correction algorithm on the results of the measurement study (Article 3).
Another source of uncertainty is the different measurement performance by different measurement devices. A comparison of measurements taken with an EME Spy 120 (Satimo, France) and an ExpoM-RF (Fields at Work, Switzerland) during nine school visits of the HERMES baseline investigation in 2012 showed that DECT and WLAN measurements by the EME Spy 120 device were for most of the school visits clearly higher than those by the ExpoM-RF device (factors ranging from 1.5 to 300 for WLAN and from 0.2 to 260 for DECT). This comparison is in line with the finding of Lauer et al. (2012) that the EME Spy 120 device overestimates DECT exposure.

Another limitation of personal measurements with exposimeters is the assessment of the exposure from wireless communication devices operating close to the body (Inyang et al. 2008; Röösli et al. 2010). The exposure from the use of mobile phones close to the body is not measured adequately by body-worn exposimeters, since the measured exposure highly depends on the distance between the measurement device and the emitting mobile phone and this distance is not necessarily the same as the distance between the mobile phone and the body (Inyang et al. 2008; Röösli et al. 2010). Consequently, the measured exposure likely is not the personal exposure from the own mobile phone use. Thus, personal measurements have to be combined with a dosimetric approach (Article 4) quantifying the exposure from the own use of devices as it is demonstrated in article 3.

9.3 The influence of mobile phone use on personal measurements

Since the exposure from the own mobile phone use is covered by the near-field part of the dose calculations, an estimation for the exposure from other mobile phones not influenced by the own mobile phone has to be derived. To quantify this exposure, the measured uplink exposure that is affected by the own mobile phone use (as demonstrated in article 3) has to be separated into exposure from the own and from other mobile phones. In article 3, a crude approach using the average uplink measurements for the participants reporting not to use mobile internet on their mobile phone is presented. This approach is useful if, as in article 3, the aim is to calculate the daily dose for a typical HERMES participant. However, this approach does not provide individual uplink exposure from other mobile phones, but a common exposure for all participants. Therefore, other approaches have to be found. For that purpose, more research is needed investigating the influence of the own mobile phone use on personal uplink measurements. A possible approach would be:

1) Performance of measurements of the uplink exposure of pre-defined call and data traffic scenarios in a controlled setting.
2) Recording of the mobile phone use (calls including network used, data traffic including data rate and network used (mobile network, WLAN)) during personal measurements using either an application installed on the mobile phone of the participants (for instance (Goedhart et al. 2015)) or, if personal measurements are nested within a cohort study, operator-recorded mobile phone use data for the time period of the personal measurements.

With these two steps, uplink measurements can be adjusted for personal mobile phone use resulting in uplink exposure from other mobile phones in the surroundings.
The same approach could be followed to adjust WLAN measurements for the personal use of WLAN for mobile internet on the mobile phone.

9.4 Dose calculations for the HERMES cohort

To obtain a cumulative exposure measure taking into account several RF-EMF sources in the near-field and far-field, the absorbed radiation energy by the body, was calculated for each study participant of the HERMES cohort (Article 4). To demonstrate the developed dosimetric approach, self-reported mobile phone use was used. Since it is known that self-reported mobile phone use is inaccurate (Aydin et al. 2011; Inyang et al. 2009), we additionally calculated the cumulative dose considering the objectively recorded mobile phone call duration from the operator data for a subsample of the participants.

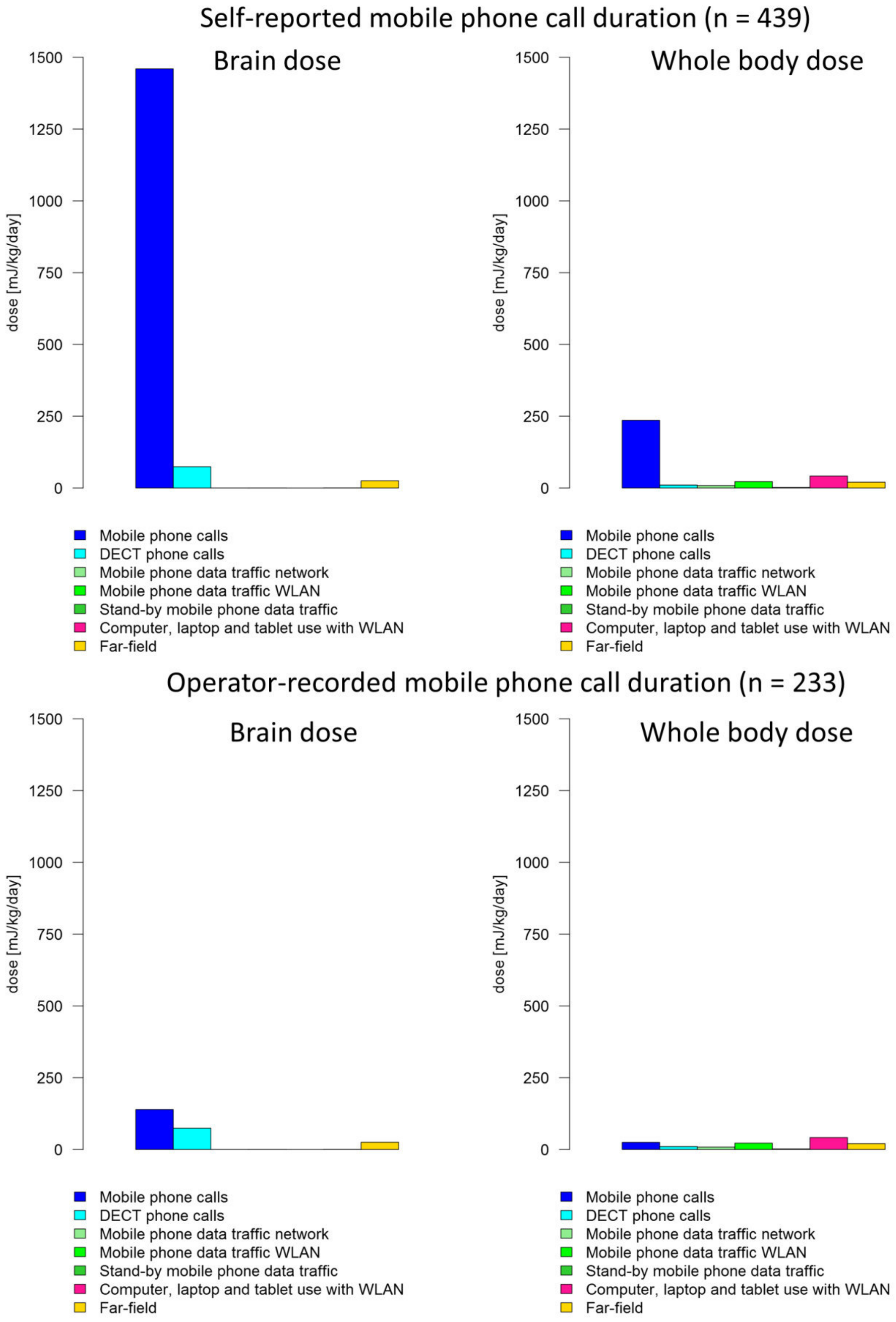
Depending on the data resource for mobile phone call duration, the contribution of mobile phone calls and data traffic to the total dose differs.
For the brain, mobile phone calls are the main contributor, whereas data traffic is negligible for both, self-reported and operator-recorded mobile phone call duration (Table 2 and Figure 7). For the whole body, the picture is different: for self-reported call duration, mobile phone calls are the main contributor to the total dose, but for operator-recorded call duration, calls and data traffic contribute equally to the total dose.
Since the self-reported mobile phone call duration tends to be overestimated (Aydin et al. 2011; Inyang et al. 2009), the objectively recorded mobile phone call duration is preferred, although there, only calls with the own mobile phone are recorded (in the HERMES cohort: on average 14.8% and 10.0% of the total call duration with other mobile phones at baseline and follow-up, respectively).
For the duration of data traffic on the mobile phone, only the self-reported duration was available.
In conclusion, mobile phone calls are the main contributor to the brain dose, DECT phone calls contribute as well. For the whole body dose, calls and data traffic contribute equally. For the whole body, the use of computers, laptops and tablets connected to WLAN makes a contribution as well.

Table 2. Mean total cumulative daily dose considering self-reported (for the whole HERMES cohort, n = 439) and operator-recorded (for the operator sample, n = 233) mobile phone call duration for the brain and the whole body and percentage on the total dose for the different near-field parts and the far-field part. Note that the other near-field parts are self-reported for both calculations of the dose.

Self-reported mobile phone calls (n = 439)		
	Brain dose	**Whole body dose**
	Total dose [mJ/kg/day]	
	1559.67	339.91
	Percentage on total dose [%]	
Mobile phone calls	93.60	69.39
DECT phone calls	4.75	2.98
Mobile phone data traffic network	0.004	2.44
Mobile phone data traffic WLAN	0.01	6.48
Stand-by mobile phone data traffic	0.0009	0.56
Computer, laptop and tablet use with WLAN	0.02	12.20
Far-field	1.62	5.95

Operator-recorded mobile phone calls (n = 233)		
	Brain dose	**Whole body dose**
	Total dose [mJ/kg/day]	
	239.12	128.96
	Percentage on total dose [%]	
Mobile phone calls	58.24	19.31
DECT phone calls	30.99	7.86
Mobile phone data traffic network	0.03	6.43
Mobile phone data traffic WLAN	0.07	17.08
Stand-by mobile phone data traffic	0.006	1.48
Computer, laptop and tablet use with WLAN	0.13	32.15
Far-field	10.53	15.69

Figure 7. Mean cumulative daily dose considering self-reported (for the whole HERMES cohort, n = 439) and operator-recorded (for the operator sample, n = 233) mobile phone call duration for the brain and the whole body for the different near-field parts and the far-field part. Note that the other near-field parts are self-reported for both calculations of the dose.



9.5 Application of the exposure measures in the HERMES study

A primary aim of the HERMES study was to disentangle between effects by the mobile phone use per se and effects by RF-EMF. The two networks used for mobile phone calls (GSM and UMTS) differ in output power by the mobile phone and therefore in radiation emitted during calls (Gati et al. 2009). Thus equal call duration in two participants with a different network distribution for calls results in different amount of RF-EMF dose originating from mobile phone calls. This basically enables to differentiate between non-radiation-related effects (mobile phone call duration) and radiation-related effects (RF-EMF dose from mobile phone calls).

For instance a daily mobile phone call duration of 2 min results in a daily brain dose of 383.8 mJ/kg if using the GSM network, 193.3 mJ/kg if using the GSM and the UMTS network for 1 min each and a dose of 2.8 mJ/kg if using the UMTS network. To set these numbers in relation: the daily brain dose from fixed site transmitters on average was 9.4 mJ/kg in the HERMES cohort.

Additionally to the exposure measures that are related to RF-EMF exposure (mobile phone calls, DECT phone calls, data traffic on the mobile phone), exposure measures that are not or only marginally related to radiation exposure were included: the frequency of outgoing text messages and the duration of gaming on computers, laptops, tablets and TV. This resulted in three groups of exposure measures:

- Non-radiation related factors in the context of mobile phone use: frequency of outgoing text messages, duration of gaming on computers, laptops, tablets and TV.
- Radiation related factors in the context of mobile phone use: mobile phone call duration, DECT phone call duration, data traffic on the mobile phone.
- RF-EMF exposure: cumulative RF-EMF dose for the brain and the whole body.

With these exposure measures, cross-sectional and longitudinal analyses were conducted to investigate if mobile phone use or RF-EMF exposure has an impact on health or behaviour and if it affects cognitive function of adolescents.

Article 5 presents and discusses behavioural problems and concentration capacity of adolescents in relation to mobile phone use and RF-EMF exposure. We found behavioural problems associated with several self-reported but not with operator-recorded exposure measures in the cross-sectional analysis. These associations were not found in the longitudinal analysis. Rather we found self-reported mobile phone call duration and dose measures associated with a *decrease* in self-reported behavioural problems over one year. These associations were not seen for operator-recorded mobile phone calls duration or parent-rated behavioural problems; therefore, this may be a chance finding. The lack of consistent exposure-response patterns in the longitudinal analysis does not indicate causal relationships but rather reverse causality.

Concentration capacity of the adolescents was negatively associated with several self-reported and objectively recorded exposure measures in the cross-sectional analysis. In the longitudinal analysis, the change of concentration capacity over one year was not associated with mobile phone use or RF-EMF dose, but with cumulative duration of gaming. This is in contrast to the finding for memory performance: observed associations with memory performance in adolescents were stronger for the dose measures compared to the use measures. This indicates that the RF-EMF dose may have a negative impact on the memory of adolescents (Schoeni et al. 2015a). However, the exposure measures were highly correlated and therefore the possibility of differentiation was limited. Furthermore, the dose measures are subject to large uncertainty (Article 4). Therefore, these results should be interpreted with caution.

Non-specific symptoms in adolescents (headache, tiredness, lack of energy, lack of concentration, exhaustibility and physical well-being) were related to wireless device use and whole body dose (Schoeni et al. 2017) but not to RF-EMF exposure from fixed site transmitters (Schoeni et al. 2016). The observed associations were stronger for the use than for the dose measures, this indicates no causal relationship between RF-EMF exposure and non-specific symptoms. Explanations for the associations between device use and health symptoms may be sleep deprivation due to mobile phone use during night as observed in (Schoeni et al. 2015b) or stress introduced by the high expected accessibility by mobile phones (Article 2).

9.6 The influence of errors and bias

Exposure measures in epidemiology are always proxies of the true exposure. Therefore, errors, the deviance of the estimated exposure from the true exposure, are unavoidable. Errors can be classified according to the type of deviance from the true value and in relation to the outcome of interest. Measurement errors in continuous variables can be *random* or *systematic* (Armstrong 1998). The error is *random*, if the estimated exposure is randomly scattered around the true value, the error is *systematic*, if the estimated exposure is on average higher or lower compared to the true value (Armstrong 1998). An example for random error is the measurement uncertainty of a measurement device. Systematic error can occur, if a measurement device is inaccurately calibrated.
If the error is not correlated with the outcome of interest, it is called *non-differential*, otherwise, if the extent of the error depends on the outcome, it is called *differential* (Armstrong 1998).

The error is quantified in relation to the true exposure which is not known and therefore can only be estimated. This can be done in comparing the exposure of interest with a gold standard method which is assumed to represent the true exposure as accurate as possible. Examples are the comparison of spot measurements (exposure of interest) with personal measurements (gold standard) (Frei et al. 2010) or the comparison of self-reported mobile phone use (exposure of interest) with operator-recorded mobile phone use (gold standard) (Aydin et al. 2011; Inyang et al. 2009; Vrijheid et al. 2009a) or with software-modified smartphones recording mobile phone use (gold-standard) (Goedhart et al. 2015).

Bias is the systematic deviation of results or of inferences from the truth (Oxford University Press 2014). Broadly, most of the biases can be grouped into *confounding bias*, *selection bias* and *information bias*. *Confounding bias* is the bias of an estimated effect of an exposure on an outcome due to the presence of common causes of the exposure and the outcome. *Selection bias* arises from the procedures applied to select individuals into the study or the analysis. This can lead to systematic differences between the characteristics of the study population and the whole population and limits the generalizability of the study results. *Information bias* is the bias in an estimate arising from errors in the data collection (Oxford University Press 2014). These errors can be non-differential or differential and this has different effects on associations: non-differential errors lead to an attenuation of a true association (Armstrong 1998). Differential errors can bias a true association towards or away from unity (Armstrong 1998). In the HERMES study data collection methods included questionnaires, RF-EMF measurements and operator records.

Confounding bias

Confounding can be dealt with at design stage in asking about potential confounders in the questionnaire and at analysis stage in applying multivariable regression modelling including potential confounders in the models. Included covariates in our analyses were age, sex, nationality, frequency of physical activity and alcohol consumption and highest educational level of the parents. In general, crude and adjusted results were similar indicating that these covariates did not introduce confounding bias. However, not all potential confounders can be measured easily. For instance, motivation may have influenced the performance of the adolescents in the cognitive tests. To act as a confounder, motivation has to be associated with the exposure as well. This is not expected for mobile phone use. However, the duration of gaming may be related to motivation; adolescents gaming longer may be less motivated because these tests bore them. Indeed, we found the duration of gaming related to a decrease in the measured concentration capacity over one year, thus it may be that motivation acted as a confounder.

Selection bias

Motivation could have influenced the decision to take part in the HERMES study. Motivated adolescents may rather take part than less motivated adolescents. But then, investigations took place in school during school time and therefore no additional effort was asked from the participants since our investigations replaced a regular school lesson. Since it is conceivable that motivated adolescents show fewer behavioural problems, behavioural problems may be underestimated in our study sample. However, we observed a broad range of behaviour in our study participants.

We included 439 adolescents in the HERMES study and almost all adolescents took part in the follow-up investigation (follow-up rate of 96.8%). The response rate of the parents in sending back the paper and pencil questionnaire was satisfactory as well (85.4% at baseline and 81.9% at follow-up). The difficult part was to recruit the schools in Central Switzerland (19.0% of the contacted schools participated in the study) and to a less extent the participation of the adolescents themselves (36.8% of the informed adolescents participated in the study). The participation rate in adolescents seemed to be dependent on group dynamics in school class. Furthermore, the parents had to give informed consent as well. The recruitment on school level has the advantage that the investigations can take place in school during school time and therefore, investigations can be conducted in a lot of adolescents at once. Since we were able to include schools in different parts of Central Switzerland, we included a broad range of adolescents in terms of place of residence, nationality and educational level of the parents reflecting socioeconomic status of the adolescents. Therefore we assume that selection bias was of minor concern for the HERMES study.

In contrary, the participation in the measurement study asked for a big effort from the adolescents. But half of the adolescents participating in the HERMES baseline investigation (50.3%) was willing to participate in the personal measurements. 121 of these adolescents were selected so that they represented a broad range of the HERMES participants according to sex, age and location of residential and school place. After data cleaning, 90 sets of measurements and corresponding diaries fulfilled the criteria to be included in the detailed personal measurements analysis (Article 3), whereas for the development of the dose surrogate (Article 4) and the analysis of personal RF-EMF measurements in relation to behaviour and concentration capacity (Article 5) relying only on average measurements over the whole measurement period, more measurement sets were included.

The 90 measurement sets fulfilling the strict criteria corresponded to 74.4% of the conducted personal measurements. Personal measurements ask for big effort by the study managers and by the participants, therefore as many measurement sets as possible should be included in the analysis. On the other hand, satisfactory quality of data is of importance as well. Most of the excluded measurement sets had to be excluded due to missing diary entries or devices running out of battery. The diary installed as an application on a smartphone made keeping a diary very convenient. The quality of the diaries may be improved by the installation of the diary application on the own mobile phone of the participants. However, this requires a smartphone and the data transfer after the measurements has to be organised. Since nowadays most of the adolescents own a smartphone, this would not imply a strong restriction, however, non-smartphone users and non-users should be able to participate as well (selection bias). The transfer of the diary data at the end of the measurements could be done via WLAN to a server. Drop outs due to empty batteries could have been easily avoided by the participants. We instructed the participants in groups of about four adolescents and they handed over the devices themselves. Perhaps an instruction right before the start of the measurement period for each participant would have improved their charging behaviour, but that would have meant bigger effort by the study managers. The trade-off between efficient realization of the study and enough instruction is difficult. Nowadays, adolescents are easily reachable via mobile phone; therefore reminders via SMS perhaps would have improved performance without more effort by the study managers.

Information bias

Regarding information bias, some exposure measures are more prone to bias compared to others. Exposure estimated using geospatial propagation modelling cannot be biased. Personal measurements can be influenced by the participants in for instance placing the measurement device close to sources such as WLAN or DECT base stations or a mobile phone. We assume, that the adolescents were not aware that we aimed at relating measured exposure to outcomes (the communicated aim was to get a better knowledge of the exposure of adolescents), therefore information bias is of minor concern regarding the results of the personal measurements (Article 3).

We found the self-reported mobile phone call duration being overestimated by a factor of 9 compared to operator-recorded call duration. Thus, as described before (Aydin et al. 2011; Inyang et al. 2009), information bias is of concern for the analyses relying on the self-reported mobile phone use. We had additionally operator-recorded mobile phone use data, these data cannot be biased. Therefore we had the opportunity to compare the results using self-reported and operator-recorded mobile phone use. And indeed, as demonstrated in article 5, we observed in the cross-sectional analysis associations of behavioural problems and self-reported exposure measures, but not with operator-recorded exposure measures. This indicates that recall bias (information bias) may affect such cross-sectional associations also found in other studies.

Behavioural problems of the adolescents were asked in the questionnaire and therefore may be biased. We had additionally parent-rated behaviour available. These data can be biased as well, but, we had at least two data sources available. Additionally, the SDQ is a validated and widely used scale. Since results were similar for self-reported and parent-rated behaviour (Article 2 and 5), information bias is of minor concern regarding the assessment of behavioural problems of the adolescents.

9.7 Improvement of the dose surrogate

To improve the developed dosimetric methodology (Article 4), we see mainly two approaches:

- The improvement of the far-field prediction for WLAN, uplink and DECT exposure.

- More detailed data about the mobile phone use of the study participants and the enrichment of knowledge about the output power of mobile phone during calls and especially for data traffic.

These two approaches are discussed in the following.

9.7.1 Prediction of the far-field exposure

Since the realization of personal measurements for a large cohort is very expensive and time-consuming, the prediction of the far-field exposure is preferred. For the exposure from fixed site transmitters, predictions of a geospatial propagation model showed good performance (Frei et al. 2010). These predictions are restricted to places that can be geocoded (such as homes, schools and workplaces); the remaining locations have to be predicted differently. Since adolescents spent most of their time at home and in school (in the HERMES cohort: 15 h 42 min at home and 4 h 43 min in school according to the diaries filled in during the personal measurements), the average measured personal exposure in a subsample for the remaining locations is sufficient for the dose calculations of the fixed site transmitters exposure. For the far-field exposure from mobile phones in the surroundings (uplink), WLAN and DECT base stations, predictions have to be done using a different approach.

The far-field exposure from other mobile phones (uplink) and from WLAN base stations was estimated by means of linear regression models based on personal measurements. For both, uplink and WLAN exposure, the explained variance by the models was about 5% (adjusted R^2). Thus it seems, that a lot of factors influence these exposures and that these factors are difficult to measure.

Uplink exposure

We did not adjust the uplink measurements for the influence of the own mobile phone but focused on variables predicting the exposure from other mobile phones. According to the deepened analysis of the personal measurements (Article 3), the use of the own mobile phone influences measured uplink exposure substantially and therefore measured uplink exposure has to be adjusted for the own mobile phone use (as discussed in chapter 9.3). It is assumed, that the model to predict the uplink exposure can be improved if using an adjusted measured uplink exposure.

WLAN exposure

The use of WLAN for mobile internet on the mobile phone did not affect measured WLAN exposure (Article 3). We did not investigate the influence of the use of the mobile phone as hotspot to connect other devices to the internet. And in the future, there may be other device features using WLAN. Therefore it would be worth to clarify if the measured WLAN exposure has to be adjusted as well to get a more accurate WLAN exposure proxy for the WLAN exposure originating from WLAN in the surroundings and not the own device.

WLAN in school and at home had little impact on the average WLAN measurements. This is in line with the fact that WLAN in school and at home were no significant predictors for the WLAN measurements (Article 3). This illustrates that it is not straightforward predicting the WLAN exposure. Possible predictors for the WLAN exposure (and therefore factors may improving the WLAN prediction model) may be the presence of WLAN hotspots not only in trains and buses (represented by the time spent in trains in the current WLAN model (Article 4)) but also in public buildings. However, these are difficult to assess.

DECT exposure

DECT exposure is difficult to measure in a proper way by personal measurement devices because of crosstalk issues. If the DECT readings by personal measurement devices can be improved, it is assumed that pieces of information such as having a DECT phone at home and if this phone is a conventional or an eco mode phone are able to predict a fair amount of the DECT exposure at home. Since it is expected that other locations (besides the workplace for adults) do not have DECT exposure, our approach of assuming only DECT exposure at home, is justifiable and can be applied in future studies as well.

9.7.2 Mobile phone use and output power of mobile phones

More detailed and accurate data about the mobile phone use of the study participants and the enrichment of knowledge about the output power of mobile phones during calls and especially for data traffic will allow to improve the dose surrogate.

Mobile phone use

Mobile phone use includes the amount of mobile phone use as well as other factors influencing the absorbed radiation energy such as the network used for calls and the use of a headset for calls resulting in a different position of the device in relation to the body.

Mobi-Expo is an international study within MobiKids (Sadetzki et al. 2014) with the aim to validate young people's recall of their mobile phone use and to characterize how young people use their mobile phones. Besides comparing self-reported mobile phone use with operator records, the self-reported use will be validated using software-modified mobile phones and an application installed on participants' own mobile phones named XMobiSense to record the mobile phone use. A pilot study distributing software-modified mobile phones for four weeks to 26 participants showed that the mobile phone handset was hold close to the head for about 90% of the recorded call time (Goedhart et al. 2015). This means a 10% reduction in the brain dose originating from mobile phone calls. All other near-field components and the far-field part together contribute less than this difference to the total brain exposure.

Another crucial piece of information for the calculation of the dose originating from mobile phone calls is the network used for calls since the output power differs for mobile phone calls in different networks (Gati et al. 2009). We used the operator-recorded proportion of the network used for calls (Article 4). This proportion is based on the recorded network for each call made and received, but only the network when the call started is recorded. The application XMobiSense records the proportion of the networks for each call and is therefore more accurate. Using application and operator records for a time period of eight months (October 2013 until May 2014) for one person, the difference in proportion of UMTS calls was +3.75% in the application records compared to the operator records. This difference results in a 6.7% reduction in the brain dose originating from mobile phone calls.

These calculations illustrate, that such pieces of information have a substantial impact on the dose calculations and therefore improve the dose surrogate.

Output power of mobile phones

Since the SAR for the absorbed energy from the use of wireless communication devices is proportional to the output power of the devices, knowledge is needed about the output power of devices. The output power depends not only on the type of device, but also on the type of use. For instance, the output power for data traffic on the mobile phone was found to be increased by a factor of 4 compared to calls on the mobile phones (Gati et al. 2009; Huang et al. 2014; Persson et al. 2012).

For the calculation of the dose originating from mobile phone calls, we took into account the network used for calls (GSM or UMTS). Other factors have an influence on the output power as well. The question is if these factors are measureable with a fair amount of effort and if they have an essential impact on the dose calculations.

The output power was higher for calls made and received in rural areas compared to urban areas (Gati et al. 2009; Kelsh et al. 2011; Lönn et al. 2004; Persson et al. 2012), higher inside buildings than outdoors (Gati et al. 2009) and surprisingly higher while being stationary compared to moving (Gati et al. 2009). These measurements of the output power were done using software-modified mobile phones or were linked to mobile phone base stations in the study area. Mobile phone circumstances were based on information of the base stations the mobile phones were connected to or the measurements were done along predefined routes. Erdreich et al. (2007) used software-modified mobile phones in combination with questionnaire data and a diary to collect information about each call made and received by 53 participants (Erdreich et al. 2007). They found increased output power levels for calls inside buildings and while being stationary, but differences were smaller compared to the other measurement studies (Gati et al. 2009; Kelsh et al. 2011; Lönn et al. 2004; Persson et al.

2012). In the framework of the Interphone study, software-modified mobile phones and questionnaire data were applied. But in contrast to the study by Erdreich et al. (2007), the collected data about the mobile phone call circumstances were asked referring to an average mobile phone use of the 516 participants (Vrijheid et al. 2009b). They found slightly increased output power level for calls done by participants indicating to use their mobile phone mainly in rural areas compared to those using it mainly in urban areas. The report of using of the mobile phone while moving in a vehicle or while being inside buildings did not have an influence on output power levels during calls. This indicates either that questionnaire data referring to average use is not accurate enough to see differences or that these factors are averaged for the mobile phone use over longer time periods. This could be figured out in comparing questionnaire data as in Vrijheid et al. (2009b) with data from studies measuring output power levels during calls (Gati et al. 2009; Kelsh et al. 2011; Lönn et al. 2004; Persson et al. 2012).

Another source of uncertainty is the calculation of the dose originating from data traffic on the mobile phone. Firstly, little is known about the output power of mobile phones during data traffic and secondly, two technologies can be used for data traffic on the mobile phone (mobile network and WLAN).

Little data is available about the output power of mobile phones during data traffic. The output power for data traffic seems to be higher compared to the output power during calls (Gati et al. 2009; Huang et al. 2014; Persson et al. 2012) and dependent on the data rate used (Gati et al. 2009; Persson et al. 2012).

We used the duration of data traffic on the mobile phone and the proportion of the use of mobile network and WLAN asked in the questionnaire since in the operator records only the amount of data traffic via network was recorded (Article 4). An application recording the duration of data traffic for the data exchange via mobile network and WLAN separately would provide more accurate data and these data would improve the dose surrogate.

9.8 Applications of the dosimetric approach

Since the dosimetric approach provides one exposure surrogate combining the near-field and the far-field part of RF-EMF exposure, it enables one to relate these parts to each other and to compare them.

For the Swiss population in 2007, it was estimated that a mobile phone call duration of 1.2 min per day corresponds to the daily whole body dose from far-field sources if the GSM network is used for calls (Lauer et al. 2013). If using the UMTS network, the call duration can substantially be increased, to 3 h per day (Lauer et al. 2013). According to the dose calculations for the HERMES cohort (Article 4), the mean brain dose originating from mobile phone base stations (downlink) for one day (24 hours) corresponds to the dose originating from a mobile phone call lasting 2.6 s if the GSM network is used and 6.1 min if the UMTS network is used. For the whole body exposure, 15.0 s for GSM calls and 34.2 min for UMTS calls correspond to the mean downlink exposure for one day. The differences between these two studies are induced by different far-field exposure levels to compare with (total far-field dose of 35.2 mJ/kg/day (Lauer et al. 2013) and downlink dose of 6.2 mJ/kg/day (Article 4)). Regarding data traffic on the mobile phone, mean daily downlink dose corresponded to 14.1 h data traffic for the brain dose and 8.6 min data traffic for the whole body dose (Article 4). These findings demonstrate that the use of the mobile phone on average contributes much more to the personal exposure compared to mobile phone base stations and other fixed site transmitters.

A mobile phone call produces exposure from the mobile phone handset and from the base station the mobile phone is connected to. Gati et al. (2010) found a reverse linear correlation between the transmitted (handset) and the received (base station) power of the mobile phone (Gati et al. 2010); the mobile phone transmitted higher power when the received signal was weak. The decrease in power by the handset for increasing power by the base station was more pronounced for the UMTS network; this is due to the faster power control in this network compared to the GSM network. The same was observed in a simulation study looking at three mobile phone call scenarios: using a conventional outdoor UMTS base station, an indoor UMTS small cell and an indoor WLAN access point (WiFi calling) to make a mobile phone call (Plets et al. 2014). Lower field strengths (downlink exposure) corresponded to higher localised SARs (uplink exposure). Using the dose approach, uplink and downlink exposure were combined and the three mobile phone call scenarios were compared. The connection to an outdoor UMTS base station was preferred for good connection to this base station, whereas the connection to an indoor UMTS small cell was preferred if the connection to the outdoor base station was bad. The same was found on the population level by Varsier et al. (2015): the dose for mobile phone calls in buildings with good connection properties was increased by a factor of 2.3 if using a small cell compared to an outdoor base station (Varsier et al. 2015).

The dosimetric approach was also used to investigate mobile phone calls in trains. On the level of a single call using a small cell (a cell placed in the train and attached to an exterior antenna on the roof of the train which is connected to an outdoor base station) corresponded to lower dose for long calls, whereas for short phone calls, it corresponded to higher dose compared to a connection to an outdoor base station (Aerts et al. 2015). This may be due to more handovers from one base station to the other during a longer call and due to the relatively larger contribution of the downlink exposure for short calls. On the population level, using a small cell in the train reduced the dose by a factor of 2.2 (Varsier et al. 2015).

The approach also allows investigating the potential of measures to minimize the exposure. Plets et al. (2015) aimed at jointly minimize the whole body dose originating from a mobile phone and the base station the device is connected to for data exchange via WLAN or the LTE network and calls via the UMTS network. On average increasing the number of indoor small cells reduced the dose by 75%. For WLAN data exchange, the dose originating from the mobile phone dominated the total dose already after a few seconds of usage, for LTE data exchange and UMTS calls, 1 to 17 minutes of usage corresponded to the dose from the base station, depending on the number of small cells in the building.

In summary, the application of the dosimetric approach allows the following conclusions: On average, the exposure from mobile phone use contributes much more to the total exposure than mobile phone base stations. Good connection to the base station results in less exposure from the mobile phone and the installation of small cells in a building or in a train reduces the exposure if the connection to outdoor base stations is bad.

9.9 Public health relevance

Mobile phones and other wireless communication devices emitting RF-EMFs are nowadays omnipresent and they undergo a rapid development. In 2014, the number of mobile phone subscriptions in Switzerland reached 11.5 Mio what corresponds to 141 subscriptions per inhabitant (ICT 2015). Worldwide, the proportion of the population covered by a 2G mobile phone network grew from 58% in 2001 to 95% in 2015 and the 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. Thus even a small risk would result in a large public health impact.

The findings of the HERMES study contribute to a more fact-based public debate regarding the installation of additional mobile phone base stations and WLAN in schools, both highly debated topics in the public. More than half of the Swiss population views radiation from mobile phone base stations as dangerous (Swiss Federal Statistical Office 2012). However, in the HERMES cohort, the exposure from mobile phone base stations contributed on average 1.8% to the whole body dose whereas the exposure from mobile phone calls contributed 69.4% (Article 4). And even for a non-mobile phone user, the exposure from environmental sources accounted only for 27% of the total daily dose, the remaining 73% of the dose originated from cordless phone calls and the use of computers, laptops and tablet connected to WLAN (Article 4). Thus, people are in control of the major part of their exposure.

Applications of the dosimetric approach illustrate that the exposure can be reduced if the quality of the connection to mobile phone base stations during calls is improved by equipping an area with more mobile phone base stations or by the installation of small cells in buildings and trains (Aerts et al. 2015; Plets et al. 2015; Varsier et al. 2015). Outdoor base stations should be preferred if the connection is of good quality and small cells should be preferred if the connection to the outdoor base station is of bad quality (Plets et al. 2014).

The results in article 3 demonstrate that a WLAN in school has very little impact on average WLAN measurements. Thus effort to reduce the exposure of children and adolescents should rather focus on their use behaviour. For instance, since the absorbed dose depends on the distance of the emitting device to the body, the brain exposure can be reduced by using a headset for mobile phone calls. Eco mode DECT phones radiate only if they are used for calls, therefore the exposure is reduced compared to conventional DECT phones.

Regarding the use of the mobile network or WLAN for calling or data traffic, the network connection should be preferred, especially if the connection to the mobile phone base station is of good quality (Plets et al. 2014).

The participation rate of adolescents was moderate (36.8%) and the study was conducted in Central Switzerland, a small part of Switzerland. This may limit the representativeness of the study cohort for the target population of Swiss adolescents. But we were able to include adolescents of different nationalities, different school levels and from urban and rural areas in Central Switzerland. Thus we expect that the conclusions of our results hold for Swiss adolescents in general.

Conclusions

In conclusion, adolescents are exposed to their mobile phone in many ways. But it depends on the aspect of this exposure whether the health, the behaviour or cognitive function of adolescents are affected.

The behaviour and the concentration capacity of adolescents were not affected by RF-EMF exposure, but behavioural problems and impaired mental health were associated with problematic mobile phone use. Therefore, problematic mobile phone use should be considered if dealing with adolescents showing impaired mental health or behavioural problems.

The exposure from environmental sources such as fixed site transmitters, WLAN and DECT base stations and mobile phones in the surroundings plays a minor role for the RF-EMF exposure compared to the exposure from the use of mobile phones, cordless phones and computers, laptops and tablets connected to WLAN.

Attending a school with WLAN or having WLAN at home has no impact on the whole body exposure of adolescents. Thus precautionary measures to reduce the exposure to RF-EMF should focus on the use of wireless communication devices.

9.10 Outlook

Mobile phones and other wireless communication devices undergo a rapid development. Thus exposure to RF-EMF develops and changes accordingly.
Following the EMF research agenda of the WHO (WHO 2010), large cohort studies are ongoing to investigate mobile phone use in adolescents. The HERMES study continues within the European project GERoNiMO (Generalized EMF research using novel methods. An integrated approach: from research to risk assessment and support to risk management), that was launched in January 2014. Objectives are to better understand mechanisms underlying possible health effects of EMF, better characterize current and future population levels of EMF exposure in Europe and to improve the health risk assessment of EMF and propose non-technological means to reduce EMF exposure (GERoNiMO 2015). This continuation using similar exposure assessment methods and outcome measures will allow having a deeper look into aspects of the HERMES study that have been investigated in the smaller HERMES cohort and look into aspects that have not been looked at so far. Within personal RF-EMF measurements conducted in the framework of the GERoNiMO investigations, the application XMobiSense was distributed among the participants. This will enable to further investigate the impact of the own mobile phone use on personal measurements.

The SCAMP (Study of Cognition, Adolescents and Mobile Phones) study, an ongoing cohort study conducted in London, UK, aims at investigating if the use of mobile phones and other wireless communication devices impacts cognitive or behavioural development in adolescents in the largest cohort study in the world to date (SCAMP 2015). The SCAMP cohort includes all 7th grade students attending participating schools and includes school assessment consisting of cognitive tasks and collecting mobile phone data and a parent online survey to collect more data about the medical history, the lifestyle and demographics of the family. The study benefits from the experience gained in the HERMES study, especially regarding personal RF-EMF measurements in adolescents and the calculation of the cumulative dose.

Within the HERMES study, exposure assessment methods used in previous studies were improved and enhanced. A novel dosimetric approach was applied to develop an RF-EMF dose surrogate taking into account the exposure originating from several RF-EMF sources. These methods can be used in future epidemiological studies investigating RF-EMF exposure and its influence on humans.

References

Aarstad J (2011) Cell phone use and behavioural problems: indications of unobserved heterogeneity in Divan et al's study J Epidemiol Community Health 65:465; author reply 465-466 doi:10.1136/jech.2010.131979

Abramson MJ, Benke GP, Dimitriadis C, Inyang IO, Sim MR, Wolfe RS, Croft RJ (2009) Mobile telephone use is associated with changes in cognitive function in young adolescents Bioelectromagnetics 30:678-686 doi:10.1002/bem.20534

Aerts S, Plets D, Thielens A, Martens L, Joseph W (2015) Impact of a Small Cell on the RF-EMF Exposure in a Train Int J Environ Res Public Health 12:2639-2652 doi:10.3390/ijerph120302639

Aerts S, Plets D, Verloock L, Martens L, Joseph W (2014) Assessment and comparison of total RF-EMF exposure in femtocell and macrocell base station scenarios Radiat Prot Dosimetry 162:236-243 doi:10.1093/rpd/nct272

Armstrong BG (1998) Effect of measurement error on epidemiological studies of environmental and occupational exposures Occup Environ Med 55:651-656

Augner C, Hacker GW (2012) Associations between problematic mobile phone use and psychological parameters in young adults Int J Public Health 57:437-441

Aydin D et al. (2011) Predictors and overestimation of recalled mobile phone use among children and adolescents Prog Biophys Mol Biol 107:356-361 doi:10.1016/j.pbiomolbio.2011.08.013

Beekhuizen J, Vermeulen R, Kromhout H, Bürgi A, Huss A (2013) Geospatial modelling of electromagnetic fields from mobile phone base stations Sci Total Environ 445-446:202-209 doi:10.1016/j.scitotenv.2012.12.020

Bianchi A, Phillips JG (2005) Psychological predictors of problem mobile phone use CyberPsychology & Behavior 8:39-51

Billieux J (2012) Problematic Use of the Mobile Phone: A Literature Review and a Pathways Model Current Psychiatry Reviews 8:000-000

Blas J, Lago FA, Fernandez P, Lorenzo RM, Abril EJ (2007) Potential exposure assessment errors associated with body-worn RF dosimeters Bioelectromagnetics 28:573-576 doi:10.1002/bem.20355

Bolte JF, 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 doi:10.1016/j.envint.2012.07.006

Bolte JF, van der Zande G, Kamer J (2011) Calibration and uncertainties in personal exposure measurements of radiofrequency electromagnetic fields Bioelectromagnetics 32:652-663 doi:10.1002/bem.20677

Breckenkamp J, Neitzke HP, Bornkessel C, Berg-Beckhoff G (2008) Applicability of an exposure model for the determination of emissions from mobile phone base stations Radiat Prot Dosimetry 131:474-481 doi:10.1093/rpd/ncn201

Briggs D, Beale L, Bennett J, Toledano MB, de Hoogh K (2012) A geographical model of radio-frequency power density around mobile phone masts Sci Total Environ 426:233-243 doi:10.1016/j.scitotenv.2012.03.066

Bürgi A et al. (2010) A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research Bioelectromagnetics 31:226-236 doi:10.1002/bem.20552

Bürgi A, Theis G, Siegenthaler A, Röösli M (2008) Exposure modeling of high-frequency electromagnetic fields J Expo Sci Environ Epidemiol 18:183-191 doi:10.1038/sj.jes.7500575

Byun YH et al. (2013a) Epidemiological characteristics of mobile phone ownership and use in korean children and adolescents Environ Health Toxicol 28:e2013018 doi:10.5620/eht.2013.28.e2013018

Byun YH et al. (2013b) Mobile phone use, blood lead levels, and attention deficit hyperactivity symptoms in children: a longitudinal study PLoS One 8:e59742 doi:10.1371/journal.pone.0059742

Cardis E et al. (2007) The INTERPHONE study: design, epidemiological methods, and description of the study population Eur J Epidemiol 22:647-664 doi:10.1007/s10654-007-9152-z

Cardis E et al. (2011) Estimation of RF energy absorbed in the brain from mobile phones in the Interphone Study Occup Environ Med 68:686-693 doi:10.1136/oemed-2011-100065

Croft RJ, Leung S, McKenzie RJ, Loughran SP, Iskra S, Hamblin DL, Cooper NR (2010) Effects of 2G and 3G mobile phones on human alpha rhythms: Resting EEG in adolescents, young adults, and the elderly Bioelectromagnetics 31:434-444 doi:10.1002/bem.20583

de Miguel-Bilbao S, Garcia J, Ramos V, Blas J (2015) Assessment of human body influence on exposure measurements of electric field in indoor enclosures Bioelectromagnetics 36:118-132 doi:10.1002/bem.21888

Divan HA, Kheifets L, Obel C, Olsen J (2008) Prenatal and postnatal exposure to cell phone use and behavioral problems in children Epidemiology 19:523-529 doi:10.1097/EDE.0b013e318175dd47

Divan HA, Kheifets L, Obel C, Olsen J (2012) Cell phone use and behavioural problems in young children Journal of epidemiology and community health 66:524-529

Elliott P, Toledano MB, Bennett J, Beale L, de Hoogh K, Best N, Briggs DJ (2010) Mobile phone base stations and early childhood cancers: case-control study Bmj 340:c3077 doi:10.1136/bmj.c3077

Erdreich LS et al. (2007) Factors that influence the radiofrequency power output of GSM mobile phones Radiat Res 168:253-261 doi:10.1667/rr0906.1

Fields at Work (2015) ExpoM-RF User Manual (version 2.1). http://www.fieldsatwork.ch/uploads/Downloads/Expom_RF_Manual-EN_v2.1.pdf

Frei P, Mohler E, Bürgi A, Fröhlich J, Neubauer G, Braun-Fahrländer C, Röösli M (2009a) A prediction model for personal radio frequency electromagnetic field exposure Sci Total Environ 408:102-108 doi:10.1016/j.scitotenv.2009.09.023

Frei P, Mohler E, Bürgi A, Fröhlich J, Neubauer G, Braun-Fahrländer C, Röösli M (2010) Classification of personal exposure to radio frequency electromagnetic fields (RF-EMF) for epidemiological research: Evaluation of different exposure assessment methods Environ Int 36:714-720 doi:10.1016/j.envint.2010.05.005

Frei P et al. (2009b) Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields Environ Res 109:779-785 doi:10.1016/j.envres.2009.04.015

Gati A, Conil E, Man-Fai W, Wiart J (2010) Duality Between Uplink Local and Downlink Whole-Body Exposures in Operating Networks Electromagnetic Compatibility, IEEE Transactions on 52:829-836 doi:10.1109/TEMC.2010.2066978

Gati A, Hadjem A, Man-Fai W, Wiart J (2009) Exposure induced by WCDMA mobiles phones in operating networks IEEE Trans Wireless Commun 8:5723-5727 doi:10.1109/TWC.2009.12.080758

GERoNiMO. (2015). http://www.crealradiation.com/index.php/geronimo-home. Accessed 8 September 2015

Goedhart G et al. (2015) Using software-modified smartphones to validate self-reported mobile phone use in young people: A pilot study Bioelectromagnetics doi:10.1002/bem.21931

Goodman R (1997) The Strengths and Difficulties Questionnaire: a research note Journal of child psychology and psychiatry 38:581-586

Gryz K, Zradzinski P, Karpowicz J (2015) The role of the location of personal exposimeters on the human body in their use for assessing exposure to the electromagnetic field in the radiofrequency range 98-2450 MHz and compliance analysis: evaluation by virtual measurements Biomed Res Int 2015:272460 doi:10.1155/2015/272460

Guxens M et al. (2013a) Maternal cell phone and cordless phone use during pregnancy and behaviour problems in 5-year-old children Journal of epidemiology and community health 67:432-438

Guxens M, Vermeulen R, Huss A (2013b) Reply to 'On the association of cell phone exposure with childhood behaviour' by Sudan et al J Epidemiol Community Health 67:980 doi:10.1136/jech-2013-202750

Ha JH, Chin B, Park D-H, Ryu S-H, Yu J (2008) Characteristics of excessive cellular phone use in Korean adolescents CyberPsychology & Behavior 11:783-784

Ha M, Im H, Lee M, Kim HJ, Kim BC, Gimm YM, Pack JK (2007) Radio-frequency radiation exposure from AM radio transmitters and childhood leukemia and brain cancer Am J Epidemiol 166:270-279 doi:10.1093/aje/kwm083

Haarala C, Bergman M, Laine M, Revonsuo A, Koivisto M, Hamalainen H (2005) Electromagnetic field emitted by 902 MHz mobile phones shows no effects on children's cognitive function Bioelectromagnetics Suppl 7:S144-150 doi:10.1002/bem.20142

Heinrich S, Thomas S, Heumann C, von Kries R, Radon K (2010) Association between exposure to radiofrequency electromagnetic fields assessed by dosimetry and acute symptoms in children and adolescents: a population based cross-sectional study Environ Health 9:75 doi:10.1186/1476-069x-9-75

Hölling H, Erhart M, Ravens-Sieberer U, Schlack R (2007) Verhaltensauffälligkeiten bei Kindern und Jugendlichen Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz 50:784-793 doi:10.1007/s00103-007-0241-7

Huang Y, Conil E, Wiart J, Varsier N, Person C (2014) Sensitivity analysis of downlink received and uplink emitted powers in a geographical area to ICT usage parameters. Paper presented at the Proceedings of the Annual Meeting of BEMS and EBEA, Capetown, South Africa, June 8-13, 2014

ICNIRP (1998) ICNIRP Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz) Health Phys 74:494-522

ICT (2015) ICT Facts & Figures. The world in 2015. http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2015.pdf

Ikeda K, Nakamura K (2014) Association between mobile phone use and depressed mood in Japanese adolescents: a cross-sectional study Environ Health Prev Med 19:187-193 doi:10.1007/s12199-013-0373-3

In-Albon T, Zumsteg U, Muller D, Schneider S (2010) Mental disorders in the pediatric setting - results of a Swiss survey Swiss Med Wkly 140:w13092 doi:10.4414/smw.2010.13092

Inyang I, Benke G, McKenzie R, Abramson M (2008) Comparison of measuring instruments for radiofrequency radiation from mobile telephones in epidemiological studies: implications for exposure assessment J Expo Sci Environ Epidemiol 18:134-141 doi:10.1038/sj.jes.7500555

Inyang I, Benke G, Morrissey J, McKenzie R, Abramson M (2009) How well do adolescents recall use of mobile telephones? Results of a validation study BMC Med Res Methodol 9:36 doi:10.1186/1471-2288-9-36

Iskra S, McKenzie R, Cosic I (2010) Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry Radiat Prot Dosimetry 140:25-33 doi:10.1093/rpd/ncp309

Kelsh MA et al. (2011) Measured radiofrequency exposure during various mobile-phone use scenarios J Expo Sci Environ Epidemiol 21:343-354 doi:10.1038/jes.2010.12

Kheifets L, Repacholi M, Saunders R, Van Deventer E (2005) The sensitivity of children to electromagnetic fields Pediatrics 116:e303-e313

Krause CM et al. (2006) Mobile phone effects on children's event-related oscillatory EEG during an auditory memory task Int J Radiat Biol 82:443-450 doi:10.1080/09553000600840922

Lauer O, Frei P, Gosselin MC, Joseph W, Röösli M, Fröhlich J (2013) Combining near- and far-field exposure for an organ-specific and whole-body RF-EMF proxy for epidemiological research: a reference case Bioelectromagnetics 34:366-374 doi:10.1002/bem.21782

Lauer O, Leidenberger, P., Müri, M., Zahner, M., Fröhlich, J. (2011) A Novel Measurement System for Environmental Exposure Monitoring. Paper presented at the ACM SenSys 2011, Seattle, WA, USA,

Lauer O, Neubauer G, Röösli M, Riederer M, Frei P, Mohler E, Fröhlich J (2012) Measurement setup and protocol for characterizing and testing radio frequency personal exposure meters Bioelectromagnetics 33:75-85 doi:10.1002/bem.20687

Lee TM, Ho SM, Tsang LY, Yang SH, Li LS, Chan CC, Yang SY (2001) Effect on human attention of exposure to the electromagnetic field emitted by mobile phones Neuroreport 12:729-731

Lönn S, Forssen U, Vecchia P, Ahlbom A, Feychting M (2004) Output power levels from mobile phones in different geographical areas; implications for exposure assessment Occup Environ Med 61:769-772 doi:10.1136/oem.2003.012567

Loughran SP, Benz DC, Schmid MR, Murbach M, Kuster N, Achermann P (2013) No increased sensitivity in brain activity of adolescents exposed to mobile phone-like emissions Clin Neurophysiol 124:1303-1308 doi:10.1016/j.clinph.2013.01.010

Merzenich H, Schmiedel S, Bennack S, Bruggemeyer H, Philipp J, Blettner M, Schuz J (2008) Childhood leukemia in relation to radio frequency electromagnetic fields in the vicinity of TV and radio broadcast transmitters Am J Epidemiol 168:1169-1178 doi:10.1093/aje/kwn230

Moosbrugger H, Goldhammer F (2007) FAKT-II Frankfurter Adaptiver Konzentrationsleistungs-Test II Manual Verlag Hans Huber, Hogrefe AG, Bern

Neubauer G, Cecil S, Giczi W, Petric B, Preiner P, Frohlich J, Röösli M (2010) The association between exposure determined by radiofrequency personal exposimeters and human exposure: a simulation study Bioelectromagnetics 31:535-545 doi:10.1002/bem.20587

ONIR (1999) Ordinance relating to protection from non-ionizing radiation (ONIR) of 23rd December 1999 SR 814710

Oxford University Press (2014) A Dictionary of Epidemiology, Sixth Edition.

Pedrero Perez EJ, Rodriguez Monje MT, Ruiz Sanchez De Leon JM (2012) [Mobile phone abuse or addiction. A review of the literature] Adicciones 24:139-152

Persson T, Tornevik C, Larsson LE, Loven J (2012) Output power distributions of terminals in a 3G mobile communication network Bioelectromagnetics 33:320-325 doi:10.1002/bem.20710

Plets D, Joseph W, Aerts S, Vanhecke K, Vermeeren G, Martens L (2014) Prediction and comparison of downlink electric-field and uplink localised SAR values for realistic indoor wireless planning Radiat Prot Dosimetry 162:487-498 doi:10.1093/rpd/ncu019

Plets D et al. (2015) Joint minimization of uplink and downlink whole-body exposure dose in indoor wireless networks Biomed Res Int 2015:943415 doi:10.1155/2015/943415

Preece AW et al. (2005) Effect of 902 MHz mobile phone transmission on cognitive function in children Bioelectromagnetics Suppl 7:S138-143 doi:10.1002/bem.20128

Protégeles (2005) Seguridad infantil y costumbres de los menores en la telefonía móvil. Estudio realizado para el Defensor del Menor. http://www.protegeles.com/docs/estudio_telefonia.pdf

Ravens-Sieberer U et al. (2008) The KIDSCREEN-52 quality of life measure for children and adolescents: psychometric results from a cross-cultural survey in 13 European countries Value Health 11:645-658 doi:10.1111/j.1524-4733.2007.00291.x

Redmayne M, Smith E, Abramson MJ (2013) The relationship between adolescents' well-being and their wireless phone use: a cross-sectional study Environ Health 12:90 doi:10.1186/1476-069x-12-90

Riddervold IS et al. (2008) Cognitive function and symptoms in adults and adolescents in relation to rf radiation from UMTS base stations Bioelectromagnetics 29:257-267 doi:10.1002/bem.20388

Röösli M et al. (2010) Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol Environ Health 9:23 doi:10.1186/1476-069x-9-23

Sadetzki S et al. (2014) The MOBI-Kids Study Protocol: Challenges in Assessing Childhood and Adolescent Exposure to Electromagnetic Fields from Wireless Telecommunication

Technologies and Possible Association with Brain Tumor Risk Front Public Health 2:124 doi:10.3389/fpubh.2014.00124
Sanchez-Martinez M, Otero A (2009) Factors associated with cell phone use in adolescents in the community of Madrid (Spain) CyberPsychology & Behavior 12:131-137
SCAMP. (2015). http://www.scampstudy.org/. Accessed 8 September 2015
Schoeni A, Roser K, Burgi A, Roosli M (2016) Symptoms in Swiss adolescents in relation to exposure from fixed site transmitters: a prospective cohort study Environ Health 15:77 doi:10.1186/s12940-016-0158-4
Schoeni A, Roser K, Roosli M (2015a) Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: A prospective cohort study in adolescents Environ Int 85:343-351 doi:10.1016/j.envint.2015.09.025
Schoeni A, Roser K, Roosli M (2015b) Symptoms and Cognitive Functions in Adolescents in Relation to Mobile Phone Use during Night PLoS One 10:e0133528 doi:10.1371/journal.pone.0133528
Schoeni A, Roser K, Roosli M (2017) Symptoms and the use of wireless communication devices: A prospective cohort study in Swiss adolescents Environ Res 154:275-283 doi:10.1016/j.envres.2017.01.004
Söderqvist F, Carlberg M, Hardell L (2008) Use of wireless telephones and self-reported health symptoms: a population-based study among Swedish adolescents aged 15-19 years Environ Health 7:18 doi:10.1186/1476-069x-7-18
Sudan M, Kheifets L, Arah OA, Olsen J (2013) On the association of cell phone exposure with childhood behaviour J Epidemiol Community Health 67:979 doi:10.1136/jech-2013-202495
Swiss Federal Statistical Office (2012) Wahrnehmung von Umweltqualität und Umweltverhalten Ergebnisse der Omnibus-Erhebung 2011.
The KIDSCREEN Group Europe (2006) The KIDSCREEN Questionnaires - Quality of life questionnaires for children and adolescents. Handbook Lengerich: Pabst Science Publishers
Thielens A et al. (2015a) On-body calibration and measurements using a personal, distributed exposimeter for wireless fidelity Health Phys 108:407-418 doi:10.1097/hp.0000000000000238
Thielens A, Agneessens S, Verloock L, Tanghe E, Rogier H, Martens L, Joseph W (2015b) On-body calibration and processing for a combination of two radio-frequency personal exposimeters Radiat Prot Dosimetry 163:58-69 doi:10.1093/rpd/ncu056
Thielens A et al. (2013) Personal distributed exposimeter for radio frequency exposure assessment in real environments Bioelectromagnetics 34:563-567 doi:10.1002/bem.21793
Thomas R, Sanders S, Doust J, Beller E, Glasziou P (2015) Prevalence of attention-deficit/hyperactivity disorder: a systematic review and meta-analysis Pediatrics 135:e994-1001 doi:10.1542/peds.2014-3482
Thomas S et al. (2010a) Use of mobile phones and changes in cognitive function in adolescents Occup Environ Med 67:861-866 doi:10.1136/oem.2009.054080
Thomas S, Heinrich S, von Kries R, Radon K (2010b) Exposure to radio-frequency electromagnetic fields and behavioural problems in Bavarian children and adolescents Eur J Epidemiol 25:135-141 doi:10.1007/s10654-009-9408-x
Thomas S, Kuhnlein A, Heinrich S, Praml G, Nowak D, von Kries R, Radon K (2008a) Personal exposure to mobile phone frequencies and well-being in adults: a cross-sectional study based on dosimetry Bioelectromagnetics 29:463-470 doi:10.1002/bem.20414
Thomas S, Kuhnlein A, Heinrich S, Praml G, von Kries R, Radon K (2008b) Exposure to mobile telecommunication networks assessed using personal dosimetry and well-being in children and adolescents: the German MobilEe-study Environ Health 7:54 doi:10.1186/1476-069x-7-54
Thomée S, Härenstam A, Hagberg M (2011) Mobile phone use and stress, sleep disturbances, and symptoms of depression among young adults-a prospective cohort study BMC Public Health 11:66

Thuróczy G, Molnár F, Jánossy G, Nagy N, Kubinyi G, Bakos J, Szabó J (2008) Personal RF exposimetry in urban area annals of telecommunications - annales des télécommunications 63:87-96 doi:10.1007/s12243-007-0008-z

Urbinello D, Röösli M (2013) Impact of one's own mobile phone in stand-by mode on personal radiofrequency electromagnetic field exposure J Expo Sci Environ Epidemiol 23:545-548 doi:10.1038/jes.2012.97

Valentini E, Ferrara M, Presaghi F, De Gennaro L, Curcio G (2010) Systematic review and meta-analysis of psychomotor effects of mobile phone electromagnetic fields Occup Environ Med 67:708-716 doi:10.1136/oem.2009.047027

Valic B, Kos B, Gajsek P (2015) Typical exposure of children to EMF: exposimetry and dosimetry Radiat Prot Dosimetry 163:70-80 doi:10.1093/rpd/ncu057

Valic B, Trcek T, Gajsek P (2009) Personal exposure to high frequency electromagnetic fields in Slovenia. Paper presented at the Joint Meeting of the Bioelectromagnetics Society and the European Bio Electromagnetics Association, Davos, Switzerland, 14–19 June 2009

Varsier N et al. (2015) A novel method to assess human population exposure induced by a wireless cellular network Bioelectromagnetics 36:451-463 doi:10.1002/bem.21928

Viel JF, Cardis E, Moissonnier M, de Seze R, Hours M (2009) Radiofrequency exposure in the French general population: band, time, location and activity variability Environ Int 35:1150-1154 doi:10.1016/j.envint.2009.07.007

Vrijheid M et al. (2009a) Recall bias in the assessment of exposure to mobile phones J Expo Sci Environ Epidemiol 19:369-381 doi:10.1038/jes.2008.27

Vrijheid M et al. (2009b) Determinants of mobile phone output power in a multinational study: implications for exposure assessment Occup Environ Med 66:664-671 doi:10.1136/oem.2008.043380

WHO (2010) WHO Research Agenda for Radiofrequency Fields.

Willemse I, Waller G, Süss D (2014) JAMES Jugend, Aktivitäten, Medien - Erhebung Schweiz, Factsheet Befunde 2014. Zurich University of Applied Sciences.

Yang YS, Yen JY, Ko CH, Cheng CP, Yen CF (2010) The association between problematic cellular phone use and risky behaviors and low self-esteem among Taiwanese adolescents BMC Public Health 10:217 doi:10.1186/1471-2458-10-217

Yen CF, Tang TC, Yen JY, Lin HC, Huang CF, Liu SC, Ko CH (2009) Symptoms of problematic cellular phone use, functional impairment and its association with depression among adolescents in Southern Taiwan J Adolesc 32:863-873 doi:10.1016/j.adolescence.2008.10.006

Young KS (1996) Internet Addiction: The Emergence of a New Clinical Disorder. Paper presented at the 104th Annual Meeting of the American Psychological Association, Toronto, Canada, 1996

Zheng F et al. (2014) Association between mobile phone use and inattention in 7102 Chinese adolescents: a population-based cross-sectional study BMC Public Health 14:1022 doi:10.1186/1471-2458-14-1022

Zulkefly SN, Baharudin R (2009) Mobile Phone Use Amongst Students in a University in Malaysia: Its Correlates and Relationship to Psychological Health European Journal of Scientific Research 37:206-218

Publication list of the HERMES study

In the following, the publications that resulted from the HERMES study are listed.

Included in this thesis

Article 1
Foerster M., Roser K., Schoeni A., Röösli M. (2015) Problematic mobile phone use in adolescents: derivation of a short scale MPPUS-10. Int J Public Health. 60(2):277-286. doi: 10.1007/s00038-015-0660-4

Article 2
Roser K., Schoeni A., Foerster M., Röösli M. (2015) Problematic mobile phone use of Swiss adolescents: is it linked with mental health or behaviour. Int J Public Health. 61(3):307-15. doi:10.1007/s00038-015-0751-2

Article 3
Roser K., Schoeni A., Struchen B., Zahner M., Fröhlich J., Röösli M. (2017) Personal radiofrequency electromagnetic field exposure measurements in Swiss adolescents. Environ Int. 99:303-314. doi: 10.1016/j.envint.2016.12.008

Article 4
Roser K., Schoeni A., Bürgi A., Röösli M. (2015) Development of an RF-EMF Exposure Surrogate for Epidemiologic Research. Int J Environ Res Public Health. 12(5):5634-5656. doi: 10.3390/ijerph120505634

Article 5
Roser K., Schoeni A., Röösli M. (2016) Mobile phone use, behavioural problems and concentration capacity in adolescents: a prospective study. Int J Hyg Environ Health. 219(8):759-769. doi: 10.1016/j.ijheh.2016.08.007

Included in Anna Schöni's thesis

Schoeni A., Roser K., Röösli M. (2015) Symptoms and Cognitive Functions in Adolescents in Relation to Mobile Phone Use during Night. PLoS One. 10(7):e0133528. doi: 10.1371/journal.pone.0133528

Schoeni A., Roser K., Röösli M. (2015) Memory performance, wireless communication and exposure to radiofrequency electromagnetic fields: A prospective cohort study in adolescents. Environ Int. 85:343-351. doi: 10.1016/j.envint.2015.09.025

Schoeni A., Roser K., Röösli M. (2017) Symptoms and the use of wireless communication devices: a prospective cohort study in Swiss adolescents. Environ Res. 154:275-283. doi: 10.1016/j.envres.2017.01.004

Schoeni A., Roser K., Röösli M. (2016) Symptoms in Swiss adolescents in relation to exposure from fixed site transmitters: a prospective cohort study. Environ Health. 15(1):77. doi: 10.1186/s12940-016-0158-4

Curriculum vitae

Name	Katharina Roser
Date of birth	30th July 1986
Nationality	Swiss

Education

2012 – 2015	**PhD in Epidemiology** at the Swiss Tropical and Public Health Institute (Swiss TPH) in Basel
2008 – 2011	**Master of Science in Mathematics** at the University of Basel
2005 – 2008	**Bachelor of Science in Mathematics** at the University of Basel
2000 – 2005	**Matura** at the Gymnasium Kirschgarten in Basel with main subject "physics and applications in mathematics" ("Physik und Anwendungen der Mathematik")

Advanced training

2012 – 2015

Epidemiological Concepts, University of Basel, 3 ECTS

Data analysis in Epidemiology, University of Basel, 2 ECTS

Epidemiological exposure assessment, University of Basel, 1 ECTS

Statistical modelling, University of Basel, 2 ECTS

Introduction to the statistical Software R, SSPH+ PhD Program in Public Health, 0.75 ECTS

Epidemiological Data Analysis: Advanced Methods for Exposure-Response Modeling, SSPH+ PhD Program in Public Health, 2 ECTS

Conducting qualitative research in health: Data Analysis, SSPH+ PhD Program in Public Health, 1 ECTS

Biostatistics II, University of Basel, 4 ECTS

Analysis of Data with Measurements Below the Detection Limit, SSPH+ PhD Program in Public Health, 1 ECTS

Multilevel Modeling: Analysis of Clustered Data, SSPH+ PhD Program in Public Health, 1 ECTS

Chronic disease and molecular epidemiology, University of Basel, 1 ECTS

Advanced Stata programming, University of Basel, 1 ECTS

Key Issues in International and Public Health, University of Basel, 2 ECTS

GIS for Public Health, SSPH+ PhD Program in Public Health, 1.5 ECTS

Statistical analysis with missing data using multiple imputation and inverse probability weighting, Swiss Epidemiology Winter School 2014, 1.5 ECTS

Writing a journal article – and getting it published, Swiss Epidemiology Winter School 2014, 1.5 ECTS

Systematic Reviews and Meta-Analysis: a Practical Approach, SSPH+ PhD Program in Public Health, 1 ECTS

Causal Inference in Observational Epidemiology, Swiss Epidemiology Winter School 2015, 1.5 ECTS

Workshop: Introduction to Structural Equation Modeling with R and lavaan, PhD Program in Health Sciences, Luzern, 1 ECTS

Teaching activities

2012 – 2015 Assistance of lecture *Infection biology and epidemiology* for students in Biology, University of Basel

Tutorial *Epidemiological Methods* for students in Master of Science in Epidemiology, University of Basel

Statistics Practical for students in Medicine, University of Basel

Tutorial (Körper – Subjekt – Umwelt) for students in Medicine, University of Basel

Assistance of lecture *Biostatistics*, University of Basel

List of publications

Peer-reviewed publications

See *publication list of the HERMES study*.

Other publications

Röösli M., Roser K., Schoeni A., Rechsteiner D., Foerster M. (2014) Verhaltensprobleme durch Handynutzung?. Bildung Schweiz (3) 7-8.

Röösli M., Foerster M., Roser K., Schöni A., Urbinello D., Struchen B. (2015) Strichprobenkonzept für Messungen der nicht-ionisierenden Strahlung mit Exposimetern. Basel: Schweizerisches Tropen- und Public Health-Institut, im Auftrag des Bundesamtes für Umwelt (BAFU).

Conference contributions

Oral presentations

16.08.2013 Integrated electromagnetic field exposure assessment: modelling, personal measurements, questionnaires, mobile phone traffic data and apps

Roser K., Schoeni A., Röösli M.

Swiss Public Health Conference 2013, Zürich, Switzerland

22.08.2013 Propagation modelling, mobile phone traffic data, questionnaires, personal measurements and mobile phone apps: an integrated approach for exposure assessment

Roser K., Schoeni A., Röösli M.

Environment and Health Conference of ISEE, ISES and ISIAQ 2013, Basel, Switzerland

21.10.2014 Development of an RF-EMF exposure surrogate for epidemiologic research from modelling, personal measurements and operator data

Roser K., Schoeni A., Röösli M.

ISEE-Europe 2014, Barcelona, Spain

22.05.2015 Personal RF-EMF exposure in Swiss adolescents

Roser K., Schoeni A., Röösli M.

AT-RASC 2015, Gran Canaria, Spain

Poster presentations

21.10.2012 HERMES Health Effects Related to Mobile phonE use in adolescentS: a prospective cohort study

Roser K., Schoeni A., Röösli M.

EMF Health Risk Research, Monte Verità, Switzerland

12.06.2013 RF-EMF exposure in schools in Central Switzerland

Roser K., Schoeni A., Röösli M.

BioEM 2013, Thessaloniki, Greece

24.08.2014 Development of an RF-EMF exposure surrogate for epidemiologic research from modelling, personal measurements and operator data

Roser K., Schoeni A., Röösli M.

ISEE 2014, Seattle, USA

Awards

2015 Young Scientist Award
AT-RASC 2015, Gran Canaria, Spain