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

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Introduction

Mobile phones are nowadays omnipresent, in particular among adolescents. A recent representative survey in 1,086 Swiss adolescents aged 12 to 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 7,000 adolescents aged 11 to 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 (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 1,508 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 1,508 German adolescents (Heinrich et al. 2010) and mobile phone calls were not found to be associated with ADHD symptoms in 2,422 Korean children (Byun et al. 2013) or inattention in 7,102 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.

Methods

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.

Exposures

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.

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.

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; Bürgi et al. 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.

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.

Outcomes

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.

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-minute 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 seconds. 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.

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 (< 50^{th} percentile) and two other categories defined by 50^{th} – 75^{th} percentile and > 75^{th} 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.

Results

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.

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.

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]	1'411.45 (2'277.75)	13.35	22'607.55	1'466.63	1'268.45 (2'243.28)	13.35	22'607.55	1'208.74	1'420.85 (1'978.51)	18.08	16'233.21	1'578.91	1'258.33 (1'850.67)	18.08	13'168.28	1'296.60
whole body dose [mJ/kg/d]	322.42 (451.85)	6.52	6'630.07	260.66	294.83 (384.63)	6.52	4'064.68	220.02	322.49 (430.77)	11.66	6'043.61	260.15	302.64 (467.86)	16.02	6'043.61	223.86
operator sample																
brain dose [mJ/kg/d]	-	-	-	-	209.83 (329.07)	14.45	3'400.08	181.72	-	-	-	-	234.50 (431.64)	22.62	4'787.14	175.88
whole body dose [mJ/kg/d]	-	-	-	-	122.58 (84.90)	11.72	607.05	100.62	-	-	-	-	124.54 (86.79)	16.23	756.06	84.08

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.

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).

	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	
	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)
Behavioural problems																	
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)*
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)
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)
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)
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)
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)*
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)*
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)
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)
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)
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)
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)*
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)
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)
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)

[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 means more strengths.
[e] Prevalence of problematic lack of *total strengths*.

Behavioural problems

In the cross-sectional analyses, *SDQ Adolescents total strengths* were not associated with any of the exposure variables (Table 3 and Figure 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 (Figure 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 Figures 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 3. Crude and 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. Significant results ($p < 0.05$) are indicated in bold. For corresponding figures see Figures 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)
SDQ Adolescents total difficulties				
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)
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)
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)
SDQ Adolescents total strengths				
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	0.04 (-0.02, 0.09)	0.03 (-0.02, 0.09)	0.01 (-0.10, 0.13)	0.00 (-0.13, 0.13)
SMS sent [x/d]				
Usage related to RF-EMF exposure	-0.08 (-0.28, 0.12)	-0.19 (-0.39, 0.01)	-0.01 (-0.25, 0.23)	0.06 (-0.19, 0.32)
self-reported	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 data traffic mobile phone [min/d]				
duration cordless phone calls [min/d]				
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	-0.02 (-0.06, 0.03)	-0.02 (-0.07, 0.02)	-0.08 (-0.20, 0.03)	-0.08 (-0.20, 0.04)
volume data traffic mobile phone [MB/d]				
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)
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)

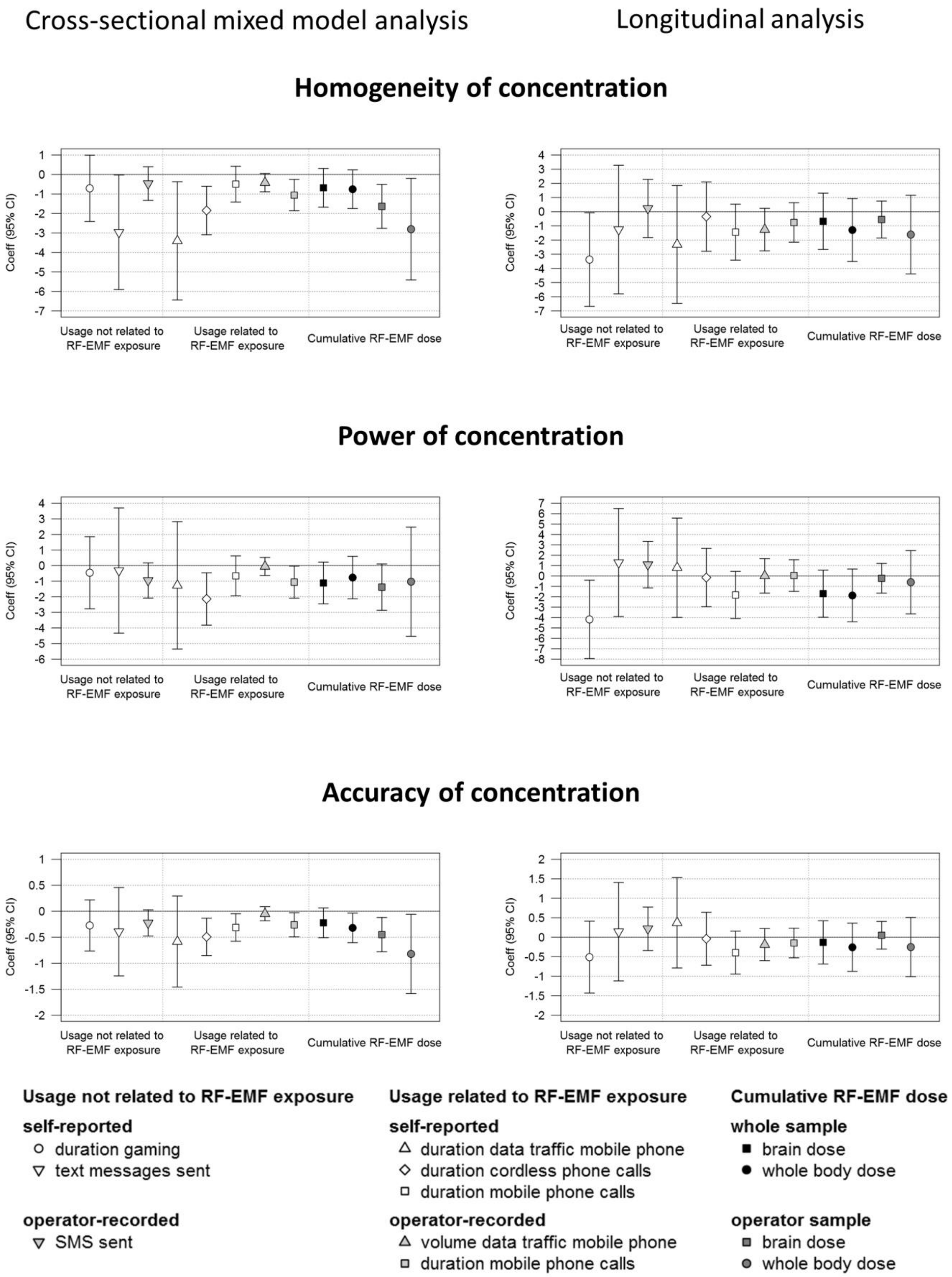
whole-body dose [mJ/kg/d]	-0.08 (-0.25, 0.09)	-0.08 (-0.25, 0.09)	-0.04 (-0.24, 0.15)	-0.03 (-0.24, 0.17)

[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.

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 (Figure 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).

Figure 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.



Personal measurements

In the subset of 91 adolescent with personal measurements, mean total RF-EMF exposure was 66.8 µW/m² (interquartile range = 64.5 µW/m), mean total exposure without uplink (mobile phone handsets) was 24.7 µW/m² (35.7 µW/m), mean fixed site transmitters exposure 17.0 µW/m² (16.0 µW/m) and mean downlink exposure (mobile phone base stations) 12.7 µW/m² (11.5 µW/m²). *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.

Table 4. Crude and adjusted 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.

	n[e]	crude Coeff (95% CI)	adjusted[f] Coeff (95% CI)
Behavioural problems			
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 parent's questionnaire).

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 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 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 minutes 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).

Conclusions

We have confirmed previous cross-sectional studies reporting associations between behavioural problems and self-reported duration of wireless devices. 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.

Acknowledgements

The HERMES study is funded by the Swiss National Science Foundation (project number 138190). Personal measurements were partly supported by the Swiss Research Foundation for Electricity and Mobile Communication (reference number 41). Many thanks go to the study participants and their parents for participating in the HERMES study.

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.

Competing financial interests

The authors declare no competing financial interests.

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Electronic Supplementary Material 1 Additional tables and figures for results for behavioural problems (SDQ), concentration capacity (FAKT) and personal RF-EMF measurements.